SCIENTIFIC AMERICAN

MAGNETIC BUBBLES

ONE DOLLAR

June 1971

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UOP IS WORKING TO SWEETEN THIS BABY'S BREATH.

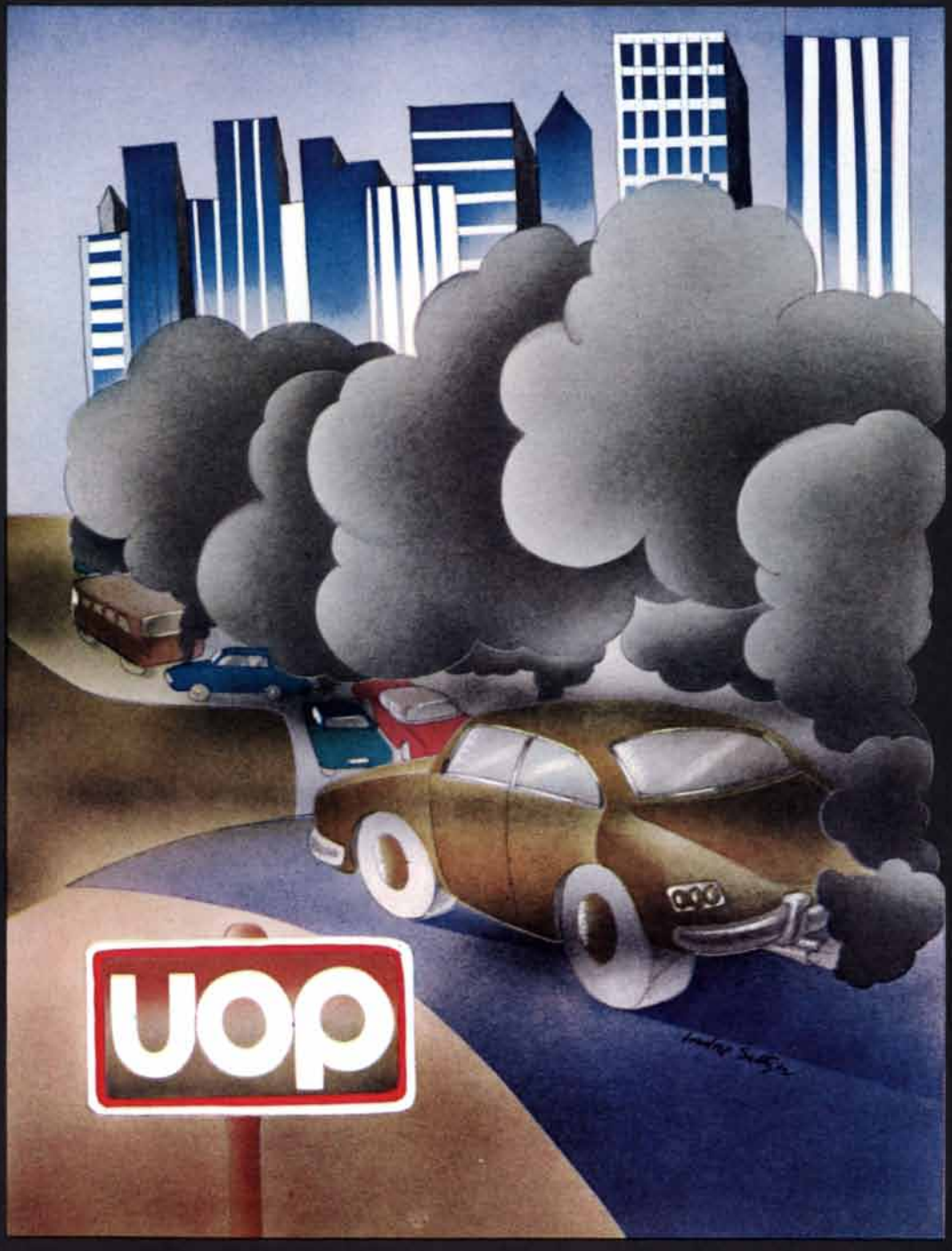
UOP is deeply involved in finding ways to eliminate automotive pollution—economically—for both industry and consumers.

For the automobile industry UOP has developed a muffler-like catalytic converter for cars using lead-free gasoline. It cleanses the exhaust of up to 90% of the nitrogen oxides, carbon monoxide and unburned hydrocarbons, meeting all published government standards.

Since catalytic converters operate at maximum efficiency with lead-free gasolines, UOP has developed economical refining processes for the petroleum industry to produce unleaded gasolines with octane ratings matching existing regular and premium fuels.

Thus UOP keeps up with the changing times, moving forward on two fronts against the mounting crisis of automotive pollution.

UOP is the nation's leading supplier of processes and technology for the petroleum industry to produce automotive fuels and for desulphurizing other petroleum products. In a related area the company manufactures a broad line of industrial air and water pollution control equipment.



UOP

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"Why pay more than $65 a month for a time-sharing terminal?"

Z. V. Zakarian, president, Western Union Data Services Company.

For $65 a month you can lease a Model 33 ASR exchange data terminal with acoustic coupler from Western Union Data Services Company for use with any telephone anywhere in your company. And chances are $65 is a lot less than you are presently paying.

The exchange data terminal 33 works with virtually all time sharing services. So even if you're not currently using this terminal, there's a good chance the 33 is compatible. (To make sure, just ask your time sharing service.)

If your requirements call for Model 33's Data-Phone,* or Data Access Arrangements, we can supply them too at equally attractive rates. We even have terminals with wheels so you can move them to any office location.

Regardless of which data terminal configuration you select, you can depend on Western Union Data Services Company for nationwide servicing, applications engineering, training and support.

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western union data services company

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SCIENCE/SCOPE

A laser cloth-cutting system -- described as "the first major advance in apparel manufacturing since the sewing machine" -- was demonstrated recently by Genesco, Inc., world's largest apparel company, and Hughes, the system's developer. It consists of a computer which stores programmed cutting instructions, a positioning device, the laser, and a conveyor.

The laser beam cuts garments one at a time from a single layer of cloth with amazing speed and much greater accuracy than the old method, which cuts them from many layers. The laser head is stationary; its beam is directed by a pentaprism arrangement of silicon mirrors along the outline of the pattern programmed by the computer.

The DC-10 multiplex passenger entertainment and service system, which will go into regular passenger service aboard the McDonnell Douglas jumbo jet later this year, is now in service in the first class sections of a Boeing 747 which American Airlines retrofitted in order to evaluate the Hughes-built system. It provides a choice of 12 stereo or monaural music programs and two movie sound tracks, plus control of reading lights and attendant call lights and chimes. Use of multiplexing techniques and Hughes' custom metal oxide semiconductors and hybrid devices results in a weight saving of over 400 pounds in aircraft wiring.

A lightweight hand-held holography camera, which Hughes originally developed for NASA to determine the feasibility of taking three-dimensional microscopic photos of the lunar surface, may have important industrial applications. Its 3-D images would be valuable for non-destructive testing, stress and vibration analysis, biomedical and industrial microscopy, and flow-field visualization in wind tunnel testing of aircraft designs. The holocamera weighs only 17 lbs. and fits into a 12x13x6-inch case.

Early Bird celebrated its sixth birthday by relaying the first message ever sent directly from Hawaii to the east coast of the U.S. by a commercial satellite. The pioneer synchronous communications satellite, designed to operate for 18 months, was retired in 1969 after operating over the Atlantic for almost four years. Today, its fuel exhausted, Early Bird is drifting in orbital retirement over the Pacific.

Microwave Engineers: the expanding market for advanced microwave amplifiers and multipliers utilizing transistors and IMPATT and Varactor diodes is creating career opportunities at Hughes' Electron Dynamics Division. Requirements: EE degree and experience in the design and development of solid state amplifiers, multipliers, cavities, filters, and ferrite devices. Please write: Mr. R. F. Wolfe, Hughes EDD, P.O. Box 2999, Torrance, CA 90509. Hughes is an equal opportunity employer.

An all-plastic missile body has been developed for the U.S. Air Force by Hughes. Plastic reinforced with chopped glass fibers is molded into four identical segments, which are then bonded together. During two structural tests, there were no failures below the design levels at temperatures up to 270°F and missiles tested to destruction withstood two times the required loads. Advantages of plastic missile bodies include low cost, reduced radar reflection, greater resistance to corrosion and fewer accidental dents and scars from field handling.

Creating a new world with electronics

HUGHES

HUGHES AIRCRAFT COMPANY

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Established 1845 **SCIENTIFIC AMERICAN** June 1971 Volume 224 Number 6

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THE COVER

The photomicrograph on the cover shows a simple experimental "track" of Permalloy *T*'s and bars printed lithographically on the surface of a magnetic material within which magnetic "bubbles" can be made to appear. In the article "Magnetic Bubbles" (*page 78*) Andrew H. Bobeck and H. E. D. Scovil of the Bell Telephone Laboratories describe how cylindrical magnetic domains ("bubbles") have been made the basis for a new high-density information-storage technology. In the picture on the cover the magnetic wafer is in a neutral condition, with the magnetic domains taking the form of serpentine strips. Because half of the wavy domains point up and half point down they rotate polarized light in opposite directions and thus can be made to appear bright and dark when photographed through a polarizing filter. By immersing the wafer in an external magnetic field perpendicular to its surface, one set of domains can be made to expand while the set of opposite polarization shrinks. At a certain critical value of the external field the shrinking domains that have only a single wall contract into bubbles (*see illustration on page 81*). By applying an in-plane rotating magnetic field the bubbles can be made to follow the pattern of *T*'s and bars, as illustrated in the second sequence from the top on page 86.

THE ILLUSTRATIONS

Cover photograph by Ben Rose

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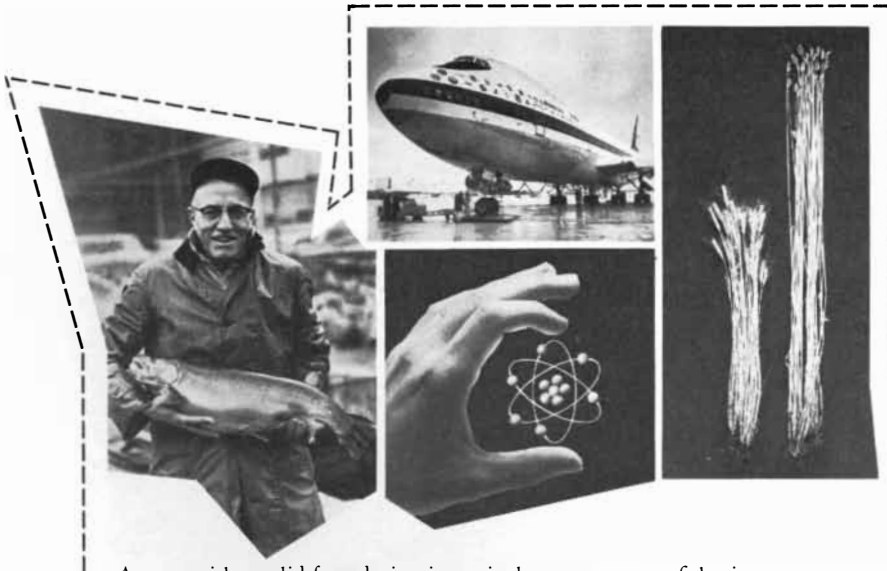
Explore the future in Washington State.



A state with a solid foundation in agriculture, aerospace, fisheries, forestry, nuclear energy and research, Washington is a fertile field for the exciting new breakthrough industries of the future. Washington State can supply the skilled, highly-educated and imaginative people that are vital to the growth of new industry. Washington State has a wealth of natural resources and is uniquely accessible to the national and world marketplace. In fact, *everything* your new plant or facility needs to flourish is ready to go in Washington State. Explore Washington . . . chances are you'll find what you want.

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Governor, State of Washington

Washington, I'm interested!

Daniel B. Ward, Director
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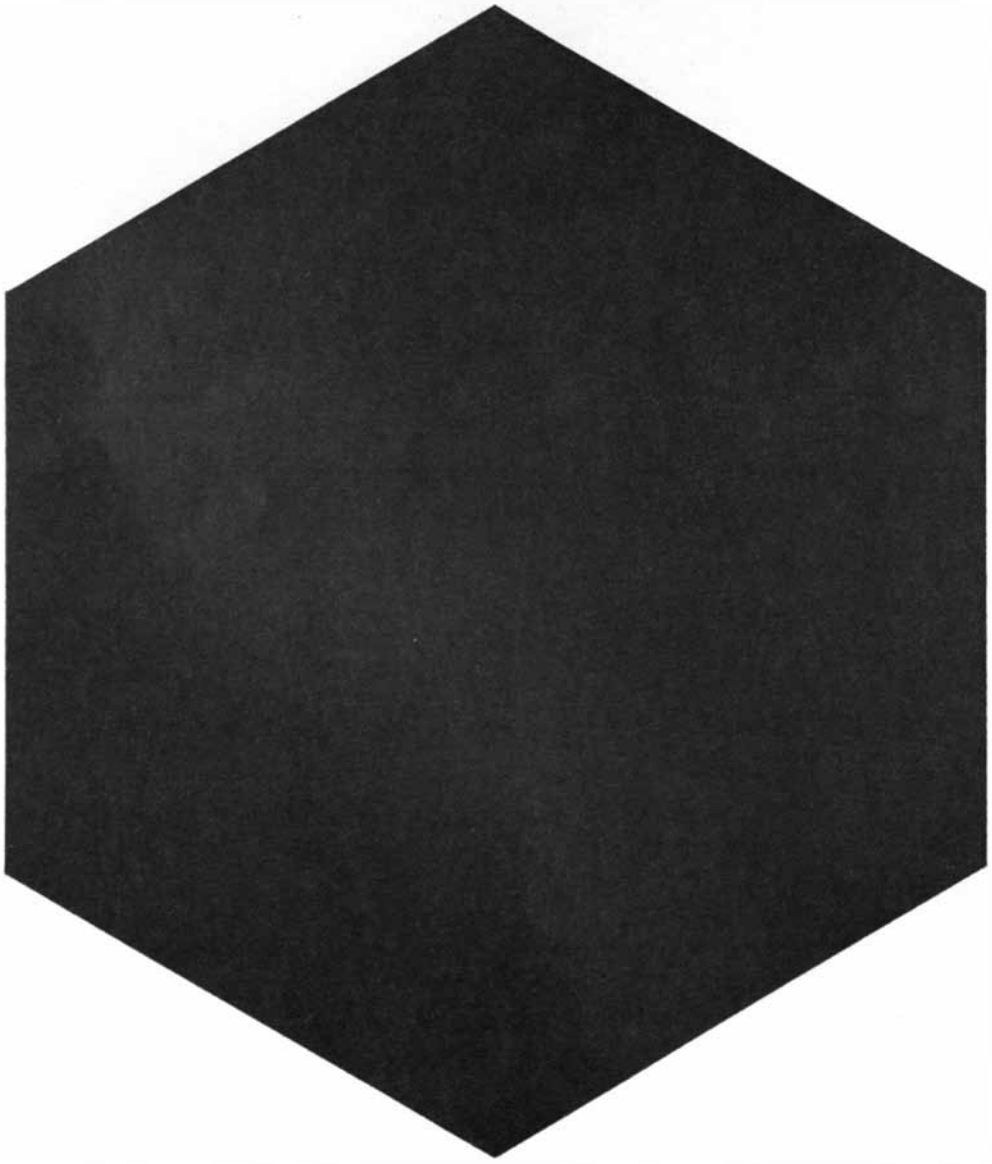
This is how most oil companies perceive something.



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This is how we perceive it.

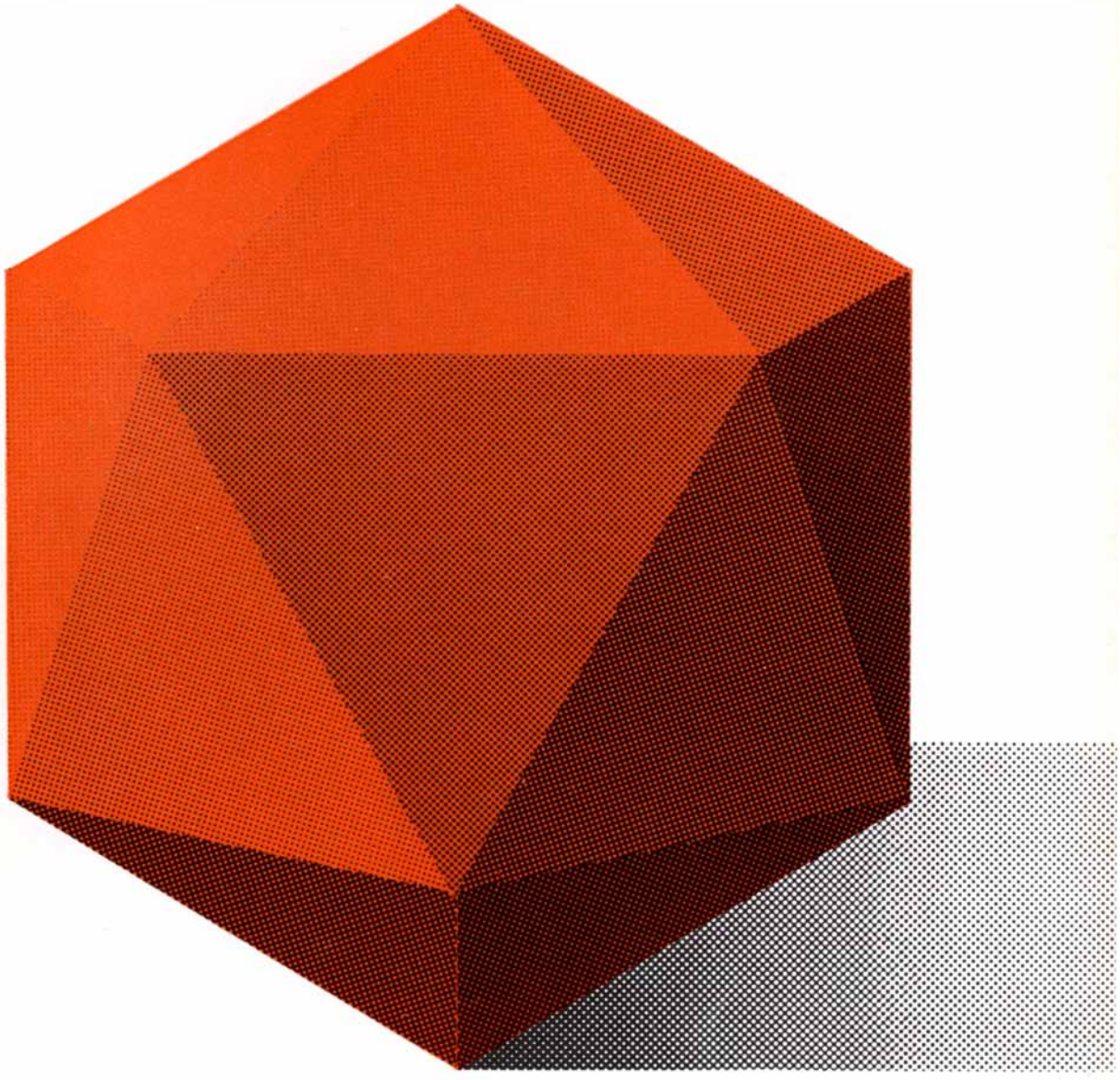
We don't see things for what they are. We see what they might become.

Almost every oil company starts with crude oil. We look at it and see our next new industrial oil.

And we don't stop working on it until we have the kind of industrial oil that's newer and better than anyone else can offer. That's why we're important to you.

AMERICAN

American Oil Company



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CalComp doesn't claim to be driving IBM right out of the business, of course.

But together with our disk drive subsidiary, Century Data, we're claiming a pretty fair share of the market. And a bigger share every month.

Last month, for example, we received orders for more than 300 disk drives.

And while over 90 percent of them will replace compatible IBM devices, we doubt if IBM will replace any of ours. For several reasons.

First, with average access times of 30 to 35 milliseconds, our disk drives are twice as fast as theirs.

Second, with electromagnetic positioning instead of mechanical pawls, detents and gears, ours are simply more reliable.

And third, ours cost less. Ten percent less on a year's lease than IBM's new, low-priced 2319 system, to be exact.

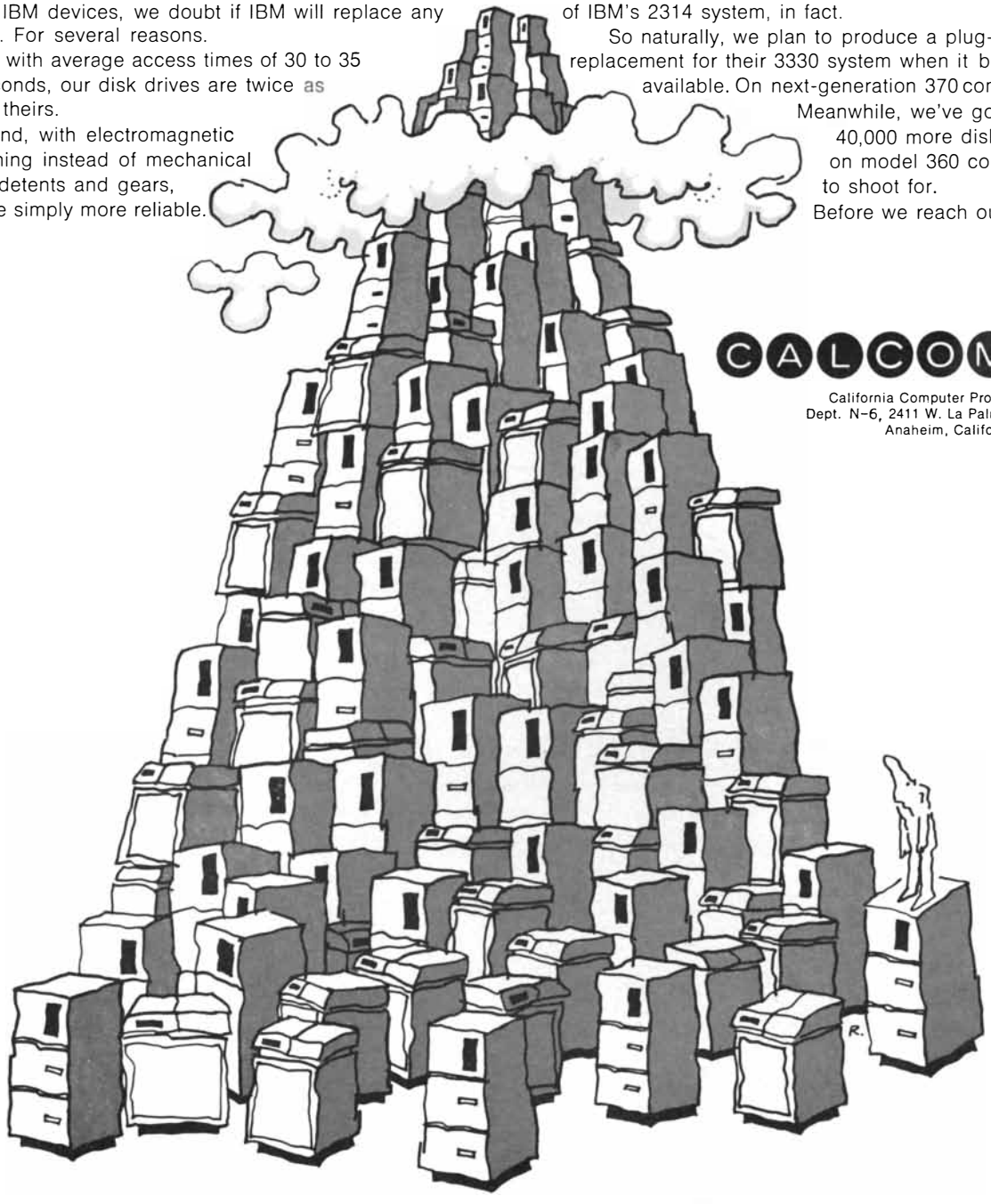
What's more, we've announced a new system of our own, called the CD 1015/215. In addition to being twice as fast as anything IBM delivers, it costs less and stores twice as much per spindle.

CalComp is the leading independent disk drive producer. The first independent to deliver a complete equivalent of IBM's 2314 system, in fact.

So naturally, we plan to produce a plug-to-plug replacement for their 3330 system when it becomes available. On next-generation 370 computers.

Meanwhile, we've got about 40,000 more disk drives on model 360 computers to shoot for.

Before we reach our peak.



CALCOMP

California Computer Products, Inc.
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WE REPLACED THIS MANY IBM DISK DRIVES LAST MONTH.

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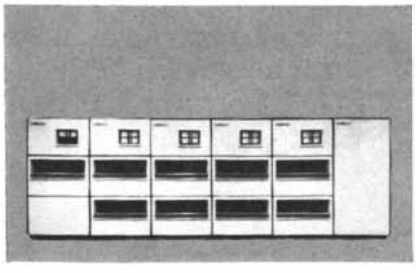

LETTERS

Sirs:

In their article "Annual Biological Clocks" [SCIENTIFIC AMERICAN, April] Eric T. Pengelley and Sally J. Asmundson present evidence for annual periodicity of physiological responses in man (e.g., quantity of 17-ketosteroids in the urine and variations in body weight and emotional state in manic-depressive subjects). I wish to draw attention to some relevant data from another field. In a study of ions in human cerebrospinal fluid (CSF) in relation to pathological conditions, Kobayashi and Kodama found a pronounced regular seasonal variation in potassium concentration ("Electrolytes in the Cerebrospinal Fluid in Children." Osamu Kobayashi and Buichi Kodama in *Mie Medical Journal,* Vol. 5, pages 97–107; 1955). The variation in normal subjects amounts to a decrease of 17 percent below the annual mean in summer and about 20 percent above the mean in winter. The standard deviations in their data lie in the range of 3 to 6 percent, and the effect appears to be significant. These workers also report seasonal variations for magnesium (high in summer, low in winter) and calcium (high in winter, low in summer) but to a smaller extent than for potassium. Changes in chloride ion were also found.

I suggest that concentrations of inorganic ions in fluids of the central nervous system may be of value in research on annual periodicity in animals and man.

PAUL GOLDBERG

Polaroid Corporation
Cambridge, Mass.

Sirs:

Michael C. Corballis and Ivan L. Beale have written an interesting article on handedness ["On Telling Left from Right"; SCIENTIFIC AMERICAN, March]. They have mentioned that there is no tenable theory to explain the predominance of right-handed individuals.

I should like to add hypothesis to the scene. It is based on the position of the fetus prior to delivery. The great majority of fetuses engage in a vertex position (head down). Of these two-thirds are in a left presentation. A transcription of the last sentence means that the fetus in the majority of cases has the left side of its body pressed up against the uterine wall. The right side, particularly the upper extremity, has more room to move in the amniotic fluid as it is not pinned by the body against the tough muscular wall. The period of engagement (entrance into the uterine canal in preparation for labor) may be weeks for a primipara (first delivery) to hours for a multipara (previous deliveries).

It is postulated, particularly for a primipara, that the right upper extremity being more mobile can be the field for the development of kinesthesis, perhaps at a maturation level where a little time advantage might be significant.

Therefore a newborn may have had an earlier facilitation for right-handedness in a two-thirds majority. At this point an objection can be raised that two-thirds does not approach the proportions of right-handedness in the populace. Then at this point sociology replaces obstetrical anatomy. The majority by social pressure will tend to increase at the expense of the minority—as it is "really the right way to do things."

HARVEY P. KOPELL, M.D.

New York University School of Medicine
New York, N.Y.

Scientific American, June, 1971; Vol. 224, No. 6. Published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Gerard Piel, president; Dennis Flanagan, vice-president; Donald H. Miller, Jr., vice-president and treasurer.

Editorial correspondence should be addressed to The Editors, SCIENTIFIC AMERICAN, 415 Madison Avenue, New York, N.Y. 10017. Manuscripts are submitted at the author's risk and will not be returned unless accompanied by postage.

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NAME

NEW ADDRESS

OLD ADDRESS

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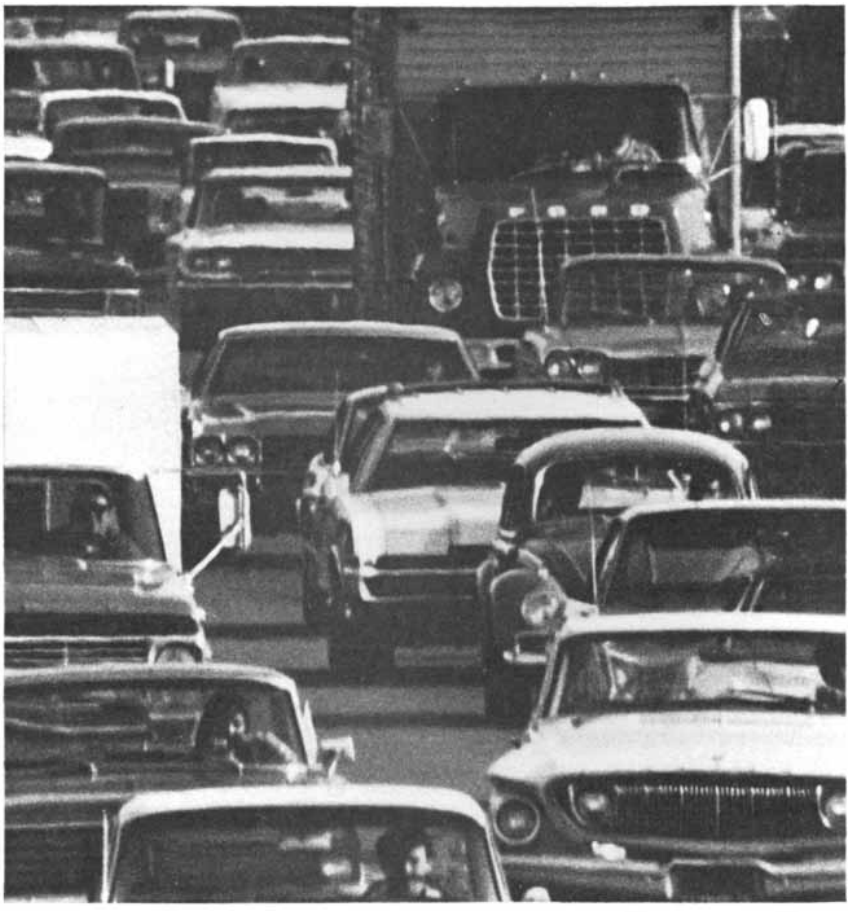
Some things are changing for the better.



Radar for the family car

For years, Sunday supplement writers have been predicting the use of radar in the family car to detect approaching vehicles and automatically avoid collisions. Although technically feasible, the idea has been completely impractical because the equipment required to measure closing velocities is much too large, takes too much power, costs over $1000, and is notoriously unreliable.

That was yesterday. Auto safety engineers can now seriously contemplate doing this part of the job with the new HP 35200A Doppler Radar Module. It weighs six ounces, operates on a few watts of 12-volt power, can be produced for less than $100 in volume and is intrinsically more reliable than almost any other part of the modern automobile. Yet it measures speed within 0.01%, easily surpassing the accuracy required for automotive use as well as for continuous traffic flow control, intrusion alarms, and rapid rail transit control.

No scientific breakthrough underlies this improvement but rather the painstaking development of a new manufacturing art that extends the advances of integrated circuits (IC's) — lower cost, greater reliability — to microwave frequencies. The products of this new technology, "thin-film hybrid IC's", get their name from the fact that all passive circuit elements and the transmission paths between them are deposited as thin films on a jewel substrate, while the active elements (transistor and diode chips) are bonded in place later. The emphasis is on achieving the circuit performance and transmission line characteristics that are essential at microwave frequencies, while preserving the dramatic cost and reliability advantages of IC's.

At HP, thin film technology has been a reality for more than two years. We produce thousands of circuits a month, some for use in our own microwave instruments, some for shipment as components. We'll be glad to answer your inquiry on our thin-film capability or send you a description of the 35200A Doppler Radar Module.

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The wavelength: a better way to measure distance

The surveyor's way of measuring distance has not really changed since before the days of the Pharaohs. He still uses an accurate ruler — engineer's chain or a surveyor's tape, usually 100 feet long — and painstakingly measures his course with it. Although extremely slow, the method has survived the ages because it was the only accurate way of doing the job.

But things are finally changing for the better. A new HP instrument, the 3800A Distance Meter, makes it possible for the surveyor to be free of his ancient chain and yet measure distance accurately in one-tenth the time, with a crew of two rather than three men.

The 3800A makes its measurements by comparing the unknown distance to the precisely measured wavelength of a modulated beam of infrared light. Here's how it works. The modulated beam is chopped 30 times a second and alternately split into two paths — an external path which is aimed at a retro-reflector placed at the other end of the course, and an internal reference path. When the two beams are recombined at the receiver optics, the phase of the reflected beam lags behind that of the reference beam a discrete amount, depending on the distance to the reflector. The 3800A measures the phase shift and converts it to distance.

Because the infrared beam is modulated at four different frequencies, it has an effective wavelength of 10, 100, 1000 and 10,000 feet, thus allowing the surveyor to make any measurement within the range of the instrument without ambiguity. He first nulls the instrument at the highest frequency to establish the fraction of 10 feet; then at successively lower frequencies, to establish the fraction of 100, 1000 and 10,000 feet respectively. The final measurement, corrected for air temperature and pressure, is completed in less than two minutes and read directly on the instrument's digital register to a resolution of 0.002 foot and an accuracy of 0.01 foot plus 10 ppm.

Measurement is continuous since the 3800A's internal reference system automatically calibrates it 30 times each second. Momentary interruptions due to traffic in the line of sight therefore do not affect the measurement. By the same token, the 3800A can be used to detect the sway of buildings and the movements of glaciers.

The new instrument weighs 17 pounds and its separate power unit, 13 pounds. Cost is less than $5000.

A practical way to automate a GC lab—one step at a time

Although gas chromatographs (GC's) are built for around-the-clock operation, most of them are used only a few hours each day. Since most GC labs operate on an eight-hour day, it simply has not made good economic sense to add a second and third shift simply to realize a fuller utilization of the GC's.

But that's no longer the only solution. Some new instruments have recently appeared on the scene that allow you to triple the output of your GC lab without increasing your staff or number of GC's. And you can do it a step at a time as your budget allows.

First there's the 7670A Automatic Sampler. Since it injects as many as 36 samples consecutively into a GC, completely unattended, it allows a single chromatographer to keep a GC productive around the clock, making well over 200 runs a week — triple his best output with manual injections. Cost is $2850.

Then there's the 3370A Integrator. It automatically quantitates the GC analysis, cutting about 10 minutes of computation per sample. Apply this to a 7670A-equipped GC and you eliminate 30 hours a week from the chromatographers' load, enough to pay for the 3370A, which costs $4950, in about four months.

The third and most decisive step to full automation is the 3360A GC Data Processing System, whose HP 2114B Computer is fully programmed for GC. It processes data simultaneously from eight GC's and automatically prepares a complete typewritten report of each analysis, cutting an additional 20 minutes of computation per sample. To understand its impact on a GC lab that has eight 3370A-equipped GC's, one must realize that the 3360A costs less than $20,000 installed, and that it is theoretically capable of processing 6000 samples a month. Even if you use the 3360A for as few as 1000 samples monthly, it will cut more than 300 hours of computation from your manpower budget, enough to pay its entire cost in little more than six months.

Write for the Fall 1970 issue of Analytical Advances, a 32-page study of the technology and economics of HP's step-by-step automation for the GC lab.

For those concerned with electrical safety as it affects the hospitalized patient, we have just published a 28-page booklet to help evaluate the level of electrical safety in existing installations and in designing new patient care areas. You may obtain this booklet or the other material mentioned in this ad by writing Hewlett-Packard, 1504 Page Mill Road, Palo Alto, California 94304; Europe: 1217 Meyrin-Geneva, Switzerland.

00110

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Measurement, Analysis, Computation

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

JUNE, 1921: "In his lecture on the structure of the atom Sir Oliver Lodge states that we may well fear future wars if the terrible secret of how to utilize the energy contained in the atom falls into the hands of an uncivilized power. Not only human life but also the whole planet could be destroyed, he asserts. Radium discharges alpha particles with sufficient force to carry them around the world in a fraction of a second at a velocity that is really only a little bit slower than that of light. This power is dormant in each atom; if we ever learn how to release and control it for our own purposes, the fuel shortage will mean nothing at all in our lives, and the invention of ways for making synthetic gasoline will go wholly out of vogue, because such fuels will be ruinously expensive alongside the atomic source of energy."

"Medieval theologians have been ridiculed because they debated how many angels could stand on the point of a pin. Prof. R. A. Millikan of the University of Chicago gives science's answer to a modern problem that is more or less comparable to this one when he isolates and measures an electron; he has recently been catching individual atoms and counting the number of electrons which each one has lost when an alpha particle from radium shoots through it. Science for some time has divided the 'indivisible' atom into its constituent parts and identified certain of these as electrons, but Prof. Millikan is the first to catch and exactly measure the charge carried by each one of these particles. Moreover, he can count the exact number of them which he has caught in a minute oil-drop, with quite as much certainty as he can enumerate his fingers and toes!"

"Dr. Hale's last annual report as director of the Mount Wilson Observatory states that with the completion of the observing platforms at the principal and Cassegrainian foci and the installation of the constant-temperature control systems for the 100-inch mirror, the great Hooker telescope—the largest in the world—is now essentially complete."

"Summer is at hand, and anything cooling is of interest. In this connection it may be asked how the reader would like to have a choice of five kinds of ice? The possibility of such a choice is not far away, according to recent discoveries in experimental science. And together with the new facts about ice, other amazing discoveries have been made. Among them is the fact that steel can be stretched more than its own length without breaking; that ordinarily soft and flexible substances are found to increase their stiffness under pressure; that water can be decreased in volume almost at will. The experiments at high pressure outlined, with others, are being conducted by Dr. P. W. Bridgman of the Jefferson Physical Laboratory at Harvard University."

"Dr. V. M. Slipher of the Lowell Observatory reports that changes in the structure of the Crab Nebula have been detected with the Lowell refractor. These observations are based on examinations of 15 photographs covering an interval of eight years."

"After the experiences of Dr. Einstein and Madame Curie, Major Leonard Darwin, fourth son of Charles Darwin, who is to visit us this summer, should come incognito or he will be killed by kindness and the reporters."

SCIENTIFIC AMERICAN

JUNE, 1871: "During the recent siege of Paris, Henry St. Claire Deville, one of the most illustrious and at the same time genial and popular of the scientific men of France, made an address to the members of the Academy of Sciences, which was the occasion of earnest debate. Deville stated, what all the world had been uttering before him, that France was conquered by the science of Germany. The very discoveries and inventions of their own men were used to destroy them. In seeking for an explanation of this disastrous state of affairs, Deville gave two adequate reasons: first, that men of science had been overlooked by the Government, and mere politicians appointed in their places; and second, that the members of the Academy had devoted themselves too exclusively to abstract science and left the world to find out what was going on in the best way it could. He proposed as a security that the Institute should appoint committees to discuss all matters relating to the Government; and at the same time seek to popularize science, and by well-edited publications to familiarize the public mind with the grand discoveries of the day."

"In the matter of popularizing science we in the United States can safely challenge criticism. There is scarcely a newspaper, magazine or weekly that has not a special scientific department, and SCIENTIFIC AMERICAN, in the course of a year, furnishes an account to its readers of every discovery or invention of importance that is made in every part of the world. The result of this wide dissemination of knowledge is that the American people are famous for their practical talent. The universal Yankee is a mystery to European nations, as they have no analogous character with which to compare him. There is more danger of our running to the opposite extreme, and of our rendering scientific knowledge superficial by too great a desire for popularizing it. It is better to strike an average, and to secure well-endowed universities as well as technological institutes."

"The famous old Novelty Works in this city, now presents an aspect of desolation. The entire floor of the principal building is empty, save that in the center stands a flying machine. We know not who is the inventor of this machine. As many of our readers are interested in the subject of aerial navigation, we place before them a description of the mechanism. It is designed to be driven by steam. A two-horsepower vertical boiler is supported on a light frame at the bottom of the machine. At one side of the top of this frame is placed one of Root's rotary engines. On the shaft of this engine is a miter gear which meshes into two others. The two driven gears are respectively keyed to a solid shaft and a hollow shaft, the former rising vertically through the latter. Thus equal but reverse motion is secured in the two shafts. Each shaft carries a propeller screw made of a light metallic framework, with blades of canvas stretched over skeleton frames of iron. We judge the diameter of the counter propellers thus formed to be about 20 feet. The object of giving them reverse motion is evidently to prevent the machine from spinning around on its vertical axis. These propellers must exert considerable elevating power, but the weight of the machine is evidently greater than their capacity."

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Basic Research at Honeywell
Research Center
Hopkins, Minnesota

PN Junctions in Mercury-Cadmium Telluride

Developments in pn junction technology in mercury-cadmium telluride will permit scientists to integrate electronics with infrared detectors.

Developments in solid state physics in the last fifteen years have provided a number of photodetector materials that are sensitive in the visible and infrared portions of the electromagnetic spectrum. Mercury-cadmium telluride, an alloy semiconductor resulting from a development that began ten years ago, is the most promising of these, but integrating it with electronic circuitry has been a formidable problem.

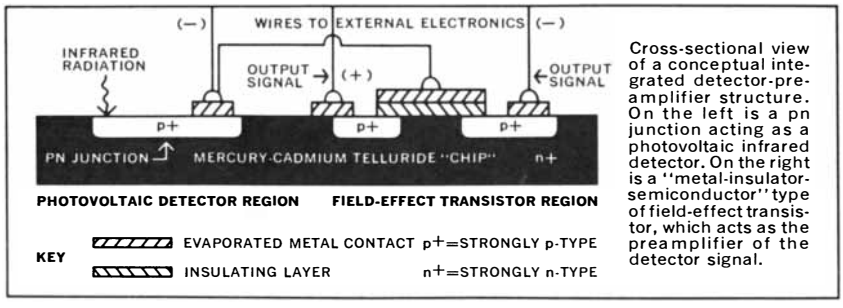
The alloy nature of mercury-cadmium telluride gives it a unique capability as a photodetector material. Because HgTe and CdTe are compounds which are miscible in all proportions, an alloy of any desired composition can be made. Furthermore, the peak photosensitivity of the alloy varies directly with its composition. Therefore it is possible to use these alloys as the materials for infrared detectors covering the wavelength interval from about 0.8 to well beyond 30 microns, or virtually all of the infrared spectrum.

Mercury-cadmium telluride detectors offer several new opportunities for infrared radiation detection, but as systems demands grow more complex, arrays of tens and even hundreds of detectors must be used. This makes electronic signal processing at the location of the detector more and more important. Electronic circuitry, therefore, will have to be integrated with the detector to amplify its signal before it is transmitted to the main electronics of the system for eventual readout.

The transistor is the active amplifying-switching device which is the heart of solid state electronics. A typical integrated electronic circuit consists of a collection of transistors, diodes, resistors and capacitors all built into a single chip of silicon, which is the most nearly ideal transistor material. However, silicon is unsuitable for detectors in general, because it is sensitive only at certain specific wavelengths. Some of these components would perform more efficiently if made out of other materials, but the nature of the transistor forces them all to be made of silicon if the circuit is to be fully integrated. This restriction has not usually been a severe problem, since the majority of electronic functions amenable to circuit integration are performed adequately by combinations of transistors and rather unsophisticated associated components. However, it is usually a handicap when it is necessary to integrate electro-optical devices. Therefore future systems will require another means of integrating signal processing with detectors.

Honeywell scientists have been moving toward a solution of this problem by developing the technology of pn junctions in HgCdTe, to permit integration of electronics in the same chip with HgCdTe infrared detectors.

After extensive research they have now developed a method of diffusing impurities into the mercury-cadmium telluride crystal to make pn junctions. This is similar to the process used for silicon transistors but HgCdTe is a new and complex material and it poses very difficult materials problems. For example, it is an alloy, and its composition must be carefully controlled. Also, mercury is volatile and tends to vaporize at low temperatures during the heating process.



Cross-sectional view of a conceptual integrated detector-preamplifier structure. On the left is a pn junction acting as a photovoltaic infrared detector. On the right is a "metal-insulator-semiconductor" type of field-effect transistor, which acts as the preamplifier of the detector signal.

The continuing pn junction technology which Honeywell is working on is now aimed at the integration of a single-stage preamplifier with a HgCdTe detector.

In addition to serving as the necessary element in a transistor, pn junctions can be used for other types of electro-optical devices such as photovoltaic detectors and infrared emitters. In a photovoltaic detector the junction separates the positive and negative charges produced by the radiation, developing a voltage across the junction. An advantage of photovoltaic detectors is that no external power supply is required to produce the photosignal, whereas photoconductive detectors must be activated. In large complex arrays this could be a great advantage.

Further advances in pn junction technology will result in several new applications of HgCdTe alloys. Infrared emitters involving a pn junction are one possibility. Since each chemical compound has a different spectrum, an infrared emitter could be used in spectrometers for pollution control and vapor detection. By measuring and monitoring the spectra of the molecules, the type and amount of vapors or pollutants could be identified.

Infrared detectors which measure the temperatures of objects by their emission of heat radiation in a variety of wavelengths are being used now in infrared mapping. In this case, a scene is scanned by an array of detectors which gives a point by point temperature profile. Once again, the crucial problem is information processing at the array.

If you are working in the area of infrared detectors or pn junctions, and want to know more about Honeywell's investigations, please contact Dr. Walter Scott, Honeywell Corporate Research Center, Hopkins, Minnesota. Honeywell carries out basic research in all of the sciences pertinent to its business at its Solid State Electronics Center, Plymouth, Minnesota, and Information Sciences Center, Cambridge, Massachusetts as well as its Corporate Research Center, Hopkins, Minnesota; under the direction of Dr. John Dempsey, Vice President of Science and Engineering.

Honeywell
The Automation Company

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You pay a lot of money for the seat belts and shoulder harnesses in your car.

How much more are you willing to pay?

One picture is worth a thousand words. Buckle your seat belt *and* harness.

We listen. Many of the letters we get relate to auto safety. People are concerned about auto safety. And their concern is fully justified.

Last year alone, 6,500 Americans never got where they were going—and never drove anywhere else again—simply because they didn't use the seat belts and shoulder harnesses they paid for in their automobile. And it's a fact 2 out of 3 drivers don't use seat belts.

That's some waste. Because safety belts, used or not, cost cold hard cash. The bill in unused equipment is several hundred million dollars a year. The cost in human life is immeasurable.

We'd like to discuss several other facts about auto safety with you. We're not trying to "sell" anything, or shift any blame.

All we want to do is clarify several misconceptions.

Misconception number one is the belief that the auto industry really doesn't care about safety—that we only made our cars safer when we were pressured into it by the government.

The fact of the matter is, Ford Motor Company promoted auto safety 15 years ago. The venture was a flop.

Back in 1956, we offered the industry's first safety package. It contained the first concave steering wheel. The first padded sun visors. A padded dash. And the first factory-installed seat belts.

No one got terribly excited about it. Apparently people didn't care about auto safety in those days.

So much for history.

Today, we have a simple motive for building safer cars. And it isn't duress from Washington.

Ford learned sometime ago that if you're going to sell a product, you'd better listen to the people you're trying to sell it to.

And we've learned that the car we market in this age had better be as safe as possible or you won't buy it. And if you don't buy, we don't eat.

But that doesn't mean cars can't be made even safer. They can. In fact, thousands of our engineers and technicians spend countless hours devising ways of improving the safety of Ford products.

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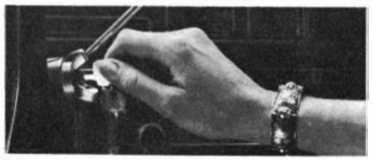
Right now, our people are researching a device that could save thousands of lives a year.

A lot of people won't like it.

It's called the Buckle-Start System. When it's installed, you must have your seat belt fastened or the car won't start.



With Buckle-Start, you *must* fasten your belts, or the car won't start.

THE AIR BAG ISSUE

An extreme measure, yes. But the probable alternative at the moment is the controversial air bag system. We don't believe it's the cure-all some people think. In its present state, the air bag is a costly, complicated device that, on impact, balloons suddenly between the passenger and the dashboard. Frankly, its reliability has a long way to go to satisfy Ford Motor Company.

The truth is, neither extreme would be under consideration if people would only use the belts and shoulder harnesses that are in their cars right now. Unfortunately, as we indicated, most people don't. In fact, the National Safety Council estimates that only about 4 percent use shoulder harnesses.

Donald L. Rosenberg
8811-E Town & Country Blvd.
Ellicott City, Maryland
21043
January 17, 1971

Ford Motor Company Listens
The American Road
Dearborn, Michigan 48121

Gentlemen:

On Sunday, January 3rd, I was very much impressed by your television commercial in which the efforts Ford is taking to produce safer cars was presented. Furthermore, in my opinion the commercial saved my life.

I was like many drivers who did not take the time to use seatbelts. Because I was so impressed with your commercial, I wore my seatbelt on Monday, January 4th. As fate would have it, I was involved in an accident, driving was propelled 20 feet and spun 180 degrees. Had I not been wearing my seatbelt, I feel certain that the accident would have been fatal.

I thank you more than mere words can express for saving my life. Also, I would appreciate any and all information

Don Rosenberg watched our TV commercial on safety. And he believes it saved his life. We're happy it did. We're only sorry more people haven't taken automobile safety to heart.

LIFEGUARD DESIGN SAFETY FEATURES

- Dual Hydraulic Brake System with warning light
- Glare-reduced instrument panel and windshield pillars
- Energy-absorbing steering column and steering wheel.
- Safety-designed armrests and door handles
- Front and rear lap belts for all seating positions.
- Shoulder belts.
- Turn indicators with lane-changing feature.
- Inside yield-away rearview mirror.
- Energy-absorbing instrument panel with padding.
- Padded sun visors.
- Locking steering column with warning buzzer.
- Two-speed or variable speed windshield wipers
- Windshield washers.
- High strength laminate safety glass windshield
- Double-yoke safety door latches and safety hinges.
- Emergency flasher, back-up lights and side marker lights.
- Energy-absorbing front seat back tops.
- Self-locking front seat backs on two-door vehicles.
- Safety-designed radio control knobs and push buttons.
- Outside rear view mirror, driver's side.
- Safety rim wheels and load-rated tires.
- Corrosion-resistant brake lines.
- Parking lamps coupled with headlamps.
- Head restraints or high back seats.
- Safety design front end structure.
- Uniform transmission shift quadrant.

WHAT WE'RE DOING

In fact, there are dozens of safety features built into every 1971 Ford product. Everything from tougher brake lines to energy-absorbing front ends. Note the chart.

Some improvements we've "borrowed." Many of our products, for example, have side guard rails in the doors. Granted, General Motors introduced the idea. But we developed our own version because the idea was too good not to use.

Another noteworthy feature is Tot-Guard, a car seat for children that's been acclaimed by safety research analysts as the safest seat of its kind ever offered.

The safest kiddie seat in the country is being ignored by most buyers.

No, it isn't free. The price is about 25 dollars. But that's a very small price when you consider the protection it affords.

Unfortunately, however, all the safety features in the world can't help an unsafe driver. And last year, the use of alcohol was involved in more than 25,000 traffic fatalities.

If you drink and drive, there isn't much Ford Motor Company can do for you. The same goes if you speed, or drive on bald tires, or vote against highway improvement, or fail to have your car safety inspected. (And did you know there are still 11 states that have no form of vehicle inspection, at all?)

Indeed, cars can be made safer. They *will* be made safer.

But the total safety problem can only be solved with your help.

You're the driver.

You're the passenger.

You're the voter.

You're the customer.

WRITE US.

But so much for our point of view.

We'd like to hear yours. Send us your likes, dislikes, wants, needs, gripes, etc. Your letter will be read, considered and answered.

WRITE:
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DEPARTMENT SA
THE AMERICAN ROAD
DEARBORN, MICHIGAN 48121

Do write us. We listen. And we listen better.

Ford

...has a better idea (we listen better)

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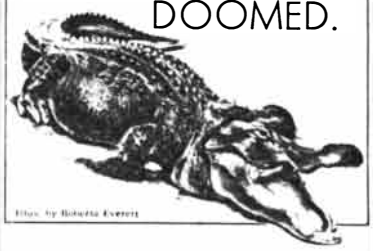
AS OLD AS THE DINOSAUR AND MAYBE JUST AS DOOMED.



If a living dinosaur were to turn up today, there would be a great stir to learn its ways and discover how it had survived. Yet the crocodilians, reptile contemporaries of the dinosaurs, have largely gone unstudied.

THE LAST OF THE RULING REPTILES, by Wilfred T. Neill, is the first book to deal broadly with the biology of alligators and crocodiles and to dispel centuries-old misconceptions. Unfortunately, it may be the last "to be written by someone who had a chance to see almost all of the modern species in life and a majority of them in their natural habitats."

THE LAST OF THE RULING REPTILES presents the most accurate and complete picture to date of ancient and modern crocodilia. This profusely illustrated, highly readable book is based on years of observation and research. Here are the most detailed accounts available of courtship, nesting, egg-laying, hatching, guarding of nest and young, feeding, fighting, and attacks on man.

Ecological changes threaten the continued existence of the crocodilians. The author warns, "the next reviewer will probably find himself relying almost wholly on earlier publications." Because it fills this important need, **THE LAST OF THE RULING REPTILES** belongs on every nature bookshelf. Order your copy today.

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Send me, postage paid, a copy of THE LAST OF THE RULING REPTILES by Wilfred T. Neill.
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Address_____
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State_____ Zip_____

THE AUTHORS

MOSHE J. LUBIN and ARTHUR P. FRAAS ("Fusion by Laser") are respectively associate professor of mechanical and aerospace sciences at the University of Rochester and associate director of the reactor division of the Oak Ridge National Laboratory. Lubin, who is also director of the laser energetics laboratory at the University of Rochester, received his bachelor's degree at the Technion in Israel in 1961 and his Ph.D. at Cornell University in 1964. In addition to the work described in the article, Lubin and his colleagues are investigating the use of high-power lasers as energy-boosters for relativistic particle beams and doing fundamental experiments concerned with the scattering of one light beam off another light beam. Fraas writes: "As a college freshman in 1934 I was so excited by a *Scientific American* article on the discovery of the neutron that I almost shifted from mechanical engineering to physics, but the depression was highly abrading and then (as now!) it was easier to get a job as an engineer than as a physicist, so that I stayed in engineering." He was graduated as a mechanical engineer from the Case Institute of Technology in 1938. After 12 years of working in industry on large power plants for aircraft, interspersed with periods of teaching, he went to Oak Ridge in 1950.

DAVID NOTON and LAWRENCE STARK ("Eye Movements and Visual Perception") are respectively assistant professor at the University of Colorado and professor of physiological optics and engineering science at the University of California at Berkeley. Noton writes: "Although my formal training is in computer science, and that is the area in which I teach, my research interests lie more in brain research and its intersection with computer science. My outside interests and hobbies are few, since I prefer an undistractedly quiet life at home. However, my wife and I have recently discovered the joys of keeping a small herd of donkeys—animals that, apart from an occasional raucous outburst, lead pretty quiet lives too. I am a member of the Association for Computing Machinery and of the American Donkey and Mule Society." Noton, who was born in England, was graduated from the University of Cambridge and took his master's degree and his Ph.D. at Berkeley. Stark, who has an A.B. from Columbia College and an M.D. from the Albany Medical College, did postdoctoral study in several fields, including electrical engineering. He taught at Yale University, the Massachusetts Institute of Technology and the University of Illinois before going to Berkeley in 1968.

RUSSELL ROSS and PAUL BORNSTEIN ("Elastic Fibers in the Body") are at the University of Washington; Ross is professor of pathology in the School of Medicine and Bornstein is associate professor of biochemistry and medicine. Ross was graduated from Cornell University in 1951 with a degree in chemistry; he received a D.D.S. from Columbia University in 1955 and a Ph.D. in pathology from the University of Washington in 1962. Bornstein was graduated from Cornell in 1954 and received an M.D. from New York University in 1958. He writes: "I do my best to convince students that biochemistry constitutes a major foundation of medicine and that, on the other hand, the advancement of medical knowledge represents a primary aim of biochemical investigation. While they think matters over for themselves, I occasionally take time off to hike in the mountains and ski."

HENRY W. KENDALL and WOLFGANG PANOFSKY ("The Structure of the Proton and the Neutron") are respectively professor of physics at the Massachusetts Institute of Technology and director of the Stanford Linear Accelerator Center at Stanford University. Kendall, who received his Ph.D. at M.I.T. in 1954, has in addition to his professional activity been concerned with environmental problems in New England and does what he calls "sporadic research" in problems of air traffic control. Panofsky, who was graduated from Princeton University in 1938 and took his Ph.D. at the California Institute of Technology in 1942, went to Stanford in 1951 as professor of physics. He has been involved intensively as an adviser on governmental science policy, including service from 1960 to 1964 as a member of the President's Science Advisory Committee.

ANDREW H. BOBECK and H. E. D. SCOVIL ("Magnetic Bubbles") are at the Bell Telephone Laboratories; Bobeck is a member of the technical staff and Scovil is director of the Solid State Device Laboratory. Bobeck, who received his bachelor's and master's degrees in electrical engineering from Purdue University in 1948 and 1949 respectively, has been with Bell Laboratories since 1949. He holds 66 patents and has 14

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others pending. His numerous hobbies include golf; besides playing avidly, he designs and builds golf clubs. Scovil, who received his bachelor's and master's degrees from the University of British Columbia and his D.Phil. from the University of Oxford, joined the technical staff of Bell Laboratories in 1955.

R. BRUCE GILLIE ("Endemic Goiter") is a National Defense Education Act Fellow at the College of Medicine of the University of Utah. "I was graduated from Brown University with a B.A. in sociology in 1967," he writes. "My particular interest was in medical sociology and especially the relationship of disease to society in history. From superstition to science the entity of disease has long been a focus of man's wonder and imagination. Aside from my academic work I take time to enjoy the great hunting, camping and fishing that the West has to offer."

C. C. and MARTHA LAMBERG-KARLOVSKY ("An Early City in Iran") have collaborated for five years in archaeological excavations at the site they describe. C. C. Lamberg-Karlovsky, who was born in Czechoslovakia, received his bachelor's degree from Dartmouth College in 1959 and his Ph.D. in 1965 from the University of Pennsylvania. He is now professor of anthropology at Harvard University and curator of Near Eastern archaeology at Harvard's Peabody Museum. Mrs. Lamberg-Karlovsky, who was graduated from Connecticut College for Women, has divided her time between caring for their two sons, who have accompanied them on the excavations, and assisting in the research following the excavations.

C. ROBERT WATTS and ALLEN W. STOKES ("The Social Order of Turkeys") are respectively a game biologist for the state of Montana and professor of animal behavior at Utah State University. Watts, who took his Ph.D. at Utah State in 1969, is responsible for the management of game species in the central part of Montana. Stokes, who is chairman of the Institute of Animal Behavior at Utah State, was graduated from Haverford College in 1936; he obtained his master's degree from Harvard University in 1940 and his Ph.D. from the University of Wisconsin in 1952. He is president of the Animal Behavior Society. The work that Watts and Stokes describe was supported by the Rob and Bessie Welder Wildlife Foundation and a predoctoral fellowship from the National Institute of Mental Health.

This announcement is neither an offer to sell nor the solicitation of an offer to buy any of these securities. The offering is made only by the Prospectus.

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Even when you've blown a fuse,
we're still on the line.

You could blow every fuse in your house and still be able to use your telephone.

Because a telephone doesn't get its power from your house circuits.

Instead, it operates from a low-voltage direct current supplied by Telephone Company batteries.

Much like the battery you have in your car, ours, too, must be constantly charged.

For this purpose we have battery chargers that convert power from the local power company.

But knowing that storms and other emergencies can sometimes affect power lines as well as our own, we have auxiliary generating equipment ready to take over at any time to keep the batteries charged.

The American Telephone and Telegraph Company and your local Bell Company are constantly working to provide reliable telephone service.

So if a blown fuse does leave you temporarily in the dark, you can at least call somebody about it.

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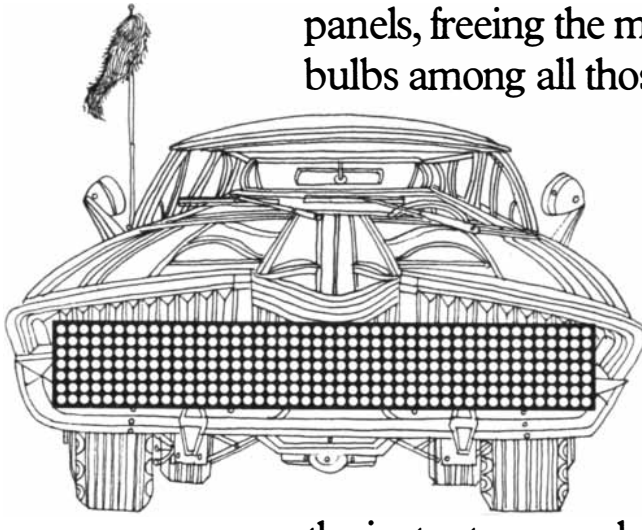
Will anyone living, live to see our little light burn out?

After 100 years of constant use, it may lose only half its brightness.

That's because we don't use a bulb, a filament or a vacuum.

We use a tiny crystal chip called a light-emitting diode. It works something like a transistor, but let's not get into all that.

Our diodes are already in use on computer panels, freeing the man who used to look for burned-out bulbs among all those hundreds of winking lights.



That's a good market. But let's look at markets to come.

How about a flat head-light as wide as your car, to evenly light the road?

Or an inch-deep color TV set?

Or a wrist watch without a dial, that shows the time in numbers at the instant you push a button?

That's part of the future we see in our crystal chips. And just a small part of the future we see in **Monsanto: the science company.**

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Established 1845 SCIENTIFIC AMERICAN June 1971 Volume 224 Number 6

Fusion by Laser

Experiments indicate that energy-releasing fusion reactions can be initiated and to some extent controlled without a confining magnetic field by focusing a powerful laser pulse on a frozen pellet of fuel

by Moshe J. Lubin and Arthur P. Fraas

The rapid evolution of high-power pulsed lasers over the past decade has made available to workers in numerous fields a new tool whose potential usefulness has just begun to be explored. Prominent among the applications that have been proposed to date are a variety of schemes aimed at exploiting the fact that the focused light from such a laser is capable of heating a small amount of matter to extremely high temperatures: in some cases to more than 50 million degrees Kelvin! To the chemist, for example, such a capability means that chemical reactions can be initiated in less than a nanosecond (a billionth of a second) and can be studied under conditions previously considered unattainable.

To the plasma physicist the unprecedented heating capability of high-power pulsed lasers is particularly exciting. In principle it opens a promising new avenue of attack on the long-standing problem of how to produce the ultrahigh-temperature plasma needed to maintain thermonuclear, or fusion, reactions under controlled conditions. Recent experiments have shown that energy-releasing fusion reactions that may ultimately lead to the production of useful electrical power can be initiated and to some extent controlled within an "inertially confined" plasma obtained by focusing a powerful laser pulse on a dense frozen pellet consisting of a mixture of the heavy hydrogen isotopes deuterium (H^2) and tritium (H^3). In this article we shall review the current status of research on the application of high-power lasers to the generation of fusion power.

The case for fusion power and the progress that has been made over the past 20 years or so by nonlaser technologies toward achieving this goal have been discussed at length in several earlier articles in this magazine, the most recent of which appeared only a few months ago [see "The Prospects of Fusion Power," by William C. Gough and Bernard J. Eastlund; SCIENTIFIC AMERICAN, February]. Suffice it to say here that controlled fusion reactions involving light isotopes such as deuterium and tritium represent a potentially inexhaustible source of inexpensive, efficient, "clean" energy for supplying all mankind's future power requirements.

The fusion-power option, however, has not yet been shown to be technologically feasible. The difficulty is twofold. First, the task of heating the light-element fuel to a sufficiently high temperature at the required density so that it will begin to "burn" slowly has proved to be harder than was anticipated. The temperature required to initiate burning varies between 50 and 100 million degrees K., depending on the fuel. Second, once the fuel is ignited, the hot, dense, gaseous mixture of ions must be held together for a long enough time so that more energy is liberated through burning than is invested in the ignition process. Attempts at confinement by means of intense magnetic fields of various geometries have so far not yielded a practical solution. In spite of the difficulties encountered in heating a gaseous mixture to such temperatures and confining the ionized gas for large fractions of a second, however, the potential return on the investment of time and money in research on this problem is so great that all the major nations of the world have substantial controlled-fusion research programs.

Before describing how high-powered lasers can play a role in the solution of this problem it will be instructive to review briefly (1) the current state of the art in the development of high-power pulsed lasers, (2) the mechanism by which the energy from a laser beam interacts with a dense medium and (3) the requirements demanded of lasers in initiating controlled fusion reactions.

A laser is a device for generating or amplifying a beam of light whose waves are both monochromatic (all the same wavelength) and coherent (all in step). The light beam emitted by a laser can be made almost perfectly parallel, its divergence angle being theoretically limited only by diffraction effects. In principle such a beam can be focused to a spot with a diameter of only a few hundred-millionths of an inch. The laser produces its coherent light beam through the interaction of electromagnetic radiation with the laser medium. By elevating more atoms to an upper energy level than exist at a lower level

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the absorption of excitation radiation produces an "inverted" atomic population in the laser. The energy stored in the inverted population is then available to amplify a propagating light wave at a particular frequency. This frequency of emission is generally different from the frequency band over which the laser medium has absorbed excitation radiation. For example, a ruby laser absorbs "pumping" light in the green region of the optical spectrum but emits coherent light in the red region.

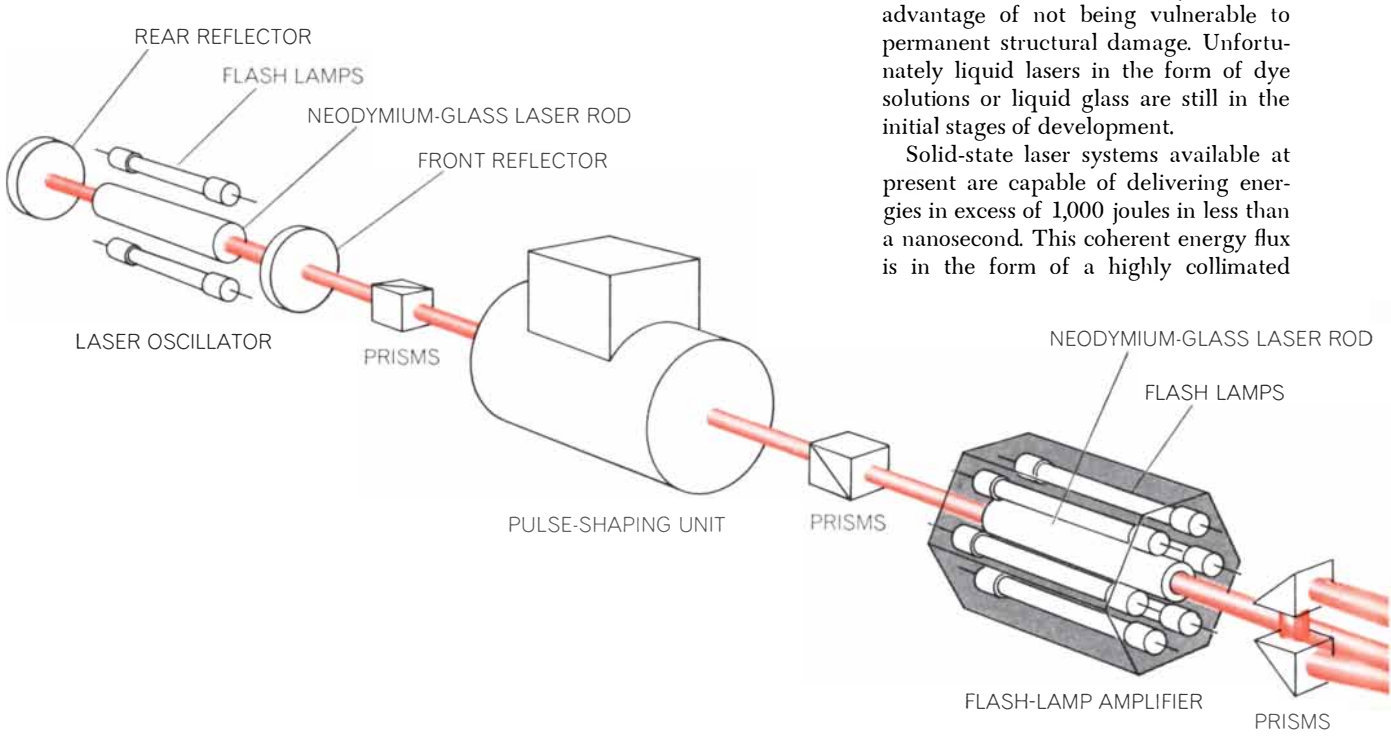
The small light pulse to be amplified is produced by a laser oscillator. For a laser to work as an oscillator some feedback mechanism must be provided. This is accomplished by the use of mirrors on both ends of the laser medium to provide a means by which waves at the emission frequency may travel back and forth through the laser. In this way oscillations are built up at the emission frequency by feeding on the inverted population until the stored energy in the laser medium is depleted, at which time emission ceases.

The first laser action in a solid material was observed in a ruby rod in 1960 by T. H. Maiman, who was then working at the Hughes Aircraft Company. Numerous other solid-state laser materials were discovered in rapid succession. The most important of these is neodymium-doped barium crown glass, in which laser action was first demonstrated in 1961 by Elias Snitzer of the American Optical Company. Whereas ruby is an expensive crystal to grow in any reasonable size, barium crown glass is comparatively inexpensive and can be manufactured in large sizes and quantities. Size becomes important in dealing with ultrahigh-power laser systems.

The end surface of the laser rod from which the coherent radiation is emitted can withstand only a limited amount of energy per square centimeter. Generally it is felt that impurities in the laser material contribute to significant absorption of the laser light, which ultimately leads to fracture of the laser medium. For example, the energy-handling capability of neodymium glass ranges between 10 and 100 joules per square centimeter, depending on the duration of the laser pulse.

At present solid-state ruby and neodymium-glass laser materials are used to obtain the highest peak-power output in pulsed operation. This is attributable in large part to the higher density of atoms available in solids to participate in the laser action. Liquids that sustain laser action hold promise for the future in high-power pulsed applications for this same reason; in addition they have the advantage of not being vulnerable to permanent structural damage. Unfortunately liquid lasers in the form of dye solutions or liquid glass are still in the initial stages of development.

Solid-state laser systems available at present are capable of delivering energies in excess of 1,000 joules in less than a nanosecond. This coherent energy flux is in the form of a highly collimated



TYPICAL HIGH-POWER LASER SYSTEM shown on these two pages was designed for use in a plasma-heating experiment. The system consists of a string of neodymium-doped barium-crown-glass components, beginning with a laser oscillator (*extreme left*), in which a low-energy laser pulse is formed. The pulse is next "tailored," or shaped both in time and space to suit a particular application, before being amplified by additional laser rods and finally by a large disk amplifier. A suitable combination of prisms sends the pulse through the disk amplifier three times. The resulting beam, some 15 centimeters in diameter, is finally focused on a deuterium droplet inside a vacuum chamber (*extreme right*) to produce a hot plasma, or ionized gas, in which fusion reactions can take place. The fusion reactions are studied by means of the energetic neutrons they emit. The peak power currently available from such a laser system before focusing exceeds 10^{13} watts; when it is focused, it is possible to achieve power densities greater than 10^{17} watts per square centimeter.

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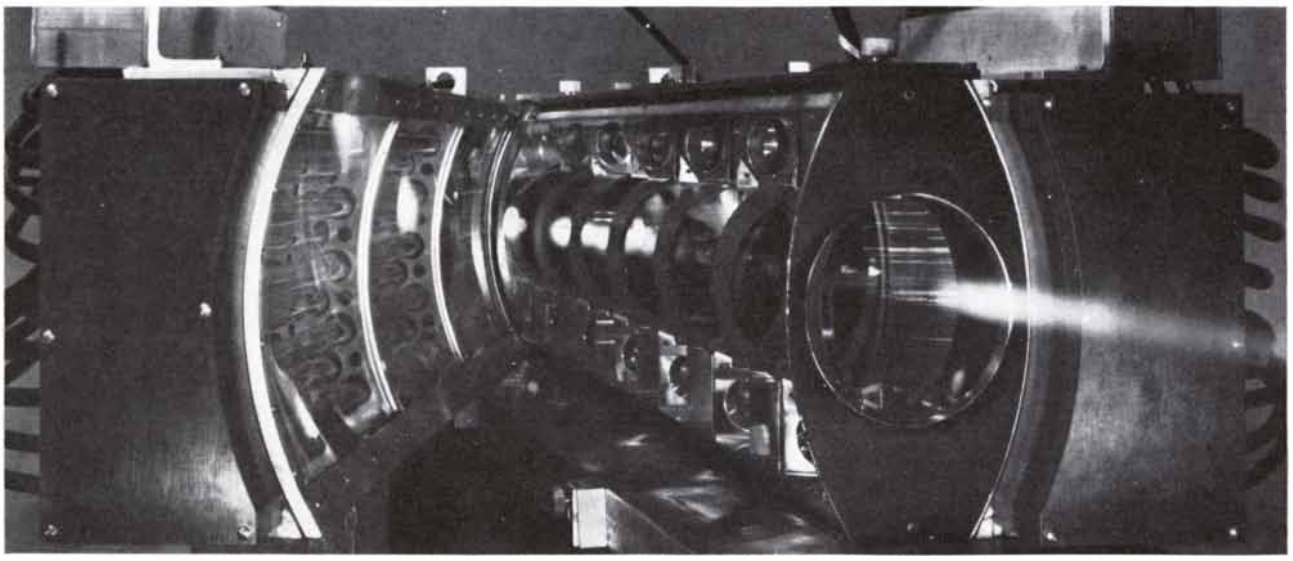
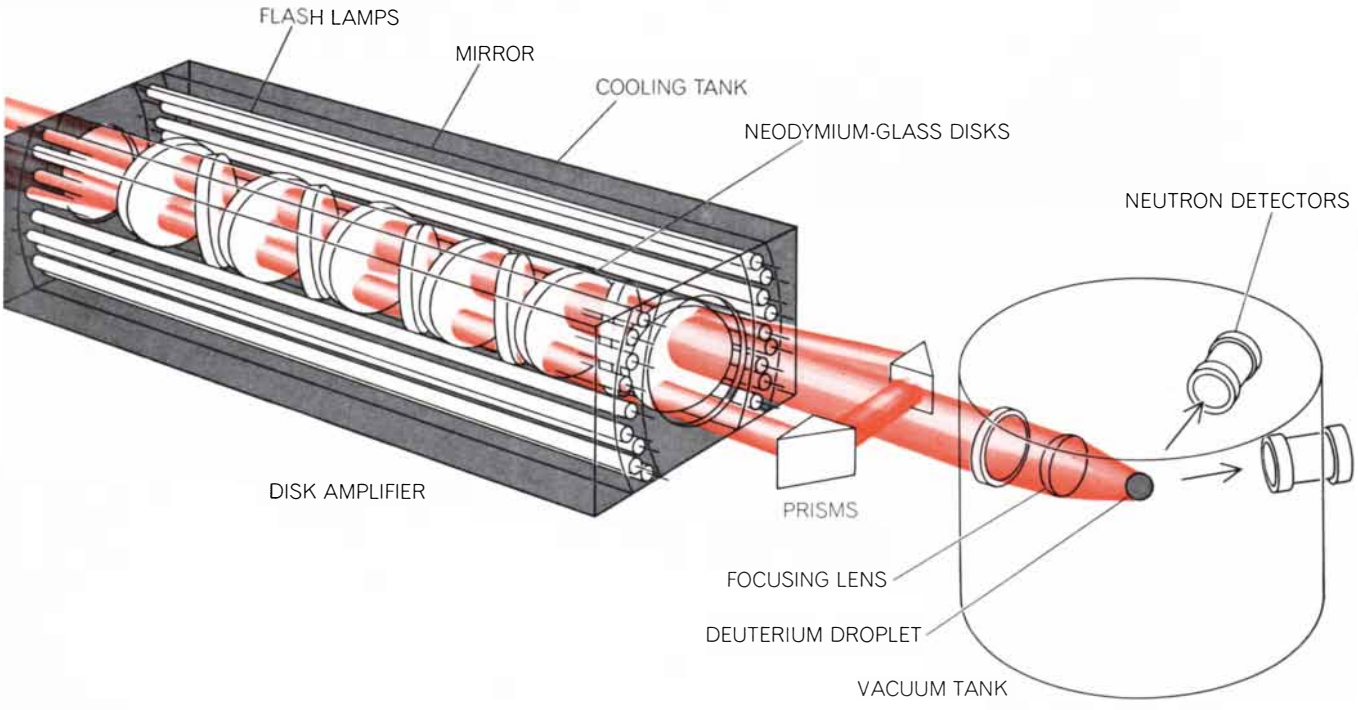


DISK AMPLIFIER is capable of emitting an output pulse with an energy of more than 1,000 joules through an aperture 15 centimeters in diameter. The neodymium-glass laser disks are mounted at an angle to the incoming laser beam in order to minimize reflection at the same time that they are excited efficiently on their faces by the flash lamps located in the reflector tanks on each side of the disks. A hundred such amplifiers arranged in parallel could in principle achieve an energy output greater than 100,000 joules.

beam with a total divergence of less than a hundredth of an angular degree. Such a beam of light starting out six inches in diameter would be less than 18 inches in diameter after traveling a mile.

In the case of a ruby laser the wavelength of the emitted laser radiation is .6943 micron. This wavelength falls in the red region of the spectrum and is therefore visible. The neodymium glass used in high-power lasers emits radiation at 1.06 microns, which is in the infrared portion of the spectrum and is not directly visible to the human eye.

A typical high-power laser system [*see illustration below*] consists of an oscillator in which a laser pulse, appropriately shaped in space and time, is formed at low energy. The pulse is an envelope containing a burst of electromagnetic radiation oscillating at the



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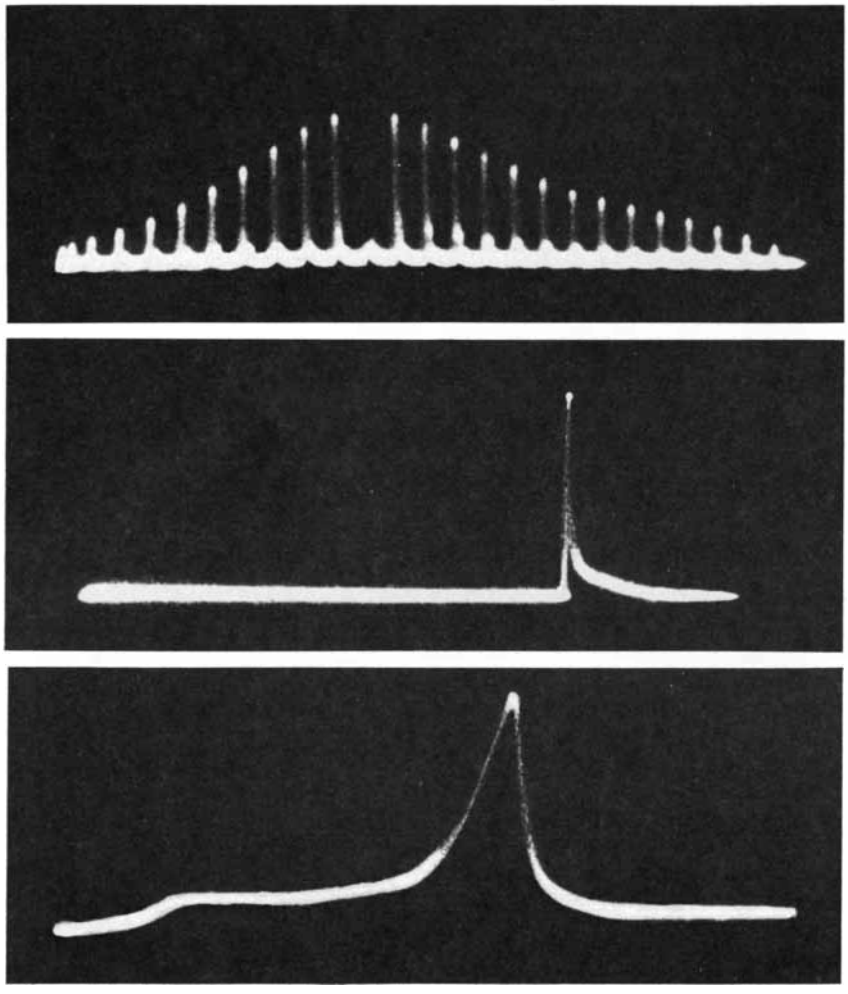
laser frequency. "Tailoring" a pulse to suit a particular application can be accomplished in a number of ways. Pulses lasting on the order of a nanosecond or longer can be reliably produced simply by chopping out a suitable portion of a fatter pulse with a fast electro-optical shutter. The shutter, activated by a high-voltage electrical pulse, is synchronized with the arrival of the longer pulse by monitoring the intensity of the laser radiation as a function of time. Such synchronization requires high-voltage switching on the time scale of a nanosecond.

Producing narrower pulses by this technique is unreliable. Instead a technique known as "mode-locking" is commonly employed [*see illustration below*]. As the energy in the laser cavity is built up and then decays, a string of such mode-locked pulses emerges from the partially transmitting mirror in the front of the cavity. An electro-optical shutter can be used here too, but only to "gate out," or select, a laser pulse with a duration far shorter than the time the shutter is open. One pulse or more can be gated out in this way. Here the duration of the laser pulse is determined solely by the components in the laser cavity. Pulses varying in duration from a billionth to a trillionth of a second have been produced in this fashion.

Once the appropriately shaped laser pulse emerges from the laser, it is directed into a string of laser amplifiers, each amplifier adding energy to the original pulse. The amplifiers usually have successively larger apertures, so that the lasing material can survive the increased energy without damage. The amplifying process itself can be called on to change the shape of the input pulse. If the intensity of the incoming pulse is large enough, most of the amplifier energy is deposited in the pulse's leading edge, thereby narrowing the width of the pulse.

The atoms in a neodymium-glass laser rod are excited by absorbing light from external flash lamps. Since the light enters the rod from the outside, more atoms near the outer edges of the rod are elevated to an excited energy state than are elevated in the interior. This undesirable situation becomes intolerable for rods more than two inches in diameter. In addition large rods are difficult to cool between pulses. One solution to the problem of exciting large-aperture amplifier stages is the disk amplifier [*see top illustration on preceding page*]. This type of amplifier consists of large neodymium-glass disks that are tilted with respect to the incoming laser beam in order to minimize reflection losses. At the same time the disks have a large projected area of minimal thickness facing the excitation flash lamps, which leads to uniform excitation. One such amplifier with an aperture of six inches is now capable of reaching a power output of 1,000 joules; 100 similar amplifiers could be arranged in parallel to achieve outputs of 100,000 joules.

Numerous available sources are capable of delivering such bursts of energy in a short time. None, however, equals the laser in the ease with which the output can be concentrated in a small volume. It is this ability to focus high-power radiation using optical elements such as lenses and mirrors that makes the laser uniquely attractive for the purpose of initiating fusion. The peak power in such a beam before focusing is more than 10^{13} watts, and when the beam is focused, it is possible to achieve power densities greater than 10^{17} watts per square centimeter. The focused energy results in a local electric field in the immediate vicinity of the focus on the order of 10^{10} volts per centimeter! It is difficult to grasp the magnitude of such enormous electric-field intensities; an example of their strength is that a free electron accelerated in a field of 10^{10} volts would reach a velocity comparable to the velocity of light in a fraction of an optical wavelength.



TAILORING OF A LASER PULSE is illustrated by this sequence of oscilloscope traces. A train of very brief "mode-locked" pulses is first produced in the oscillator section of the laser system (*top*). A single pulse is then extracted from the train (it is missing in the top trace) and is amplified (*middle*). The width of the pulse may vary between a billionth (10^{-9}) and a trillionth (10^{-12}) of a second. A low-power leading edge is often added to such a pulse (*bottom*) in order to vaporize the fuel droplet prior to heating by the main pulse.

It is well known that nuclear-fusion fuels such as deuterium and tritium liberate more energy per nucleon (neutron or proton) than nuclear-fission fuels. Unfortunately these hydrogen isotopes only burn efficiently at high temperature. Below 10 million degrees K. the burning is too slow to be useful in an energy-producing process here on the

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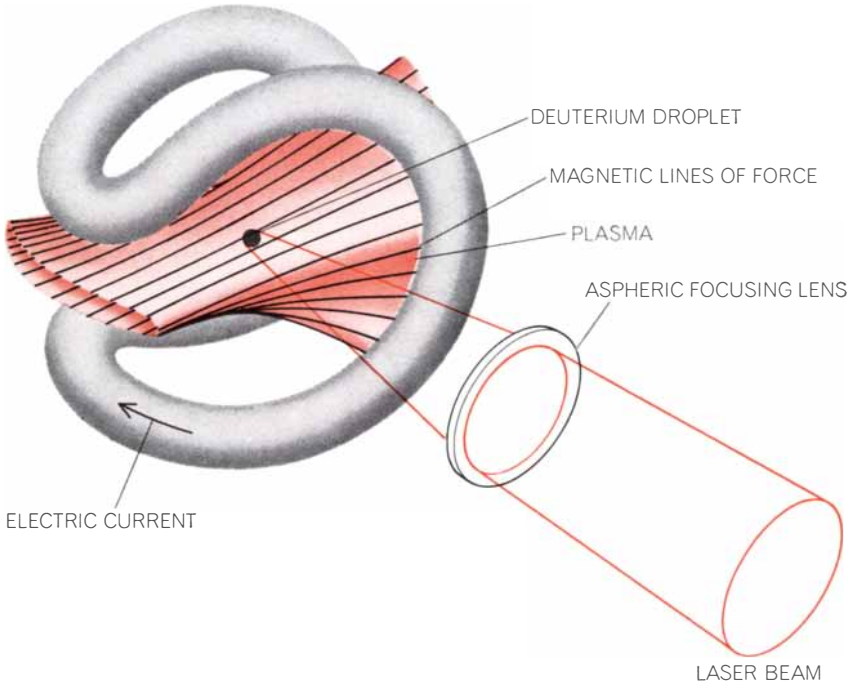
earth. The sun can burn hydrogen efficiently at lower temperatures because of its large volume. In the limited size of a laboratory plasma one must consider burning isotopes at temperatures greater than 50 million degrees K.

The traditional approach to controlled fusion has been to begin by producing a plasma that is dilute and rather cool. The plasma is next trapped in a confining magnetic field. One then proceeds to heat the plasma to a higher temperature while holding it in place with a magnetic field that is made proportionately stronger. Our present experience and understanding only allow us to heat the plasma rather gently so as not to upset the delicate balance between the hot ionized gas and the magnetic field. Although our knowledge of the forces and conditions controlling this balance has increased greatly over the past 10 years, we are not yet sure of the proper magnetic-field configuration required to contain the hot plasma long enough for significant burning to occur.

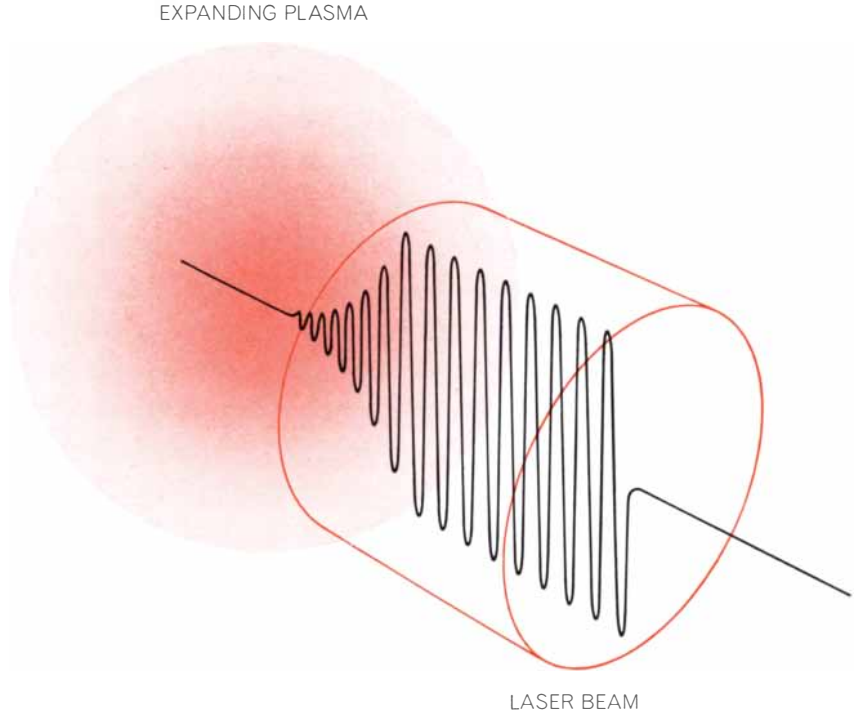
When high-power pulsed lasers began to emerge as working systems, one of their first applications in the controlled-fusion program was the production of extremely clean, well-behaved plasmas to fill existing magnetic-confinement devices [*see top illustration at right*]. The question that was asked at the time was: "Can a plasma produced by the laser heating of a small droplet of thermonuclear fuel in a magnetic field serve as the plasma required for nearly steady-state, continuous fusion reactions?"

More recently, as the energy-producing capability of high-power pulsed laser systems has increased, a second question has arisen: "Is it possible to utilize the intense burst of focused coherent radiation from the laser to raise the temperature of a suitable deuterium-tritium target high enough to produce significant burning *without* the necessity of a confining magnetic field?"

To answer these questions one must first examine how high-frequency electromagnetic radiation interacts with a dense plasma made up of electrons and positive ions. The oscillating electric field in a light beam may be absorbed, reflected, scattered and/or refracted by a material surface. Our prime interest is in the absorption of this radiation and the conversion of the electromagnetic energy of the laser beam to the thermal energy of the fusion fuel. Once a few unbound electrons are produced on the surface of the solid hydrogen isotope, these free electrons rapidly pick up energy from the incident oscillating electric field. Their energy is then trans-



FIRST USE OF HIGH-POWER LASERS in the controlled-fusion program was to produce a plasma to fill existing magnetic-confinement devices such as the one shown in this schematic drawing. An electric current flowing in the "baseball seam" winding induces a magnetic field whose energy density is lowest at the center and increases outward in all directions, thus creating a magnetic "well" in which to confine the plasma, which is generated by laser-heating a fuel droplet at the center. In an experiment carried out at the University of Rochester in 1968 a device of this type was used to produce a confined plasma with a temperature of 10 million degrees Kelvin and a density of 10^{13} ions per cubic centimeter.



LASER PULSE IS ABSORBED very efficiently by a dense, expanding sphere of plasma, with most of the absorption taking place in a thin surface layer of plasma only about a hundredth of an inch thick. As the energy of the laser beam is absorbed by the plasma, the amplitude of the oscillating electric field (*black curve*) decreases rapidly within this layer.

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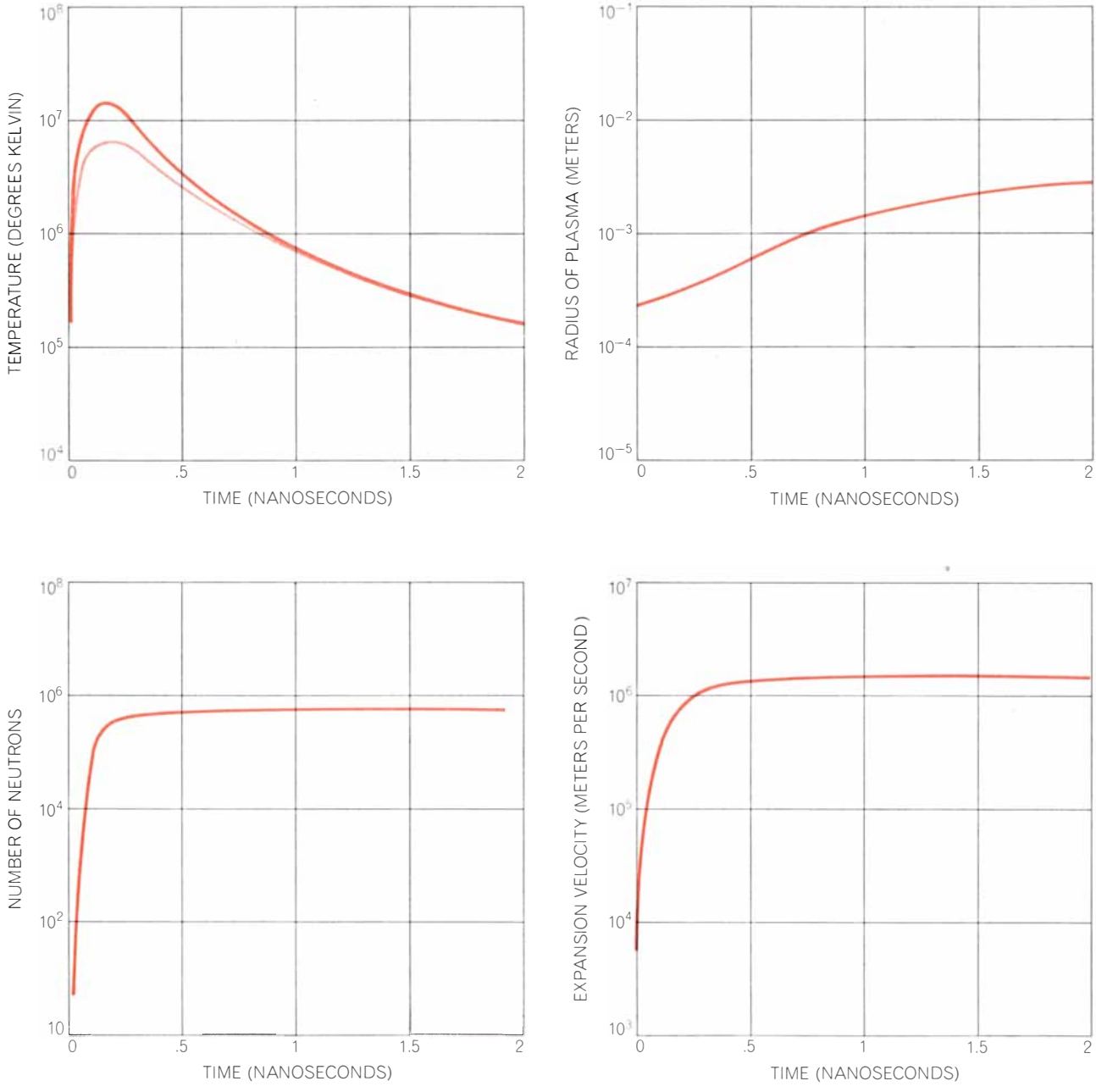
ferred to the ions in the plasma medium by means of long-range attractive interactions. Thus the heavier ions also "feel" the effect of the laser beam through the mediation of the oscillating electrons. The transfer of this energy from the electrons to the ions can be much slower than the heating of the electrons by the laser beam. In fact, it is doubtful that in a free deuterium-tritium plasma effective transfer can occur on time scales of less than 10^{-11} second. This absorption process is called collisional absorption.

If the incident radiation is to be effectively absorbed, the plasma should be opaque to it. On the other hand, it is desirable that the laser radiation not be wasted by reflection. In more quantitative terms, it is desirable that the incident light wave lose all its energy to the electrons in their first few collisions with neighboring ions. This model enables us to estimate how thick a dense plasma must be to absorb all the incident laser light. When a plasma is surrounded by a vacuum, the density of electrons and ions increases rapidly from zero at the outer surface to a maximum in the bulk of the plasma. Most of the laser radiation is absorbed in this layer of increasing density [*see bottom illustration on preceding page*]. For complete absorption in a dense plasma at thermonuclear temperatures this layer need be only .005 inch thick.

The answer to the first question has been provided by the theoretical and experimental work of laboratories throughout the world. In the U.S. a group at the United Aircraft Research Laboratories under Alan F. Haught is



TYPICAL ABSORPTION HISTORY for a laser-heated deuterium fuel pellet is represented by these four graphs. The pellet, originally a tenth of a millimeter in diameter, was heated by a tailored laser pulse that lasted 10^{-10} second and had a peak amplitude of 10^{13} watts. Darker curve in first graph is electron temperature; lighter curve, ion temperature. The incoming pulse was absorbed solely by nonrelativistic processes and hence resulting neutron yield, a measure of success of burning, is a conservative estimate.

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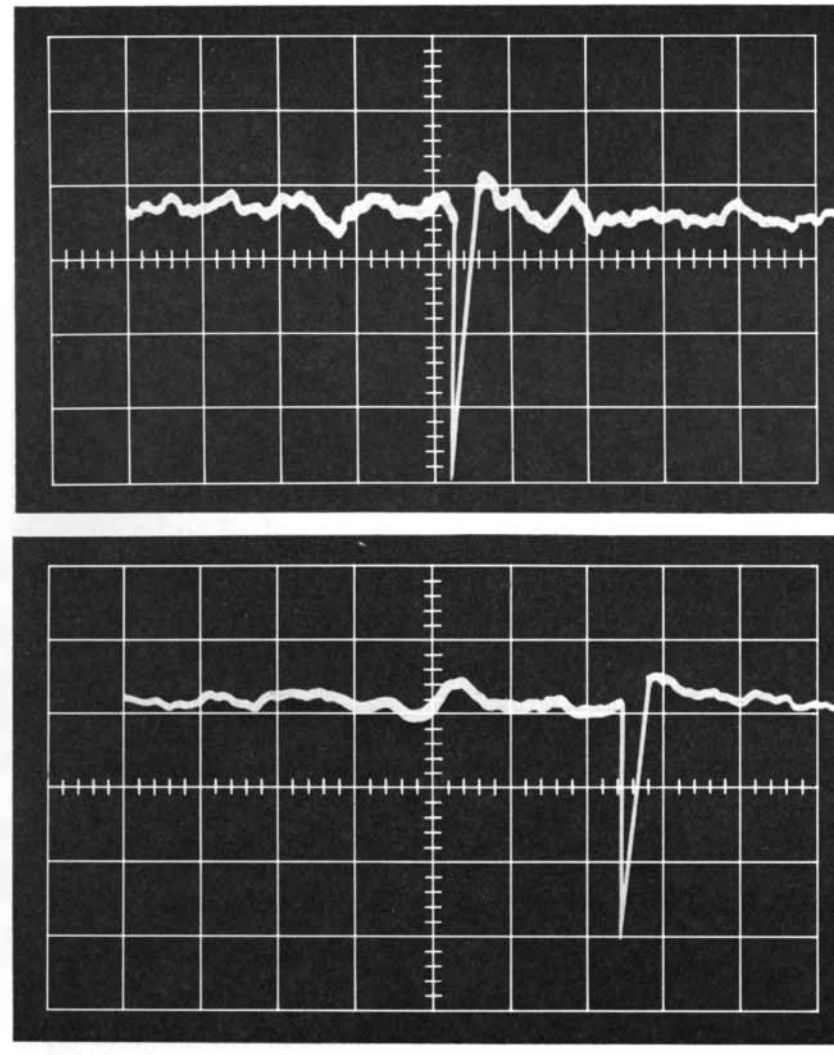
demonstrating that plasmas produced by the laser heating of small pellets can be confined in existing magnetic-field geometries over a wide range of temperatures. The resulting quasi-steady plasma, although not hot enough for significant controlled fusion reactions, can then be augmented and heated to higher temperatures by other methods. Thus clean, laser-produced plasmas can serve as the first step in the buildup to controlled fusion conditions. Since the laser plasma is only the catalyst that serves to turn on the steady-state fusion process, the low efficiency of the laser system is of no particular significance.

The second question—regarding the feasibility of laser-heating a small dense plasma to thermonuclear conditions without the necessity of a confining magnetic field—is receiving increased attention. The conditions required to achieve this result can best be understood by taking a step-by-step look at the heating process in a laser-produced plasma. In the typical experimental arrangement pulsed laser radiation is focused on a small fuel pellet of solid deuterium-tritium. The solid fuel pellet is converted to a dense plasma by the leading edge of the incident laser pulse, which is of sufficient duration to vaporize (but not significantly heat) the droplet. Once the droplet is in gaseous form the main heating pulse is applied.

The plasma does not remain stationary as it is heated. Detailed consideration of the absorption process shows that the dynamics of the expanding plasma heated by the incident radiation are vitally important to the time-dependence of the absorption. A typical absorption-time history for an initially solid droplet [*see illustration on opposite page*] shows that there is a time beyond which the plasma has expanded to a point of transparency to the incident laser light. The duration of usable laser energy for heating dense, freely expanding, small plasmas is bounded by two characteristic times. The first is the time it takes for the plasma to expand to the point where it is too dilute to continue to absorb a significant portion of the incident laser energy (a few nanoseconds). The second is the time associated with the electron-ion energy transfer. As we have mentioned, this time scale is on the order of 10^{-11} second. Hence a laser pulse with a duration of 10^{-10} second, bracketed by these two characteristic times, is well suited to this purpose. The laser energy coupled efficiently into the plasma appears initially as thermal energy, and this energy, coupled with the energy from fusion, is ultimately divided up among the fusion reaction products, radiation losses and expansion energy.



BURST OF NEUTRONS arriving successively at two detectors spaced 225 centimeters apart is signaled by the sharp deflections in these two oscilloscope traces. The difference in the arrival times is a measure of the energy of the neutrons and indicates that these particular neutrons were produced by deuterium-deuterium reactions in the experimental plasma. A similar experiment carried out with a pure hydrogen plasma yielded no neutron output.

One could in principle reduce the amount of energy that goes into expansion by using a strong containing magnetic field. To do so, however, would call for magnetic fields capable of exerting pressures of tens of millions of pounds per square inch. Such fields are not available at present.

Once the density and temperature of the ions are known as a function of time, the thermonuclear yield is easily determined. In particular, rigorous calculations on such typical configurations indicate that one can achieve a ratio of liberated energy to input energy that is greater than 1 at input energies of around 10^5 to 10^6 joules. The assumptions that form the basis of these calculations are currently being studied experimentally at a number of laboratories in the U.S. and abroad.

Neutrons resulting from fusion reactions are ideal "thermometers" to use in evaluating the success of a particular high-power heating experiment. For example, for every deuterium-tritium reaction a neutron with an energy of 14.1 million electron volts (MeV) is produced. The number of such reactions is strongly temperature-dependent. Neutrons produced by the interaction of laser light and a plasma were first reported by N. G. Basov at the Lebedev Institute in Moscow in 1963. The Russian work was followed by high-power laser-plasma neutron experiments at the Limeil Laboratory in France and at several places in the U.S., specifically the Livermore Laboratory of the University of California, the Los Alamos National Labora-

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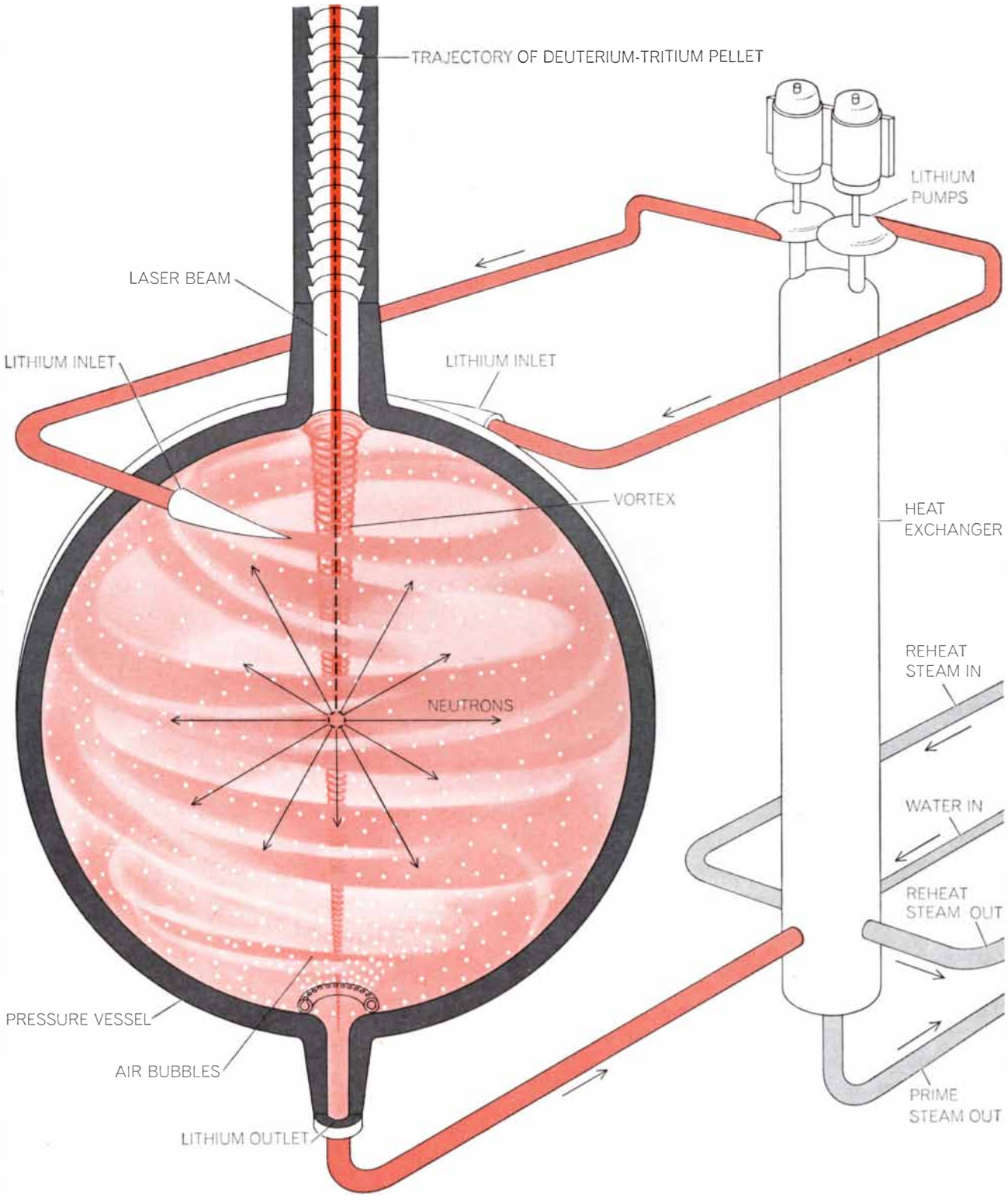

PROPOSED FUSION REACTOR was designed by workers at the Oak Ridge National Laboratory as a method for converting the fusion energy from laser-ignited deuterium-tritium pellets into useful electric power. The fusion energy would be absorbed in a pool of lithium, which would be contained in a cylindrical or spherical pressure vessel some 10 to 15 feet in diameter. A free-standing vortex would be maintained around a vertical axis by swirling the lithium at a sufficiently high velocity. A frozen pellet of deuterium-tritium would be injected into the center of the vortex cavity and would be ignited with a laser pulse when it reached the midplane. The energy deposited in the lithium as heat in the form of energetic neutrons (*black arrows*) would be removed by drawing off lithium from the bottom of the vessel, circulating it through heat exchangers and returning it through centrifugal pumps to tangential nozzles in the perimeter of the vessel. In this particular design the blast waves created by the explosion of the pellet would be attenuated to protect the pressure vessel by introducing shock-absorbing gas bubbles into the lithium pool through a perforated ring in the bottom of the vessel. The pellet-injection and laser systems would be protected by making the port for pellet injection quite long with a wall profile that would break the normal shock wave into many oblique shock waves, thus attenuating the primary blast wave.

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tory, the Sandia Corporation and the University of Rochester. Laboratories around the world have been improving on those initial results. Total neutron yields in excess of 10^5 from the deuterium-deuterium reaction have been measured using targets of deuterium with incident laser-beam energies of between 50 and 250 joules. The interpretation of these results indicates a slightly better absorption than simple collisional theory predicts.

Of special interest is the detailed study of the absorption of the incident radiation. There are a number of important contributions to the absorption that may be more significant than the simple collisional process described above and that may hence affect the energy release. Nature, however, seems to favor a freely expanding dense plasma, since the majority of these special absorption processes increase the effectiveness of the incident laser beam.

At present lasers with a properly shaped pulse can deliver 10^3 joules, whereas at least 10^5 joules is needed for significant amounts of laser-produced fusion. This laser energy can be made available using present technology, but as yet no such working system exists. Although the experimental results are few, they appear to justify optimism.

Meaningful use can be made of the energy released from a dense centimeter-size fuel pellet heated by focused laser radiation in a number of different energy-conversion applications. For example, a central station generating electric power by means of controlled thermonuclear reactions from a periodic vaporizing of deuterium-tritium pellets would look quite different from a configuration designed for use in, say, space propulsion. As an illustration let us consider the feasibility of this general scheme for a controlled thermonuclear power plant.

A method for converting the fusion energy from laser-ignited deuterium-tritium pellets into electrical power was evolved at the Oak Ridge National Laboratory early in 1969 in conjunction with fusion-power feasibility studies that have been under way there since 1967. The Oak Ridge approach to fusion entails absorption of the energy from fusion in a pool of lithium, which in turn delivers the energy as heat to a thermodynamic cycle.

The lithium pool would be contained in a cylindrical or spherical pressure vessel 10 to 15 feet in diameter and would be swirled at a sufficiently high velocity to form a free vortex around its vertical axis [*see illustration on opposite page*]. By adjusting the swirl velocity distribution properly it should be possible to obtain a central cavity with a fairly uniform diameter of perhaps five centimeters through the region from the top of the vessel to well below the midplane. A frozen pellet of deuterium-tritium would be injected into the center of the vortex cavity and would be ignited with a laser pulse when it reached the midplane. The energy deposited in the lithium as heat would be removed by drawing off lithium from the bottom of the pressure vessel, circulating it through heat exchangers and returning it to the pressure vessel. The process would be repeated perhaps every 10 seconds. The large thermal inertia in the lithium circuit would act to maintain an essentially constant flow of heat to the thermodynamic cycle.

Drawing off the lithium from the bottom of the pressure vessel would help to stabilize the vortex. After circulating through the heat exchangers the lithium would be returned through pumps to tangential nozzles in the perimeter of the pressure vessel, thereby maintaining the desired vortex.

An obvious objection to this concept is that it would not serve to yield useful amounts of power because the amount of energy one might release in each explosion would have to be kept quite small or the pressure vessel would burst. A relatively simple analysis discloses that this is indeed the case unless some measures are taken to attenuate the blast wave before it strikes the wall of the pressure vessel. In fact, several steps can be taken to increase the rate at which the energy in the shock wave is degraded. One step would be to introduce a large number of gas bubbles in order to reduce the mean density of the liquid by about 5 percent. As the shock wave traversed a gas bubble some of its energy would go into spalling liquid from the inner surface of the bubble and projecting it through the void to strike the bubble wall at the other side, where much of the kinetic energy of the projected material would be converted to thermal energy. The extent to which this would attenuate the main shock wave is difficult to estimate, but simple tests indicate that a sufficiently high bubble density could be obtained to allow an increase in the energy released per explosion by as much as a factor of 10 over the corresponding value for a pool of bubble-free lithium.

The steps outlined here are designed to reduce the intensity of the blast wave before it impinges on the pressure vessel, but they would have little or no effect on the blast wave progressing upward through the cavity in the liquid lithium toward the laser and the pellet-injection system. Fortunately the low density of the lithium vapor will diminish the intensity of the blast wave. In addition the port for pellet injection and the laser beam can be made quite long, with a wall profile that would break the normal shock wave up into a host of oblique shock waves and thus dissipate the bulk of its energy.

Let us try to visualize in detail the sequence of events in the course of one explosion cycle, beginning with the injection of the deuterium-tritium pellet into the vortex. Perhaps 10 percent of the pellet would be vaporized as it moved along its trajectory as a consequence of the absorption of heat radiated to it by the hot lithium. The remainder of the pellet would be vaporized and ionized when it was struck by the laser beam. Some of the deuterium and tritium ions would fuse, and the fusion energy released would increase the temperature of the rest of the pellet material so that about 5 percent of the ions would fuse before plasma expansion terminated the reaction. About 75 percent of the energy from the fusion reaction would go into energetic neutrons, and this energy would be absorbed as those neutrons were slowed down in the inner region of the lithium. The absorbed energy would raise the temperature of the central lithium region a few hundred degrees in about a millionth of a second and would cause the lithium to expand; this expansion, however, should be largely absorbed by contraction of the bubbles so that no severe blast wave would be generated. About 25 percent of the energy released by the fusion reaction would appear as alpha particles; these would produce ion heating and, subsequently, X rays. The energy in the X rays would be absorbed in the first millimeter or two of the lithium layer, causing the lithium in that thin layer to vaporize. The vaporized lithium together with the expanding thermonuclear plasma would induce a weak blast wave in the lithium.

The velocity of sound in hot lithium is about 15,000 feet per second. The liquid would move outward from the explosion center at a lower velocity to form a spherical cavity. The displaced liquid would move into the upper portion of the vortex cavity. This would entail a good deal of sloshing, particularly in the region of the ports for the injection of the fuel pellet and the laser beam. The geometry of the injection passage de-

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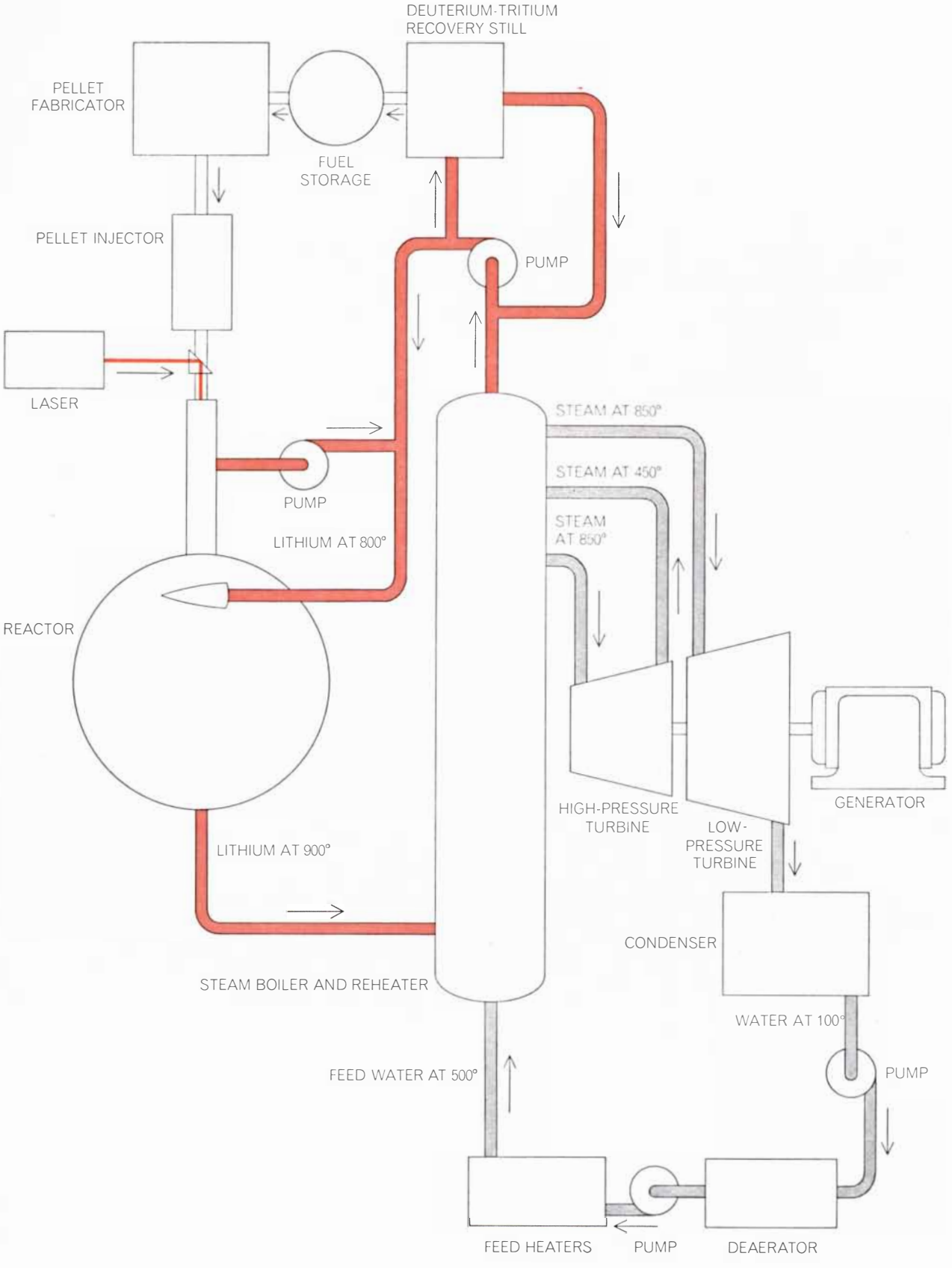

FULL-SCALE POWER PLANT incorporating many of the concepts discussed in this article might be based on a single fusion reactor in which deuterium-tritium pellets would be ignited by high-power laser pulses. The energy of the explosions would be absorbed in a tritium-breeding lithium blanket and used to generate 150 megawatts of electric power by means of a conventional steam cycle.

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signed to keep the blast wave from moving up through the ports, however, would also be effective in inhibiting the liquid from sloshing up the port.

The rotational momentum of the lithium in the pressure vessel should help to reestablish the vortex. In addition the lithium through-flow in a typical case would be so large that about 50 percent of the lithium in the vessel would be replaced each cycle.

The pressure-vessel stress problems were examined by C. V. Chester and Lawrence Dresner at Oak Ridge. They quickly reached the conclusion that the proposed system presents so many analytical complexities, particularly if the effects of gas bubbles in the liquid are included, that it is doubtful an analytical model can be developed on purely theoretical grounds. Nonetheless, it does appear that all the phenomena involved are such that the scaling law commonly used for analysis of blast effects would apply. Hence test work has proceeded with small models.

Chester and Dresner designed a series of model tests using small steel vessels and ordinary explosive charges. The first tests were run with the model pressure vessel filled with bubble-free water. The amount of explosive was increased in small increments from about 1.5 grams to about 10 grams. The dilation of the vessel at the midplane was measured with a micrometer following each test, and the results were plotted as a function of the weight of charge detonated. A line drawn through the scatter band of points was passed through the zero dilation axis to define the maximum charge that could be detonated without stressing the vessel beyond the elastic limit. The tests indicated that this value was consistent with the value determined analytically, and that it corresponded to about two grams of explosive. Thus the simplified analytical model was deemed sound and suitable for scaling to full-size vessels.

A second series of tests was run with a thin layer of sponge rubber lining the inner wall of the pressure vessel. This cushioned the blast wave enough to increase to more than four grams the amount of explosive that could be used without stressing the vessel beyond the elastic limit.

A third series of tests was run with a perforated ring placed in the bottom of the model pressure vessel. Air was admitted to the ring to provide an annular curtain of bubbles in the region near the wall of the pressure vessel. A strain gage mounted on the outside of the model in the same horizontal plane as the explosive provided a good measure of the stress in the vessel initially with no air bubbles in the vessel and later with air bubbles filling about 5 percent of the vessel.

In extrapolating these results to a full-scale system—a pressure vessel 25 times larger, with a diameter of 12.5 feet and a wall 10 inches thick—the energy released from the explosion would be increased by a factor of 25^3, or 15,625. Allowing a safety factor of two, one could employ 15 kilograms of explosive in a full-scale system using bubble-free water at room temperature. This corresponds to an energy release of 15×10^5 calories per explosion. If the explosion were repeated at a frequency of one every 10 seconds, the power output would be 6.3 megawatts.

This value of 6.3 megawatts would be the energy in the blast wave for a system in which TNT would be exploded in water with no vortex or bubbles to cushion the explosion. With TNT all the energy would go into the blast wave, but in a fusion reactor about 80 percent of the energy would appear in the form of heat in the liquid as a consequence of the slowing down and absorption of fast neutrons. Most of this energy would simply go into heating the liquid and compressing the bubbles rather than a blast wave; hence the energy output of the reactor could be approximately five times the energy producing the blast wave, that is, about 30 megawatts. The model tests indicate that the cushioning effect of the bubbles ought to reduce the intensity of the blast wave by at least another factor of 2.5, and that the use of a spherical rather than a cylindrical vessel would give another factor of two, thus allowing an increase in the rated power output to perhaps 150 megawatts. Some further increase in power may be possible as a consequence of differences in compressibility between water and high-temperature lithium, but data are not in hand to estimate the extent of this effect.

The design of a full-scale power plant was derived from the concept outlined here within the limitations imposed by basic design considerations. For example, although deuterium is cheap and readily available, tritium is not. As a result, for a deuterium-tritium fusion reactor to be economically attractive it must breed tritium. This can be done because the energetic neutrons have a substantial probability of colliding with other neutrons in the course of slowing down in a natural lithium blanket. When a neutron is absorbed in the lithium, it yields tritium plus an alpha particle. Thus a breeding ratio of perhaps 1.3 would be obtained. If the lithium pool had a radius of at least a meter, there would be virtually no neutron losses from escape or absorption in structural material, and there would be no neutron damage to the pressure vessel. Hence lithium appears to be a particularly attractive choice for the fluid to absorb the energy of the explosion.

In the choice of material for the pressure vessel, extensive compatibility tests indicate that the two most promising candidates for use with lithium are Croloy (a chrome-molybdenum steel) and a niobium alloy containing 1 percent zirconium. The operating temperature with Croloy is limited by corrosion considerations to about 900 degrees F., whereas the niobium alloy could be employed with lithium up to at least 2,000 degrees F. Niobium is very expensive, however, and requires protection from oxidation; Croloy is preferable, at least for initial studies and experiments.

In choosing a thermodynamic cycle the first logical choice is a steam Rankine cycle. Croloy is widely used in existing fossil-fueled steam plants for steam temperatures up to 1,050 degrees F. Thus if an upper temperature limit of 900 degrees is adopted for the lithium system and a 50-degree temperature drop between the lithium and the steam circuit is accepted, the reactor could be coupled to a quite conventional steam system [*see illustration on opposite page*].

It might be argued that an intermediate fluid such as an inert salt should be used between the lithium and the steam circuit, because of the large energy release associated with the lithium-water reaction that would occur if there were a leak from one system into the other. The consequences of such a leak, however, appear no more serious than those associated with the heat exchangers between the sodium-potassium and the steam system employed in fast sodium-cooled fission reactor plants. The amount of radioactivity in the lithium would be small and the loss of tritium in such an accident would not be serious.

In order to keep the thermal stresses to a modest level in the vessels and piping of the lithium system it seems desirable to keep the average temperature rise in the lithium to about 100 degrees F. This could be accomplished by using a flow rate of 2,300 gallons per minute with two pumps operating in parallel.

A physically small but economically

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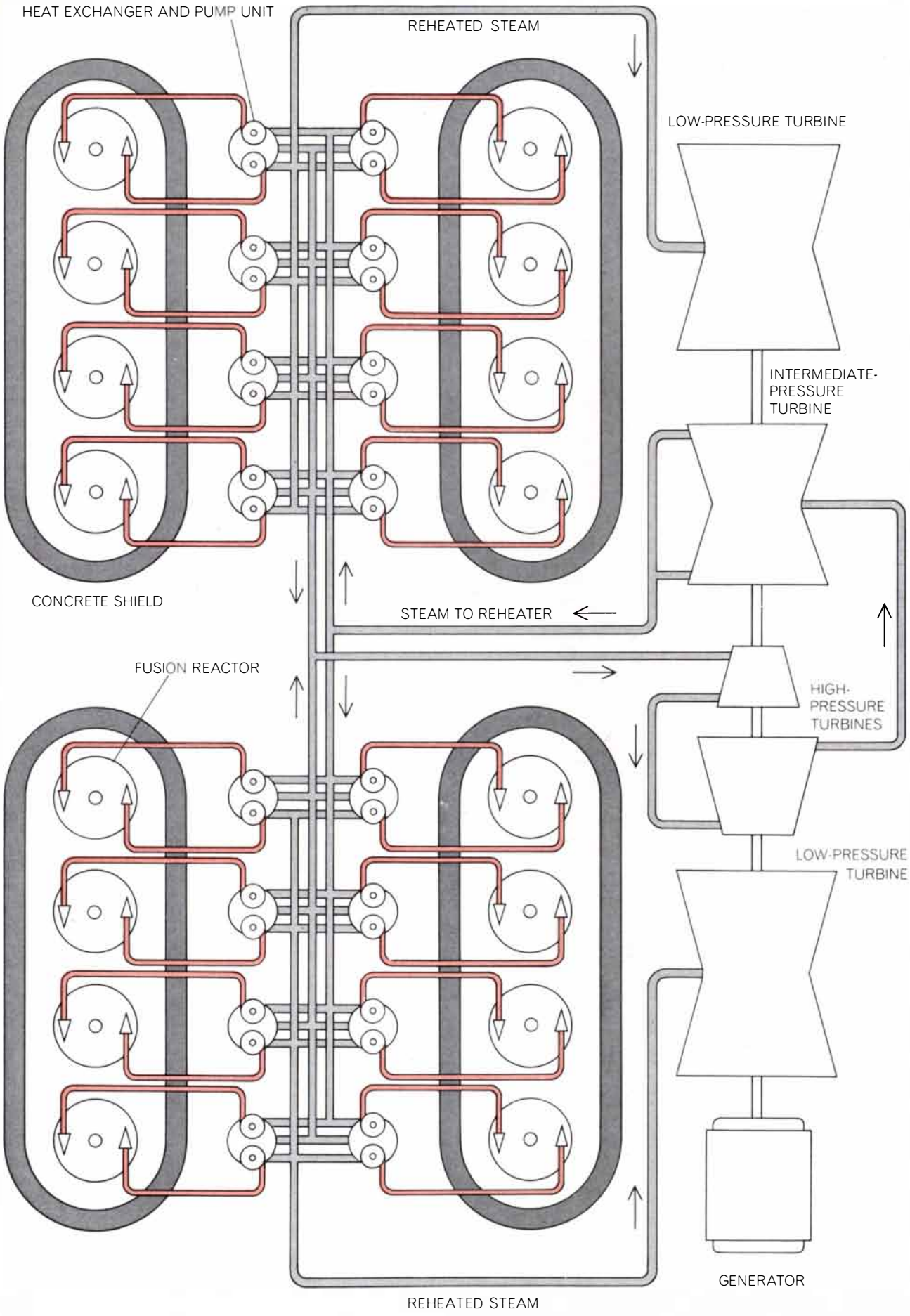

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vital portion of the plant is the fuel-recovery and fuel-reprocessing system. It has been shown that both tritium and deuterium can be removed from lithium at low cost with a small, essentially conventional distillation system. After being compressed, the deuterium-tritium mixture can be liquefied with a cryogenic system. Fuel pellets can then be manufactured by allowing liquid droplets to fall through a vacuum chamber filled with cold helium gas, which would chill the droplet and freeze it. The electric power required for the cryogenic system appears to be less than a watt per kilowatt of thermal output from the reactor; hence it should not detract appreciably from the overall thermal efficiency of the power plant. It would, of course, be necessary to add deuterium and take off a deuterium-tritium mixture to maintain the proper composition of the fuel pellets.

For plants with an output greater than 150 megawatts it might be possible to make the cushion of bubbles more effective and thus increase the power output from a vessel of a given size by a factor of two or more. Power outputs of more than about 500 megawatts per vessel will require that the size and/or thickness of the vessel be increased. This will increase the difficulties of fabrication and consequently the unit cost in dollars per pound and dollars per kilowatt of output. The alternative is to use a number of relatively small vessels operated in parallel [*see illustration on opposite page*]. The latter approach is attractive because it would make possible modular construction with one standard size or more of shop-fabricated reactor vessels coupled with appropriately sized pumps, heat exchangers and connecting pipes. This approach is particularly attractive because large steam turbines are commonly supplied with steam through many steam pipes, since provisions for thermal expansion make it advantageous to keep the diameter—and hence the capacity—of individual steam pipes to a modest level.

It should be mentioned that the type of fusion reactor proposed here differs from both fission reactors and other types of fusion reactors in that there appears to be no theoretical advantage to the use of very large units. This constitutes an important advantage for the concept.

A laser-initiated fusion-power plant built of Croloy and operated to produce steam at 850 degrees F. would have an overall thermal efficiency of about 40 percent, which is approximately that of the better fossil-fueled plants in current operation. The efficiency could be increased dramatically if the system were built of the niobium alloy and operated at a temperature of about 1,800 degrees F. That temperature would be too high for use in a steam cycle because there would be enough dissociation of the hydrogen and oxygen in the steam to cause serious attack of any structural metal that would be economically attractive. It should be possible, however, to employ a binary-vapor cycle with a potassium-vapor Rankine cycle taking heat from the lithium at perhaps 1,800 degrees F. Such a system would have an overall thermal efficiency for the cycle of about 58 percent. This would cut the waste heat rejected per electrical kilowatt to about half that for conventional steam plants, and it opens the possibility of even higher efficiencies of heat utilization by integration with industrial and urban heating systems.

There is little point in developing the proposed power plant unless it looks attractive economically. If a suitable laser system can be built at a reasonable cost—a major question that cannot be resolved at this stage—it appears that the capital cost of the rest of the system should be no higher than the capital cost of more conventional plants. Certainly the cost of the steam system should be the same as that of similar steam systems in current use. The lithium circuit and steam boiler should cost about the same as the corresponding equipment projected for the circuit of the sodium-cooled fast-breeder fission reactor. Moreover, the pressure vessel would be relatively simple compared with those currently employed in water-cooled fission reactors. The weight of a spherical pressure vessel with an inside diameter of 12.5 feet and a wall thickness of 10 inches would be about 200,000 pounds. Assuming a 40 percent thermal efficiency, such a plant would yield an electrical output of about 60,000 kilowatts. Assuming a unit cost of $3 per pound, the vessel would cost $600,000, or about $10 per kilowatt. The cost of other items, such as the cryogenic systems for fuel recovery and pellet fabrication, appears to be a small fraction of the overall cost of the plant.

The operating cost for fuel should be low indeed. The cost of the deuterium and lithium would be about $200 per pound and $15 per pound respectively. This would yield a cost of only about three cents per million BTU (British thermal units) compared with current prices of about 40 cents per million BTU for fossil fuels. Inasmuch as capital charges are roughly the same as fuel costs in conventional fossil-fuel plants, this in turn indicates that the proposed laser-initiated fusion-power plant would be economically attractive even if the capital cost were twice as high.

One of the major problems associated with fission reactors stems from the large inventory of radioactive material inherently present and the potential hazard to the public that it represents. Because of this factor as much as 30 percent of the capital cost of a fission reactor plant may stem from elaborate provisions to prevent or contain any conceivable accident that might release radioactive material to the environment. The only radioactive material of consequence in the proposed fusion-power plant would be tritium, and estimates indicate that it would represent a total hazard potential that would be lower than that of a comparable fission reactor by a factor of about a million. This should reduce costs and greatly ease siting problems.

The design studies of full-scale laser-initiated fusion-power plants make the concept look attractive and therefore raise questions with respect to the development problems. Clearly the most vital are concerned with the laser and the pellet-ignition process. Can a sufficiently powerful laser be built and pulsed to ignite the pellet? If so, will the yield of fusion energy be many times more than the energy input to the laser? How effectively can the blast wave be attenuated by entraining a substantial fraction of gas bubbles in a swirling pool of lithium? These are the principal questions that must be answered experimentally before one can say whether or not the proposed concept is really feasible. There are, of course, many other difficult development problems, but none appears so difficult as to raise doubts about the feasibility of the concept.

THOUSAND-MEGAWATT POWER PLANT might be composed of 16 fusion-reactor modules, each with its associated heat exchanger and pump unit. The system would produce steam at a temperature of 850 degrees Fahrenheit and a pressure of about 1,200 pounds per square inch to drive a combination of high-pressure and intermediate-pressure turbines with one reheat to 850 degrees for a pair of low-pressure turbines. With the addition of a potassium-vapor "topping" cycle operating at a turbine-inlet temperature of 1,800 degrees the overall thermal efficiency of such a system could be brought as high as 58 percent.

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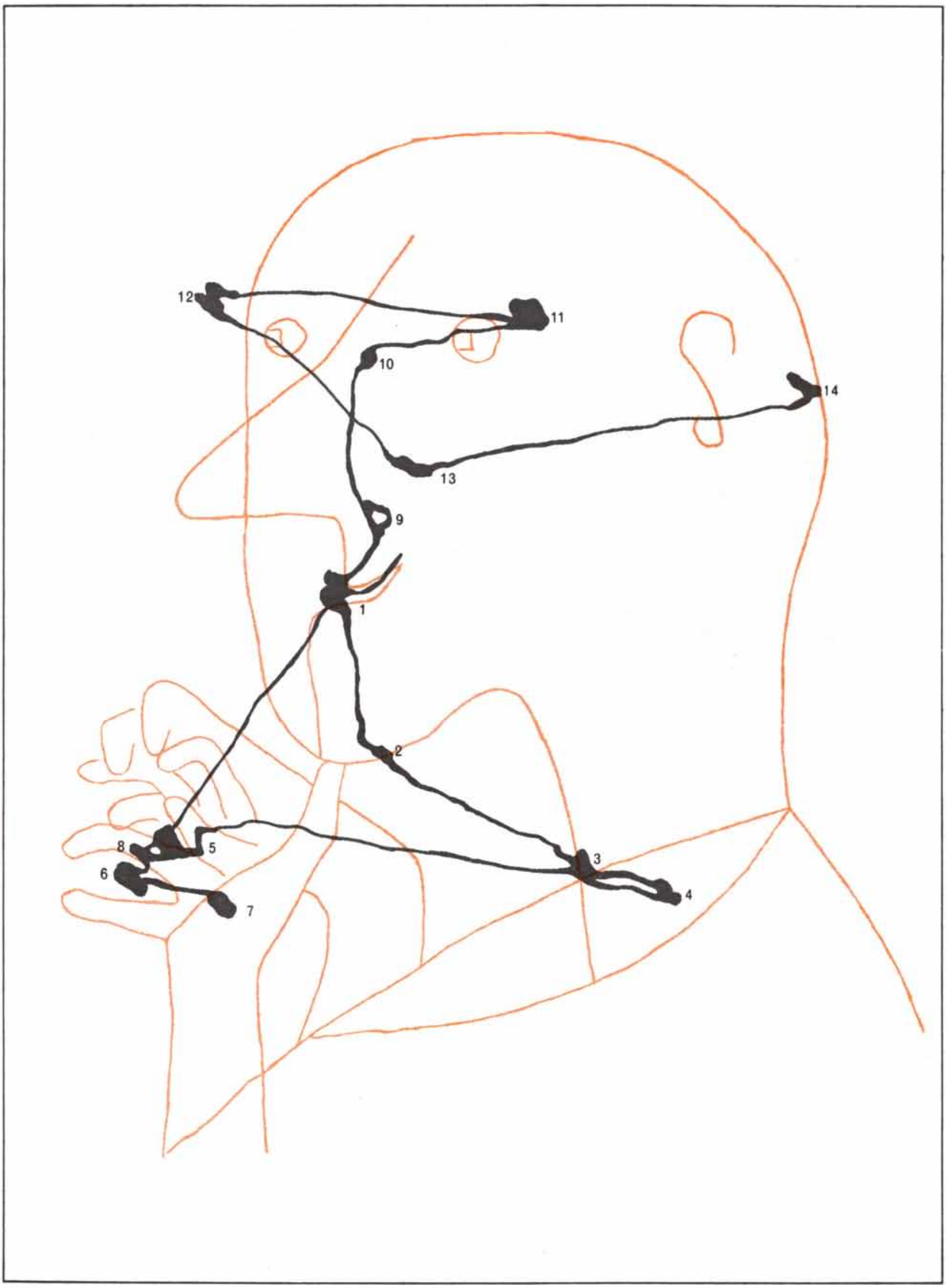

EYE MOVEMENTS made by a subject viewing for the first time a drawing adapted from Paul Klee's "Old Man Figuring" appear in black. Numbers show the order of the subject's visual fixations on the picture during part of a 20-second viewing. Lines between them represent saccades, or rapid movements of eyes from one fixation to the next. Saccades occupy about 10 percent of viewing time.

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Eye Movements and Visual Perception

Recordings of the points inspected in the scanning of a picture and of the path the eyes follow in the inspection provide clues to the process whereby the brain perceives and recognizes objects

by David Noton and Lawrence Stark

The eyes are the most active of all human sense organs. Other sensory receptors, such as the ears, accept rather passively whatever signals come their way, but the eyes are continually moving as they scan and inspect the details of the visual world. The movements of the eyes play an important role in visual perception, and analyzing them can reveal a great deal about the process of perception.

We have recently been recording the eye movements of human subjects as they first inspected unfamiliar objects and then later recognized them. In essence we found that every person has a characteristic way of looking at an object that is familiar to him. For each object he has a preferred path that his eyes tend to follow when he inspects or recognizes the object. Our results suggest a new hypothesis about visual learning and recognition. Before describing and explaining our experiments more fully we shall set the stage by outlining some earlier experiments that have aided the interpretation of our results.

Eye movements are necessary for a physiological reason: detailed visual information can be obtained only through the fovea, the small central area of the retina that has the highest concentration of photoreceptors. Therefore the eyes must move in order to provide information about objects that are to be inspected in any detail (except when the object is quite small in terms of the angle it subtends in the visual field). The eye-movement muscles, under the control of the brain, aim the eyes at points of interest [see "Control Mechanisms of the Eye," by Derek H. Fender, SCIENTIFIC AMERICAN, July, 1964, and "Movements of the Eye," by E. Llewellyn Thomas, SCIENTIFIC AMERICAN, August, 1968].

During normal viewing of stationary objects the eyes alternate between fixations, when they are aimed at a fixed point in the visual field, and rapid movements called saccades. Each saccade leads to a new fixation on a different point in the visual field. Typically there are two or three saccades per second. The movements are so fast that they occupy only about 10 percent of the viewing time.

Visual learning and recognition involve storing and retrieving memories. By way of the lens, the retina and the optic nerve, nerve cells in the visual cortex of the brain are activated and an image of the object being viewed is formed there. (The image is of course in the form of neural activity and is quite unlike the retinal image of the object.) The memory system of the brain must contain an internal representation of every object that is to be recognized. Learning or becoming familiar with an object is the process of constructing this representation. Recognition of an object when it is encountered again is the process of matching it with its internal representation in the memory system.

A certain amount of controversy surrounds the question of whether visual recognition is a parallel, one-step process or a serial, step-by-step one. Psychologists of the Gestalt school have maintained that objects are recognized as wholes, without any need for analysis into component parts. This argument implies that the internal representation of each object is a unitary whole that is matched with the object in a single operation. More recently other psychologists have proposed that the internal representation is a piecemeal affair—an assemblage of parts or features. During recognition the features are matched serially with the features of the object step by step. Successful matching of all the features completes recognition.

The serial-recognition hypothesis is supported mainly by the results of experiments that measure the time taken by a subject to recognize different objects. Typically the subject scans an array of objects (usually abstract figures) looking for a previously memorized "target" object. The time he spends considering each object (either recognizing it as a target object or rejecting it as being different) is measured. That time is normally quite short, but it can be measured in various ways with adequate accuracy. Each object is small enough to be recognized with a single fixation, so that eye movements do not contribute to the time spent on recognition.

Experiments of this kind yield two general results. First, it is found that on the average the subject takes longer to recognize a target object than he does to reject a nontarget object. That is the result to be expected if objects are recognized serially, feature by feature. When an object is compared mentally with the internal representation of the target object, a nontarget object will fail to match some feature of the internal representation and will be rejected without further checking of features, whereas target objects will be checked on all features. The result seems inconsistent with the Gestalt hypothesis of a holistic internal representation matched with the object in a single operation. Presumably in such an operation the subject would take no longer to recognize an object than he would to reject it.

A second result is obtained by varying the complexity of the memorized target object. It is found that the subject takes longer to recognize complex target objects than to recognize simple ones. This result too is consistent with the serial-recognition hypothesis, since more features must be checked in the more complex object. By the same token the result

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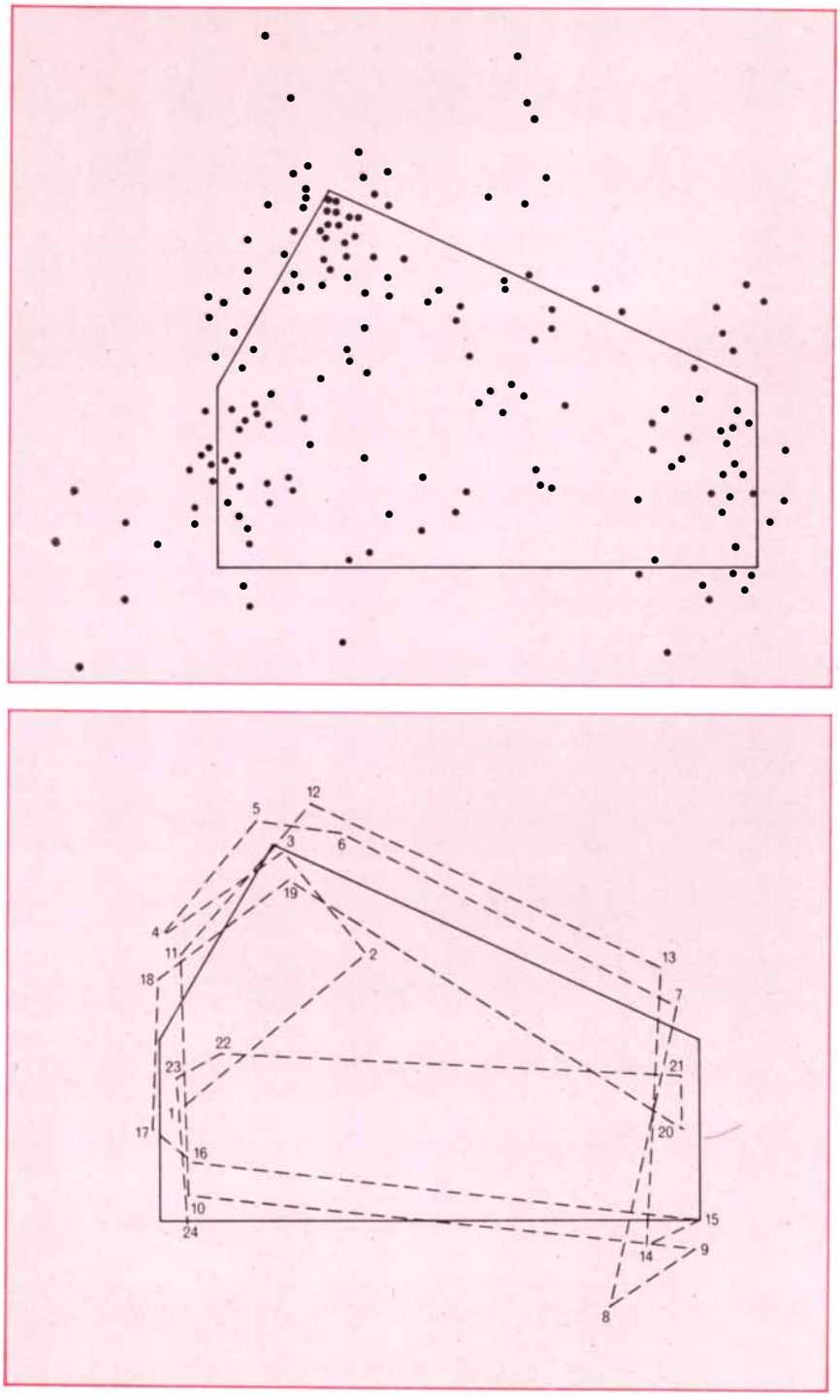
also appears to be inconsistent with the Gestalt hypothesis.

It would be incorrect to give the impression that the serial nature of object recognition is firmly established to the exclusion of the unitary concept advanced by Gestalt psychologists. They have shown convincingly that there is indeed some "primitive unity" to an object, so that the object can often be singled out as a separate entity even before true recognition begins. Moreover, some of the recognition-time experiments described above provide evidence, at least with very simple objects, that as an object becomes well known its internal representation becomes more holistic and the recognition process correspondingly becomes more parallel. Nonetheless, the weight of evidence seems to support the serial hypothesis, at least for objects that are not notably simple and familiar.



IMPORTANCE OF ANGLES as features that the brain employs in memorizing and recognizing an object was apparent in experiments by Leonard Zusne and Kenneth M. Michels at Purdue University. They recorded fixations while subjects looked at drawings of polygons for eight seconds. At top is one of the polygons; the dots indicate the fixations of seven subjects. Sequence of fixations by one subject in an eight-second viewing appears at bottom.

If the internal representation of an object in memory is an assemblage of features, two questions naturally suggest themselves. First, what are these features, that is, what components of an object does the brain select as the key items for identifying the object? Second, how are such features integrated and related to one another to form the complete internal representation of the object? The study of eye movements during visual perception yields considerable evidence on these two points.

In experiments relating to the first question the general approach is to present to a subject a picture or another object that is sufficiently large and close to the eyes so that it cannot all be registered on the foveas in one fixation. For example, a picture 35 centimeters wide and 100 centimeters from the eyes subtends a horizontal angle of 20 degrees at each eye—roughly the angle subtended by a page of this magazine held at arm's length. This is far wider than the one to two degrees of visual field that are brought to focus on the fovea.

Under these conditions the subject must move his eyes and look around the picture, fixating each part he wants to see clearly. The assumption is that he looks mainly at the parts of the picture he regards as being its features; they are the parts that hold for him the most information about the picture. Features are tentatively located by peripheral vision and then fixated directly for detailed inspection. (It is important to note that in these experiments and in the others we shall describe the subject is given only general instructions, such as "Just look at the pictures," or even no instructions at all. More specific instructions, requiring him to inspect and describe some specific aspect of the picture, usually result in appropriately directed fixations, as might be expected.)

When subjects freely view simple pictures, such as line drawings, under these conditions, it is found that their fixations tend to cluster around the angles of the picture. For example, Leonard Zusne and Kenneth M. Michels performed an experiment of this type at Purdue University, using as pictures line drawings of simple polygons [*see illustration on*

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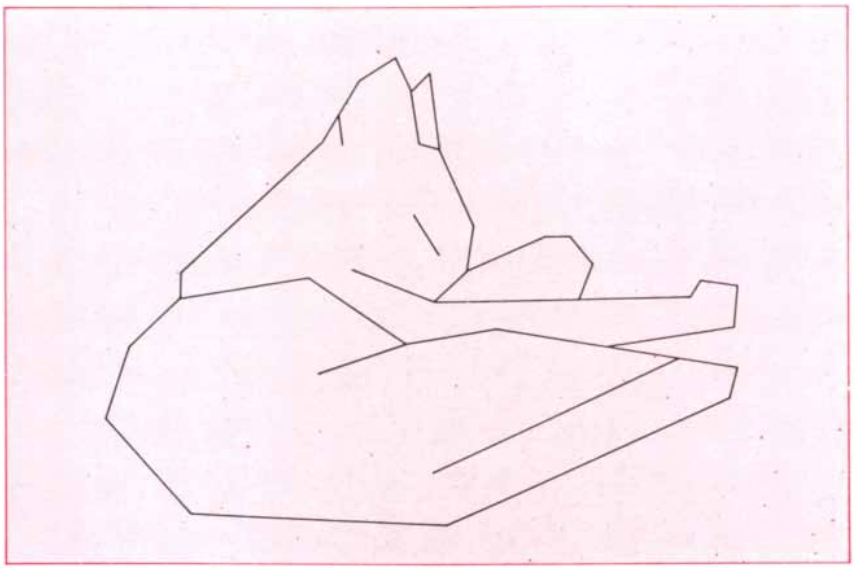
opposite page]. From the fixations made by their subjects in viewing such figures it is clear that the angles of the drawings attracted the eyes most strongly.

Our tentative conclusion is that, at least with such line drawings, the angles are the principal features the brain employs to store and recognize the drawing. Certainly angles would be an efficient choice for features. In 1954 Fred Attneave III of the University of Oregon pointed out that the most informative parts of a line drawing are the angles and sharp curves. To illustrate his argument he presented a picture that was obtained by selecting the 38 points of greatest curvature in a picture of a sleeping cat and joining the points with straight lines [*see top illustration at right*]. The result is clearly recognizable.

Additional evidence that angles and sharp curves are features has come from electrophysiologists who have investigated the activity of individual brain cells. For example, in the late 1950's Jerome Y. Lettvin, H. R. Maturana, W. S. McCulloch and W. H. Pitts of the Massachusetts Institute of Technology found angle-detecting neurons in the frog's retina. More recently David H. Hubel and Torsten N. Wiesel of the Harvard Medical School have extended this result to cats and monkeys (whose angle-detecting cells are in the visual cortex rather than the retina). And recordings obtained from the human visual cortex by Elwin Marg of the University of California at Berkeley give preliminary indications that these results can be extended to man.

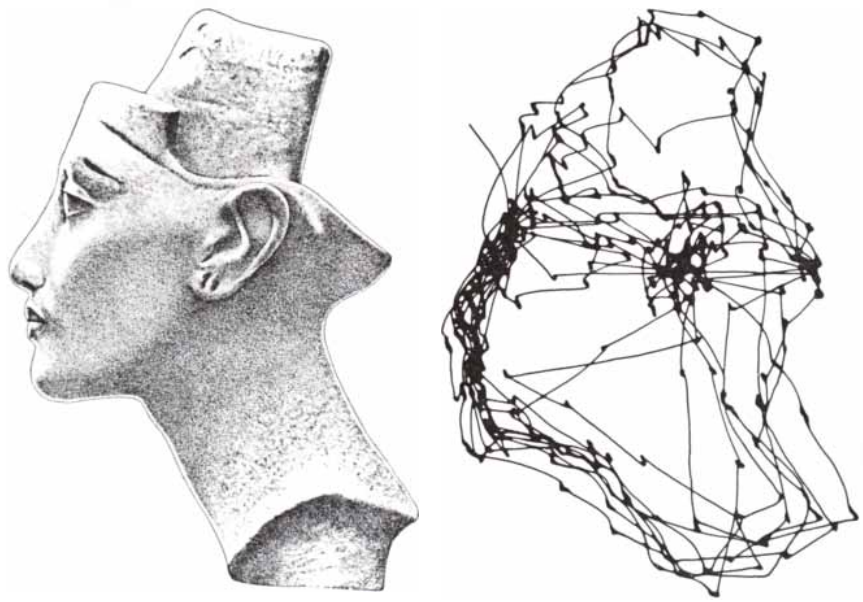
Somewhat analogous results have been obtained with pictures more complex than simple line drawings. It is not surprising that in such cases the features are also more complex. As a result no formal description of them has been achieved. Again, however, high information content seems to be the criterion. Norman H. Mackworth and A. J. Morandi made a series of recordings at Harvard University of fixations by subjects viewing two complex photographs. They concluded that the fixations were concentrated on unpredictable or unusual details, in particular on unpredictable contours. An unpredictable contour is one that changes direction rapidly and irregularly and therefore has a high information content.

We conclude, then, that angles and other informative details are the features selected by the brain for remembering and recognizing an object. The next question concerns how these features are integrated by the brain into a whole—the internal representation—so that one sees the object as a whole, as an object rather than an unconnected sequence of features. Once again useful evidence comes from recordings of eye movements. Just as study of the locations of fixations indicated the probable nature of the features, so analysis of the order of fixations suggests a format for the interconnection of features into the overall internal representation.



SHARP CURVES are also important as features for visual identification, as shown by Fred Attneave III of the University of Oregon in a picture made by selecting the 38 points of greatest curvature in a picture of a sleeping cat and joining them with straight lines, thus eliminating all other curves. The result is still easily recognizable, suggesting that points of sharp curvature provide highly useful information to the brain in visual perception.

The illustration below shows the fixations made by a subject while viewing a photograph of a bust of the Egyptian queen Nefertiti. It is one of a series of recordings made by Alfred L. Yarbus of the Institute for Problems of Information Transmission of the Academy of Sciences of the U.S.S.R. The illustration



REGULARITIES OF EYE MOVEMENT appear in a recording of a subject viewing a photograph of a bust of Queen Nefertiti. At left is a drawing of what the subject saw; at right are his eye movements as recorded by Alfred L. Yarbus of the Institute for Problems of Information Transmission in Moscow. The eyes seem to visit the features of the head cyclically, following fairly regular pathways, rather than crisscrossing the picture at random.

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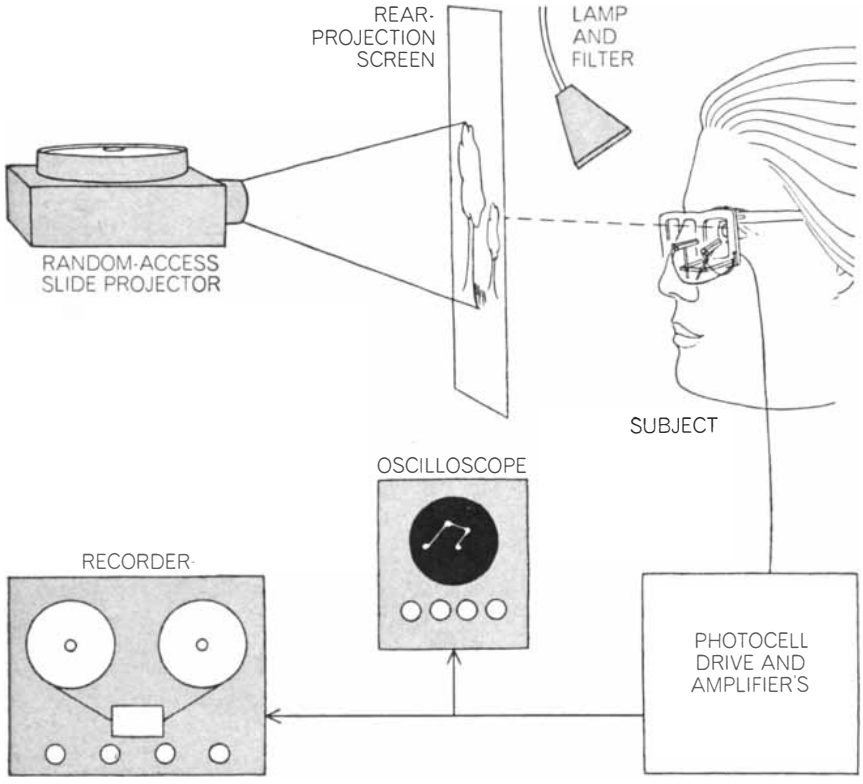

EXPERIMENTAL PROCEDURE employed by the authors is depicted schematically. The subject viewed pictures displayed on a rear-projection screen by a random-access slide projector. Diffuse infrared light was shined on his eyes; his eye movements were recorded by photocells, mounted on a spectacle frame, that detected reflections of the infrared light from one eyeball. Eye movements were displayed on oscilloscope and also recorded on tape.

shows clearly an important aspect of eye movement during visual perception, namely that the order of the fixations is by no means random. The lines representing the saccades form broad bands from point to point and do not crisscross the picture at random as would be expected if the eyes visited the different features repetitively in a random order. It appears that fixation on any one feature, such as Nefertiti's eye, is usually followed by fixation on the same next feature, such as her mouth. The overall record seems to indicate a series of cycles; in each cycle the eyes visit the main features of the picture, following rather regular pathways from feature to feature.

Recently at the University of California at Berkeley we have developed a hypothesis about visual perception that predicts and explains this apparent regularity of eye movement. Essentially we propose that in the internal representation or memory of the picture the features are linked together in sequence by the memory of the eye movement required to look from one feature to the next. Thus the eyes would tend to move from feature to feature in a fixed order, scanning the picture.

Most of Yarbus' recordings are summaries of many fixations and do not contain complete information on the ordering of the fixations. Thus the regularities of eye movements predicted by our hypothesis could not be definitely confirmed from his data. To eliminate this constraint and to subject our hypothesis to a more specific test we recently made a new series of recordings of eye movements during visual perception.

Our subjects viewed line drawings of simple objects and abstract symbols as we measured their eye movements (using photocells to determine the movements of the "white" of the eye) on magnetic tape and recorded them [*see illustration above*]. We thereby obtained a permanent record of the order of fixations made by the subjects and could play it back later at a lower speed, analyzing it at length for cycles and other regularities of movement. As in the earlier experiments, the drawings were fairly large and close to the subject's eyes, a typical drawing subtending about 20 degrees at the eye. In addition we drew the pictures with quite thin lines and displayed them with an underpowered slide projector, throwing a dim image on a screen that was fully exposed to the ordinary light in the laboratory. In this way we produced an image of low visibility and could be sure that the subject would have to look directly (foveally) at each feature that interested him, thus revealing to our recording equipment the locus of his attention.

Our initial results amply confirmed the previous impression of cycles of eye movements. We found that when a subject viewed a picture under these conditions, his eyes usually scanned it following—intermittently but repeatedly—a fixed path, which we have termed his "scan path" for that picture [*see illustration on opposite page*]. The occurrences of the scan path were separated by periods in which the fixations were ordered in a less regular manner.

Each scan path was characteristic of a given subject viewing a given picture. A subject had a different scan path for every picture he viewed, and for a given picture each subject had a different scan path. A typical scan path for our pictures consisted of about 10 fixations and lasted for from three to five seconds. Scan paths usually occupied from 25 to 35 percent of the subject's viewing time, the rest being devoted to less regular eye movements.

It must be added that scan paths were not always observed. Certain pictures (one of a telephone, for example) seemed often not to provoke a repetitive response, although no definite common characteristic could be discerned in such pictures. The commonest reaction, however, was to exhibit a scan path. It was interesting now for us to refer back to the earlier recordings by Zusne and Michels, where we observed scan paths that had previously passed unnoticed. For instance, in the illustration on page 36 fixations No. 4 through No. 11 and No. 11 through No. 18 appear to be two occurrences of a scan path. They are identical, even to the inclusion of the small reverse movement in the lower right-hand corner of the figure.

This demonstration of the existence of scan paths strengthened and clarified our ideas about visual perception. In accordance with the serial hypothesis, we assume that the internal representation of an object in the memory system is an assemblage of features. To this we add a crucial hypothesis: that the features are assembled in a format we have termed a "feature ring" [*see illustration on page 40*]. The ring is a sequence of sensory and motor memory traces, alternately recording a feature of

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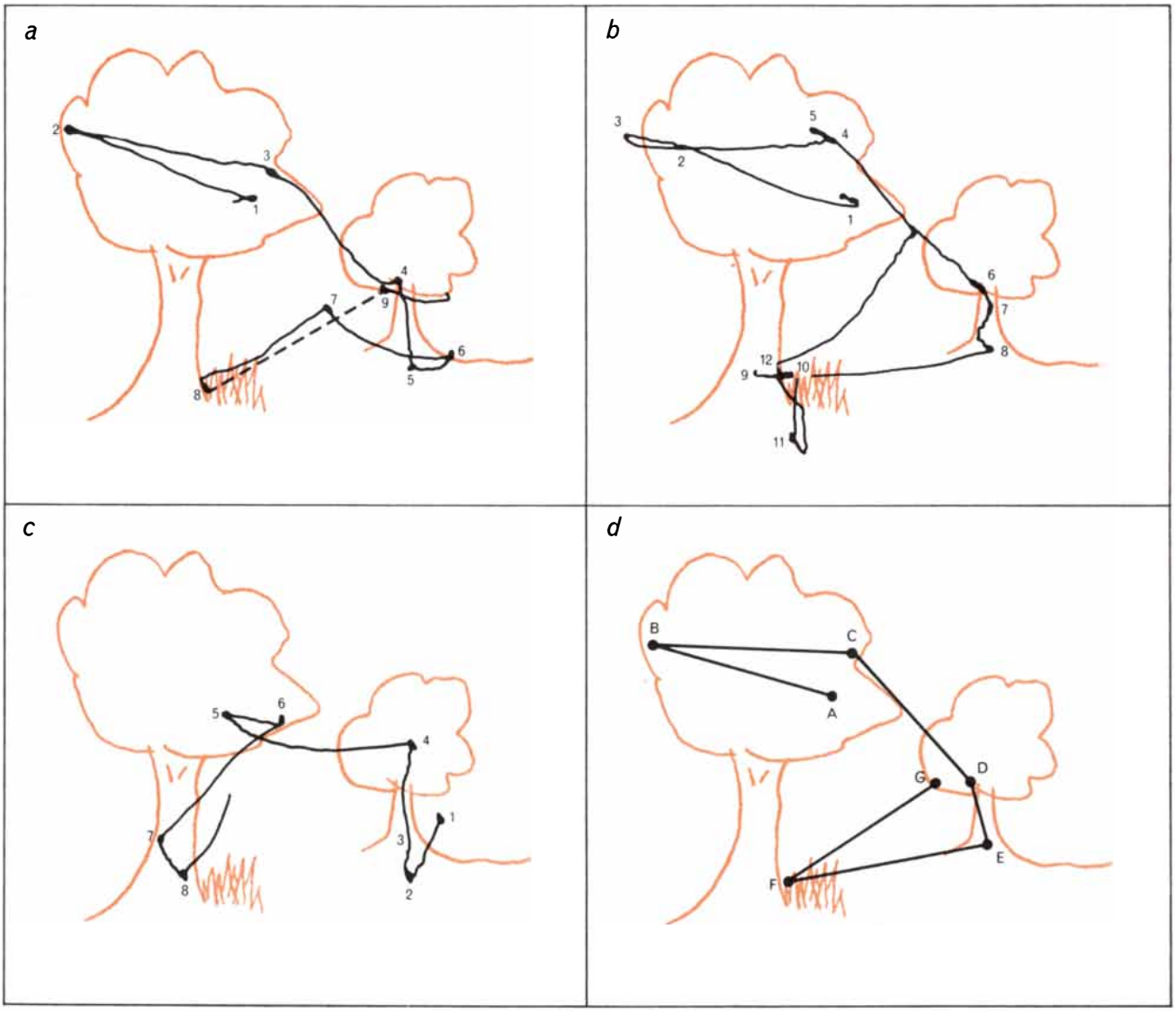
the object and the eye movement required to reach the next feature. The feature ring establishes a fixed ordering of features and eye movements, corresponding to a scan path on the object.

Our hypothesis states that as a subject views an object for the first time and becomes familiar with it he scans it with his eyes and develops a scan path for it. During this time he lays down the memory traces of the feature ring, which records both the sensory activity and the motor activity. When he subsequently encounters the same object again, he recognizes it by matching it with the feature ring, which is its internal representation in his memory. Matching consists in verifying the successive features and carrying out the intervening eye movements, as directed by the feature ring.

This hypothesis not only offers a plausible format for the internal representation of objects—a format consistent with the existence of scan paths—but also has certain other attractive features. For example, it enables us to draw an interesting analogy between perception and behavior, in which both are seen to involve the alternation of sensory and motor activity. In the case of behavior, such as the performance of a learned sequence of activities, the sensing of a situation alternates with motor activity designed to bring about an expected new situation. In the case of perception (or, more specifically, recognition) of an object the verification of features alternates with movement of the eyes to the expected new feature.

The feature-ring hypothesis also makes a verifiable prediction concerning eye movements during recognition: The successive eye movements and feature verifications, being directed by the feature ring, should trace out the same scan path that was established for the object during the initial viewing. Confirmation of the prediction would further strengthen the case for the hypothesis. Since the prediction is subject to experimental confirmation we designed an experiment to test it.

The experiment had two phases, which we called the learning phase and the recognition phase. (We did not, of



REGULAR PATTERN of eye movement by a given subject viewing a given picture was termed the subject's "scan path" for that picture. Two of five observed occurrences of one subject's scan path as he looked at a simple drawing of trees for 75 seconds are shown here (*a*, *b*). The dotted line between fixations 8 and 9 of *a* indicates that the recording of this saccade was interrupted by a blink. Less regular eye movements made between these appearances of the scan path are at *c*. Subject's scan path is idealized at *d*.

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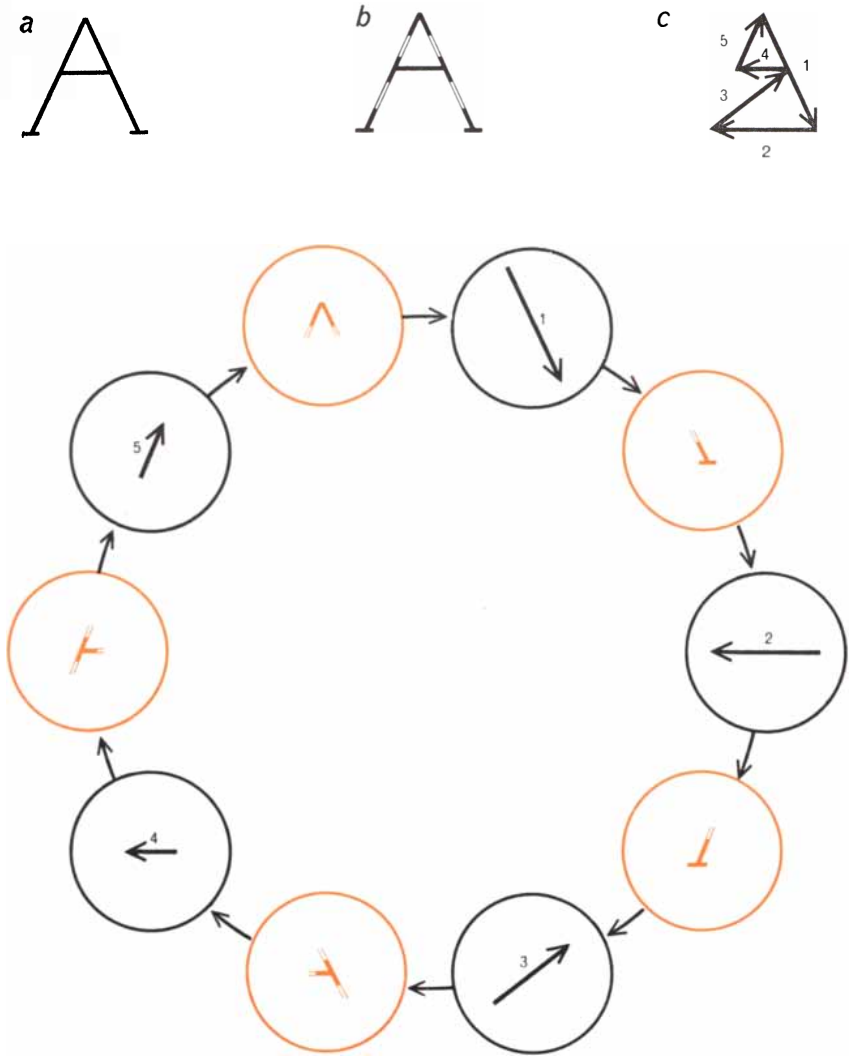

FEATURE RING is proposed by the authors as a format for the internal representation of an object. The object (*a*) is identified by its principal features (*b*) and is represented in the memory by them and by the recollection of the scan path (*c*) whereby they were viewed. The feature ring therefore consists of sensory memory traces (*color*) recording the features and motor memory traces (*black*) of the eye movements from one feature to the next.

course, use any such suggestive terms in briefing the subjects; as before, they were simply told to look at the pictures.) In the learning phase the subject viewed five pictures he had not seen before, each for 20 seconds. The pictures and viewing conditions were similar to those of the first experiment. For the recognition phase, which followed immediately, the five pictures were mixed with five others the subject had not seen. This was to make the recognition task less easy. The set of 10 pictures was then presented to the subject three times in random order; he had five seconds to look at each picture. Eye movements were recorded during both the learning phase and the recognition phase.

When we analyzed the recordings, we were pleased to find that to a large extent our predictions were confirmed. Scan paths appeared in the subject's eye movements during the learning phase, and during the recognition phase his first few eye movements on viewing a picture (presumably during the time he was recognizing it) usually followed the same scan path he had established for that picture during the learning phase [*see illustration on opposite page*]. In terms of our hypothesis the subject was forming a feature ring during the learning-phase occurrences of the scan path; in the recognition phase he was matching the feature ring with the picture, following the scan path dictated by the feature ring.

An additional result of this experiment was to demonstrate that different subjects have different scan paths for a given picture and, conversely, that a given subject has different scan paths for different pictures [*see illustration on page 42*]. These findings help to discount certain alternative explanations that might be advanced to account for the occurrence of scan paths. The fact that a subject has quite different scan paths for different pictures suggests that the scan paths are not the result of some fixed habit of eye movement, such as reading Chinese vertically, brought to each picture but rather that they come from a more specific source, such as learned feature rings. Similarly, the differences among subjects in scan paths used for a given picture suggest that the scan paths do not result from peripheral feature detectors that control eye movements independent of the recognition process, since these detectors might be expected to operate in much the same way in all subjects.

Although the results of the second experiment provided considerable support for our ideas on visual perception, certain things remain unexplained. For example, sometimes no scan path was observed during the learning phase. Even when we did find a scan path, it did not always reappear in the recognition phase. On the average the appropriate scan path appeared in about 65 percent of the recognition-phase viewings. This is a rather strong result in view of the many possible paths around each picture, but it leaves 35 percent of the viewings, when no scan path appeared, in need of explanation.

Probably the basic idea of the feature ring needs elaboration. If provision were made for memory traces recording other eye movements between features not adjacent in the ring, and if the original ring represented the preferred and habitual order of processing rather than the inevitable order, the occasional substitution of an abnormal order for the

RECURRENCE OF SCAN PATH during recognition of an object is predicted by the feature-ring hypothesis. A subject viewed the adaptation of Klee's drawing (*a*). A scan path appeared while he was familiarizing himself with the picture (*b, c*). It also appeared (*d, e*) during the recognition phase each time he identified the picture as he viewed a sequence of familiar and unfamiliar scenes depicted in similar drawings. This particular experimental subject's scan path for this particular picture is presented in idealized form at *f*.

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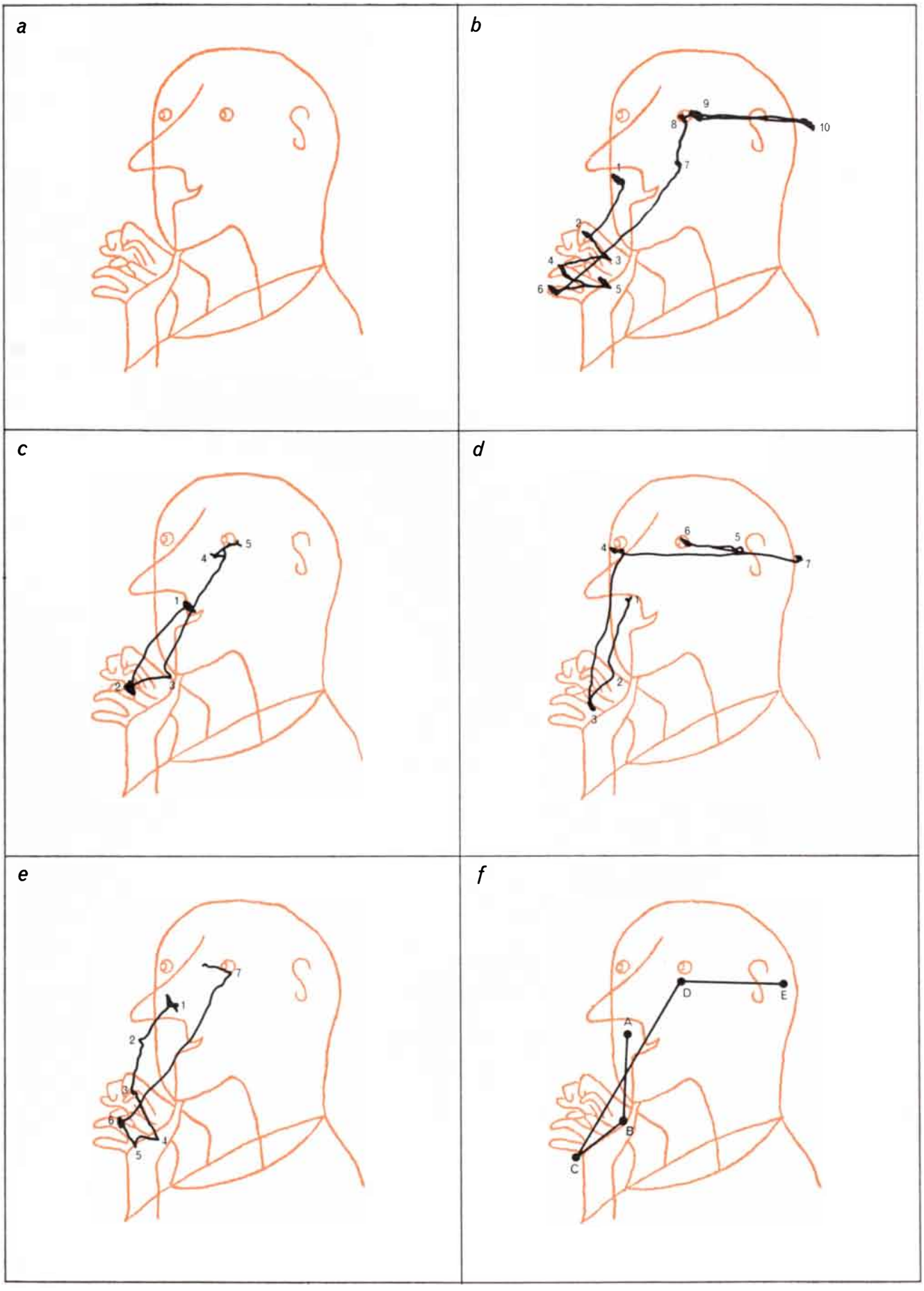

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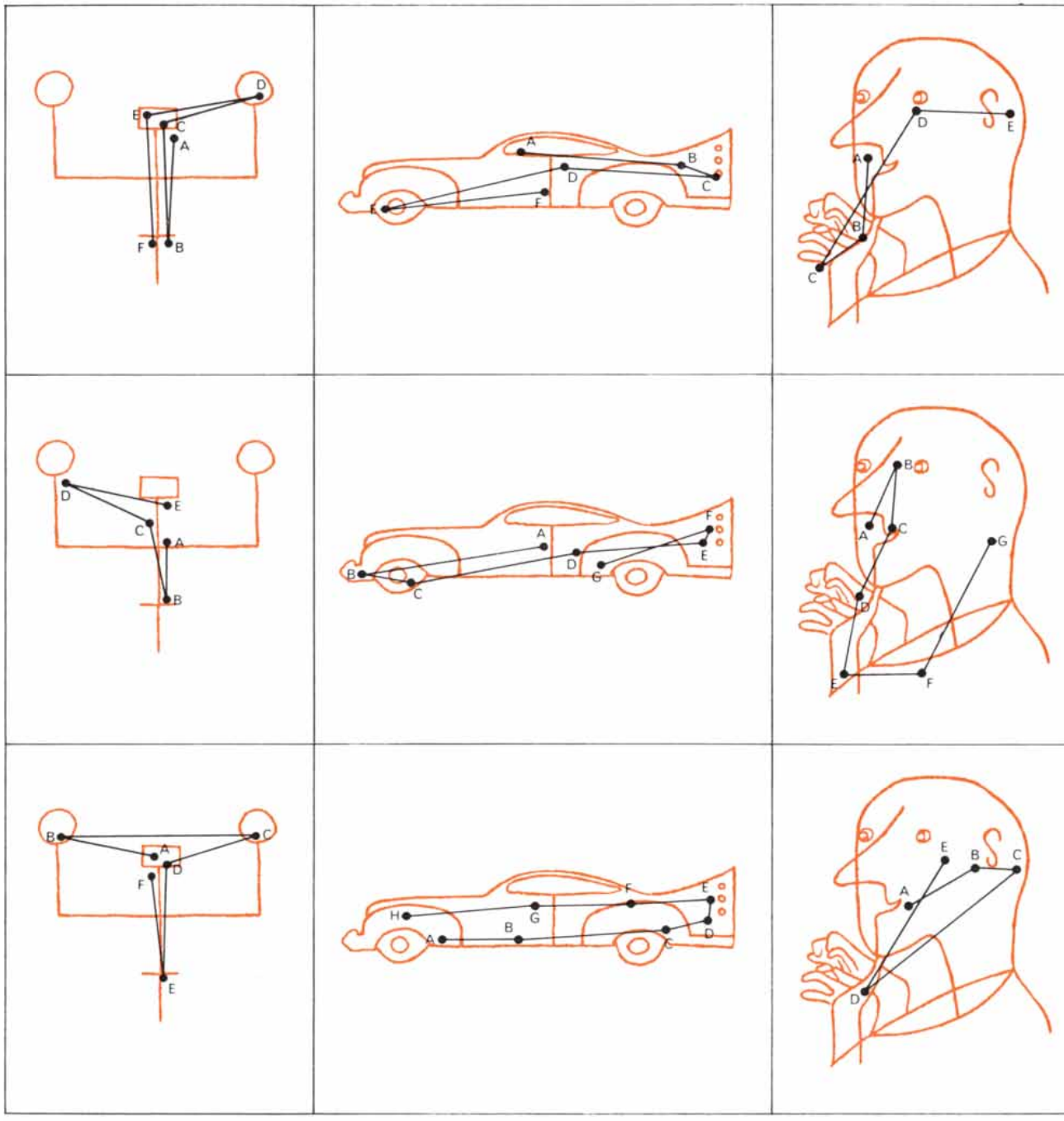
scan path would be explained [*see top illustration on opposite page*].

It must also be remembered that the eye-movement recordings in our experiments were made while the subjects viewed pictures that were rather large and close to their eyes, forcing them to look around in the picture to see its features clearly. In the more normal viewing situation, with a picture or an object small enough to be wholly visible with a single fixation, no eye movements are necessary for recognition. We assume that in such a case the steps in perception are parallel up to the point where an image of the object is formed in the visual cortex and that thereafter (as would seem evident from the experiments on recognition time) the matching of the image and the internal representation is carried out serially, feature by feature. Now, however, we must postulate instead of eye movements from feature to feature a sequence of internal shifts of attention, processing the features serially and following the scan path dictated by the feature ring. Thus each motor memory trace in the feature ring records a shift of attention that can be executed either externally, as an eye movement, or internally, depending on the extent of the shift required.

In this connection several recordings made by Lloyd Kaufman and Whitman Richards at M.I.T. are of interest. Their subjects viewed simple figures, such as a drawing of a cube, that could be taken in with a single fixation. At 10 randomly chosen moments the subject was asked



VARIETY IN SCAN PATHS is shown for three subjects and three pictures. Each horizontal row depicts the scan paths used by one subject for the three pictures. Vertically one sees how the scan paths of the three subjects for any one picture also varied widely.

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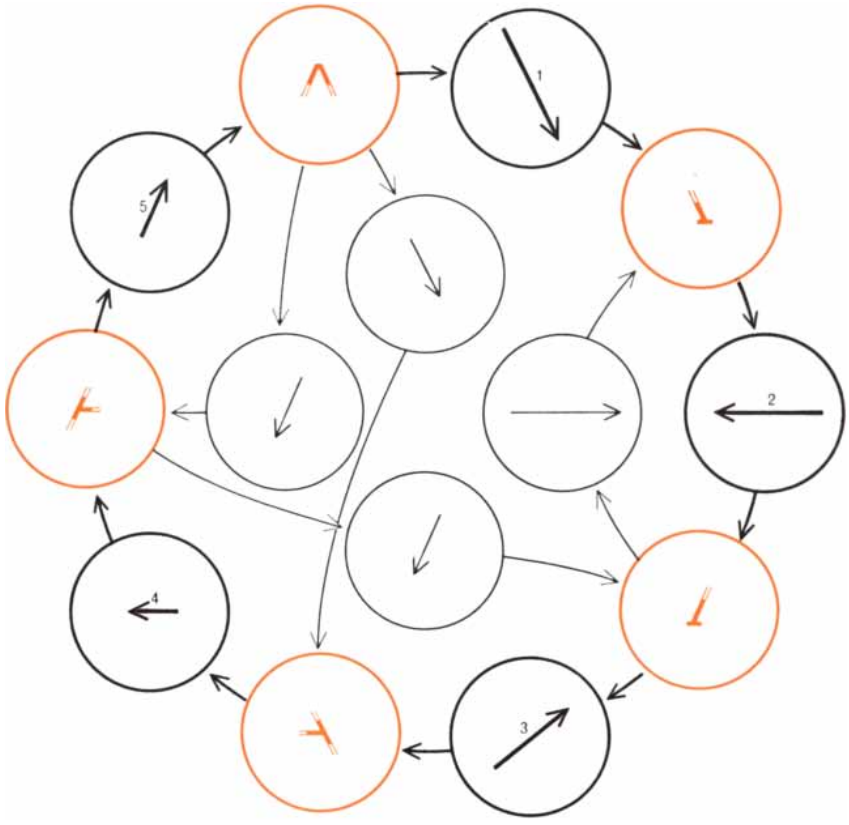
to indicate where he thought he was looking. His answer presumably showed what part of the picture he was attending to visually. His actual fixation point was then recorded at another 10 randomly selected moments [*see bottom illustration at right*]. The results suggest that the subject's attention moved around the picture but his fixation remained fairly steady near the center of the picture. This finding is consistent with the view that smaller objects too are processed serially, by internal shifts of attention, even though little or no eye movement is involved.

It is important to note, however, that neither these results nor ours prove that recognition of objects and pictures is necessarily a serial process under normal conditions, when the object is not so large and close as to force serial processing by eye movements. The experiments on recognition time support the serial hypothesis, but it cannot yet be regarded as being conclusively established. In our experiments we provided a situation that forced the subject to view and recognize pictures serially with eye movements, thus revealing the order of feature processing, and we assumed that the results would be relevant to recognition under more normal conditions. Our results suggest a more detailed explanation of serial processing—the feature ring producing the scan path—but this explanation remains conditional on the serial hypothesis.

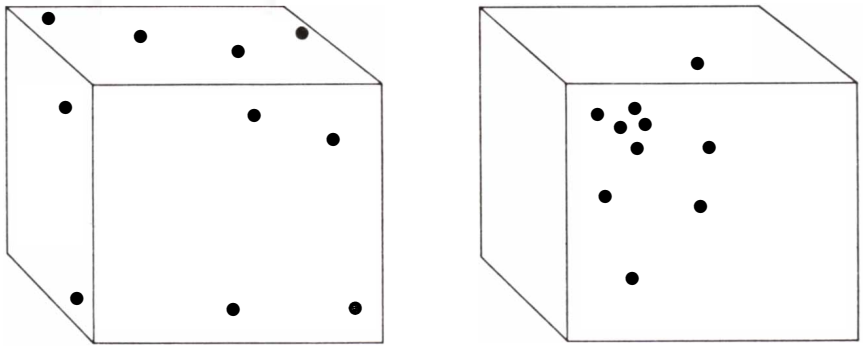


MODIFIED FEATURE RING takes into account less regular eye movements that do not conform to scan path. Several movements, which appeared in 35 percent of recognition viewings, are in center of this ring. Outside ring, consisting of sensory (*black*) and motor memory traces (*color*), represents scan path and remains preferred order of processing.

In sum, we believe the experimental results so far obtained support three main conclusions concerning the visual recognition of objects and pictures. First, the internal representation or memory of an object is a piecemeal affair: an assemblage of features or, more strictly, of memory traces of features; during recognition the internal representation is matched serially with the object, feature by feature. Second, the features of an object are the parts of it (such as the angles and curves of line drawings) that yield the most information. Third, the memory traces recording the features are assembled into the complete internal representation by being connected by other memory traces that record the shifts of attention required to pass from feature to feature, either with eye movements or with internal shifts of attention; the attention shifts connect the features in a preferred order, forming a feature ring and resulting in a scan path, which is usually followed when verifying the features during recognition.

Clearly these conclusions indicate a distinctly serial conception of visual learning and recognition. In the trend to look toward serial concepts to advance the understanding of visual perception one can note the influence of current work in computerized pattern recognition, where the serial approach has long been favored. Indeed, computer and information-processing concepts, usually serial in nature, are having an increasing influence on brain research in general.

Our own thoughts on visual recognition offer a case in point. We have developed them simultaneously with an analogous system for computerized pattern recognition. Although the system has not been implemented in working form, a somewhat similar scheme is being used in the visual-recognition system of a robot being developed by a group at the Stanford Research Institute. We believe this fruitful interaction between biology and engineering can be expected to continue, to the enrichment of both.



INTERNAL SHIFTS OF ATTENTION apparently replace eye movements in processing of objects small enough to be viewed with single fixation. A subject's attention, represented by statements of where he thought he was looking, moved around picture (*left*), whereas measured fixation point (*right*) remained relatively stationary. Illustration is based on work by Lloyd Kaufman and Whitman Richards at the Massachusetts Institute of Technology.

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ELASTIC FIBERS IN THE BODY

These fibers enable tissues such as skin, arteries and ligaments to stretch and rebound. Their two components have been separated, and their composition and mode of synthesis are being established

by Russell Ross and Paul Bornstein

As animals evolved from single-cell forms to many-celled ones the need arose for substances that could hold cells together in distinct units, and the process of natural selection led to the development of a complex intercellular connective tissue. In higher animals the characteristics of this connective tissue reflect the functional properties of each organ system. For example, as the blood pulses in an artery the artery wall alternately stretches and rebounds rather like rubber. The walls of the alveoli, the air sacs of the lungs, behave the same way, expanding with inhalation and relaxing with exhalation. Tissues such as skin and ligaments are also elastic. The elasticity of these various tissues is due to a remarkable biological fiber that acts like rubber but has a unique physical and chemical character of its own. This elastic fiber, one of the main components of the connective tissues mentioned, is currently under intensive study. There is a clinical interest as well as a purely scientific one in obtaining a detailed understanding of the constitution and behavior of the elastic fibers, inasmuch as certain diseases, and the process of aging itself, involve a loss of elasticity in elastic tissues, including the artery walls.

In the elastic tissues the principal components are collagen, a fibrous protein that provides considerable tensile strength, and the elastic fibers, which give the tissue stretchability. Like rubber, the elastic fibers stretch easily and rapidly with little loss of energy in heat, have moderate tensile strength when they are fully extended and rapidly retract to their original dimensions when the stress is removed. Strictly speaking, elasticity is defined in physical terms as resistance to deformation, and in those terms "highly elastic" materials are substances such as steel and glass. In common usage, however, the term "elastic" has come to be applied to materials that have a low coefficient of elasticity (that is, can be deformed by a small force) and reversibly recover their original dimensions or shape even after considerable deformation, or stretching.

Examining a suitably stained elastic tissue with the light microscope, one can clearly see the elastic fibers. In a tissue rich in collagen fibers, such as ligament, the elastic fibers are cylindrical and weave among the bundles of collagen fibers. In an artery wall the elastic fibers form concentric layers, with holes that enable the muscle cells in the wall to communicate across the layers.

When the electron microscope became available for a more detailed look at elastic fibers, investigators hoped to gain information about the structure of the fibers that would throw some light on their elasticity. The first examinations were disappointing. The fibers appeared to be merely amorphous masses of material without any distinct structure. As improvements were made in the preparation of the tissues and in the resolution of the electron microscope, however, it was eventually seen that the elastic fibers have a structure that consists of two components. One was a microfibril about 110 angstroms in diameter; the picture showed aggregates of these microfibrils clumped together in the fiber. The other component was observed to be amorphous. When it later became possible to isolate and analyze the amorphous material, it was found to be composed largely of an unusual protein called elastin. This protein had been studied earlier; it consists of a unique combination of amino acids, is markedly insoluble and has some other peculiar properties.

At the University of Washington School of Medicine we have been investigating the nature of these two components. Our inquiry is based on studies of the development of elastic fibers in animals from the fetal to the adult stage. Using the electron microscope to inspect the formation of ligament and tendon during the very first stages, we found no sign of the amorphous component in the embryonic elastic fibers. At this time the fibers appeared to consist only of the 110-angstrom microfibrils. The microfibrils' staining properties suggested that they carried a negative charge on the surface. They showed another interesting feature: as microfibrils began to make their appearance outside a cell, they lay in close intimacy to the cell, often occupying little infoldings or hollows in the cell surface. Since the groups of microfibrils during this time took a form that apparently determined the eventual shape of mature elastic fibers, it seemed that the microfibrils' development, although they were outside the cell, might be under some kind of control by the cell.

As development proceeded, the amorphous component began to show up in

ELASTIC FIBERS in the wall of a developing artery of a young guinea pig are enlarged some 80,000 diameters in this electron micrograph. An elastic fiber is seen in longitudinal section (*top right to bottom left*); others are seen in oblique section (*center right*) and in cross section (*bottom right*). Each consists of bundles of microfibrils surrounding and interpenetrating the protein elastin, which appears amorphous. The left side of the micrograph is dominated by another component of elastic tissue, collagen. It is in the form of banded fibrils. Most of the fibrils are seen in longitudinal section, some of them in cross section.

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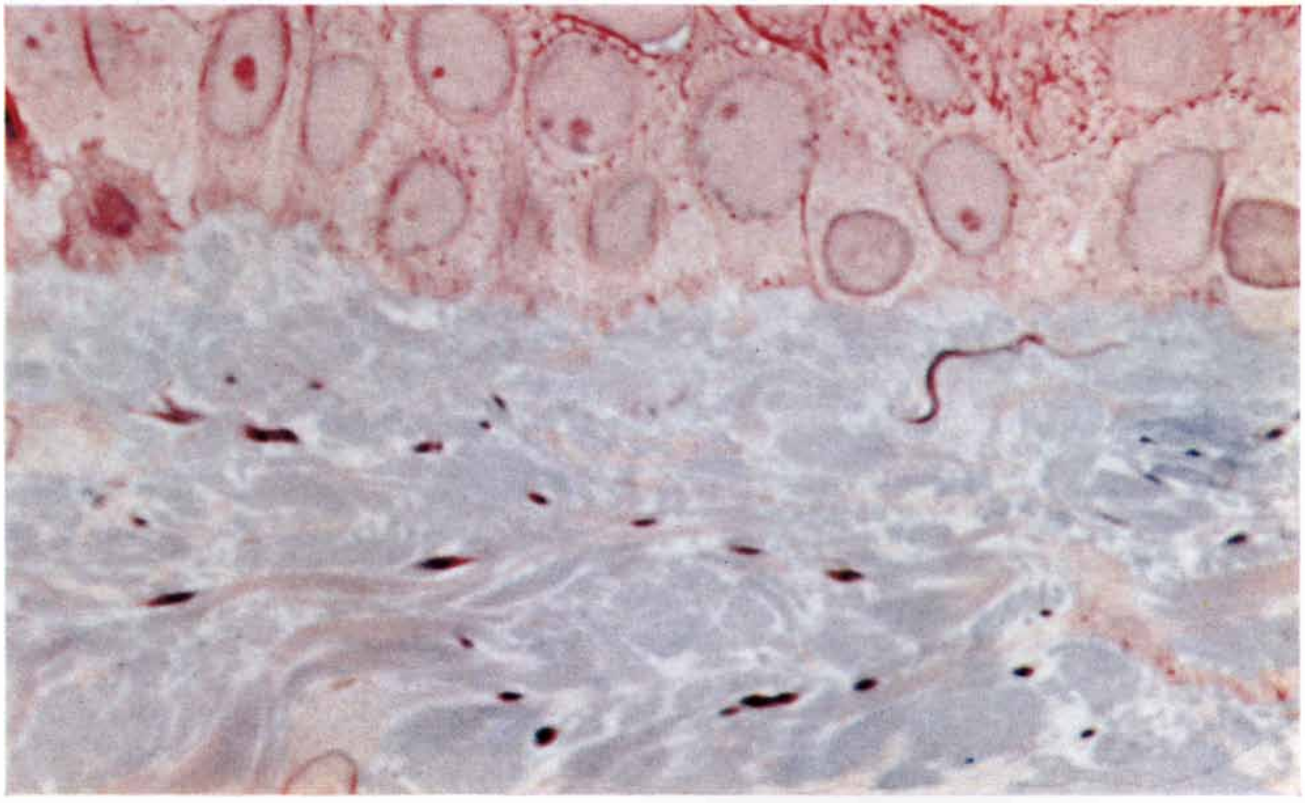
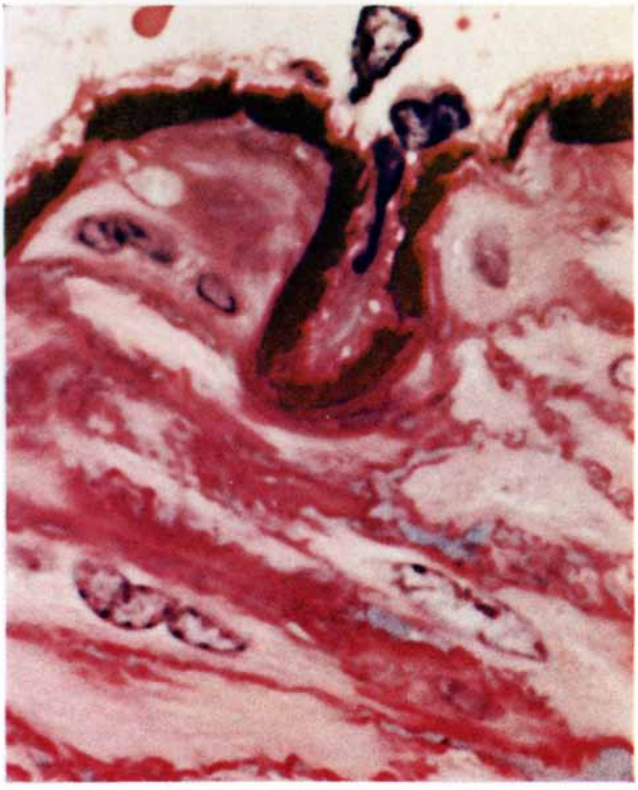


SKIN is one of the tissues that are endowed with resilience by the presence of elastic fibers. A section of human skin, enlarged 500 diameters in this photomicrograph, shows the cells of the epidermis underlain by connective tissue, largely collagen fibers (*pale blue*). The elastic fibers, which stain a deep purple-red, can be seen in the connective tissue, weaving among the collagen fibers.

ELASTIC ARTERY, the aorta, has concentric rings of elastic fibers (*purple-red*) separated by cells (*pink with blue nuclei*) and collagen fibers. Enlargement here and at right is 2,000 diameters.



MUSCULAR ARTERY, the coronary, is much narrower than the aorta. It has a single layer of elastic tissue near the inner surface. The smooth-muscle cells are separated by collagen fibers (*blue*).

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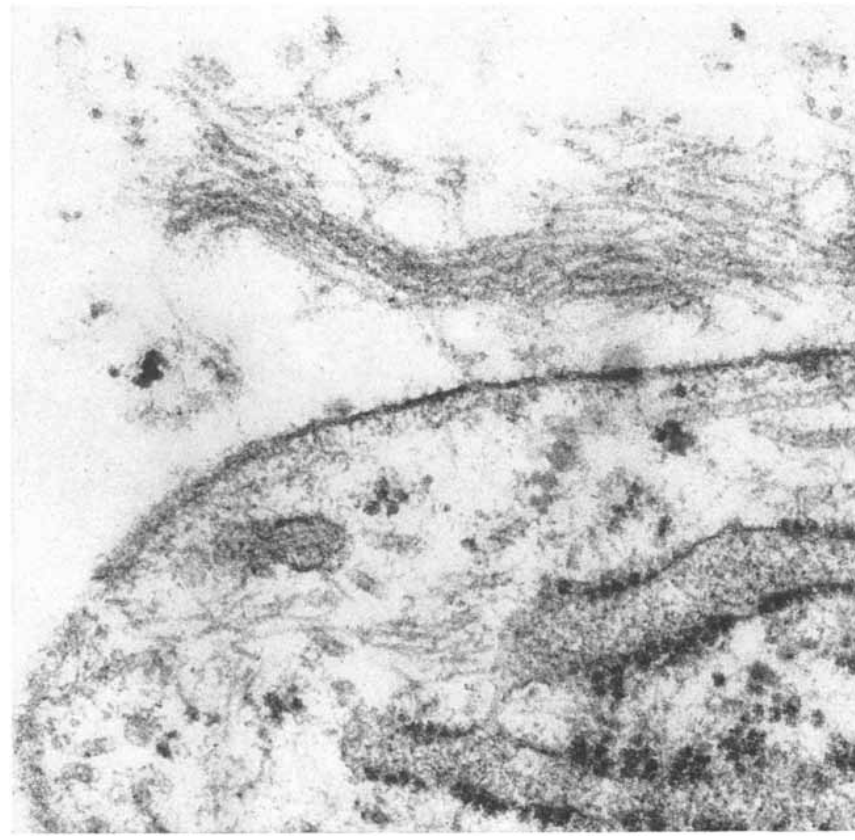
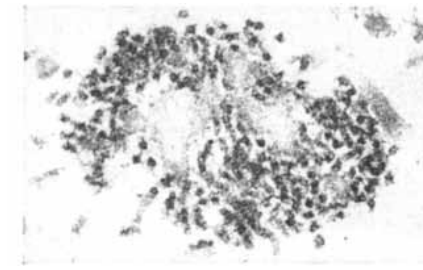
the elastic fibers, and by the time the animal had reached adulthood these fibers consisted predominantly of the amorphous material—that is, elastin—with the microfibrils then accounting for only a relatively small part of the enlarged fiber.

At this point there were several biochemical questions to consider. What was the relation of the microfibrils to the amorphous material? Was the microfibrillar protein a precursor of elastin, or was it totally unrelated to that polymer? And how was the elastin polymer synthesized? It is fairly well established that proteins built outside cells are formed from relatively small, soluble units that have been synthesized on ribosomes within the cell and then transported to the outside site where the polymer is put together. How are such soluble units assembled into the highly insoluble elastin polymer? What kind of covalent bond is used to bind the elastin polymer, and how are the bonds formed?

In order to answer these questions we had to begin by exploring the chemical characteristics of each component of the elastic fiber. This was difficult to do directly because the chemical procedures required to isolate and purify the elastic fiber and then separate elastin from the microfibrils carried a risk of changing the elastin molecule in the process.

Several laboratories had considered clues to the nature of the elastin molecule that could be derived from the known structure of rubber molecules. Tests of the responses to stress by various elastic tissues and by isolated elastic fibers had shown that the stress-strain curves (measures of the relation of deformation to stress, or load) for the elastic tissues and fibers are very similar to the curves for lightly vulcanized natural rubber. This suggested that elastin might have much the same structural characteristics as rubber. Now, in vulcanized rubber long-chain molecules of hydrocarbon are tied together in a three-dimensional network by widely spaced covalent cross-links. There is no significant electrical force of attraction or repulsion between the chains. In the natural (unstressed) state the chains are folded in random fashion. When the material is stretched, the chains line up in a crystalline array, movement of the chains being facilitated by the absence of interchain forces. The cross-links, however, limit the amount of chain slippage, and this accounts for rubber's tensile strength. When the stress is released, the chains return to their random folding—their natural state of higher entropy.





MICROFIBRILS, enlarged about 100,000 diameters, are seen at two stages in these electron micrographs. At the earliest stage of elastic-fiber formation in an elastic ligament in a young fetal calf (*above*) bundles of the 110-angstrom microfibrils lie above a cell. The second component of the fiber, elastin, appears later. The cross section of an elastic fiber in an older fetal calf (*right*) shows microfibrils surrounding newly formed elastin.

By analogy, then, one could suppose that elastin, like rubber, is composed of long-chain molecules that are tied together by scattered cross-links but do not have any fixed conformation. This conjecture is consistent with elastin's amorphous appearance; even on examination with X rays, as W. T. Astbury of the University of Leeds found many years ago, elastin shows no signs of an orderly structure, either in the resting or in the stretched state. Another observation tending to support the view that elastin molecules are relatively disordered in relation to one another is the finding on chemical analysis that most of the amino acids making up the elastin molecule are uncharged and hydrophobic (water-hating), so that in an aqueous environment any interaction between the molecules must be weak.

Some recent investigations, however, have shown that elastin has more structure than had been supposed. Torkel Weis-Fogh of the University of Cambridge found that the stretching and relaxation of elastin is accompanied by changes in the molecule's energy state, changes that can be attributed to surface interactions between the water in the tissues and the core of the elastin molecule, which is largely hydrophobic and partly structured. Recent X-ray and spectroscopic studies also indicate that elastin possesses a degree of order, influenced by the nature of the surrounding fluid. Thus the new findings suggest that elastin is not quite analogous to rubber, and we must look further to find the secret of its elasticity.

Because of its chemical inertness and resistance to hydrolysis by mild acid and alkali, elastin can be extracted from elastic tissue in fairly pure form as an insoluble residue. By exhaustive autoclav-

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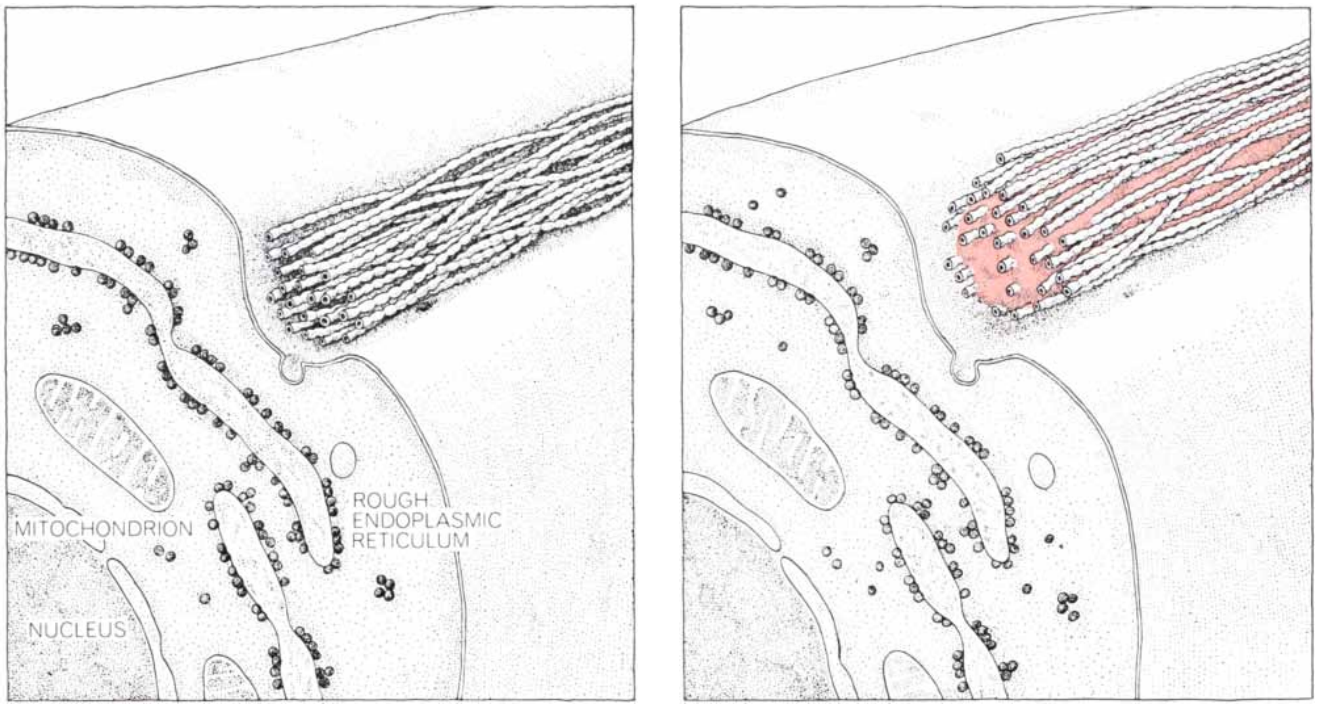
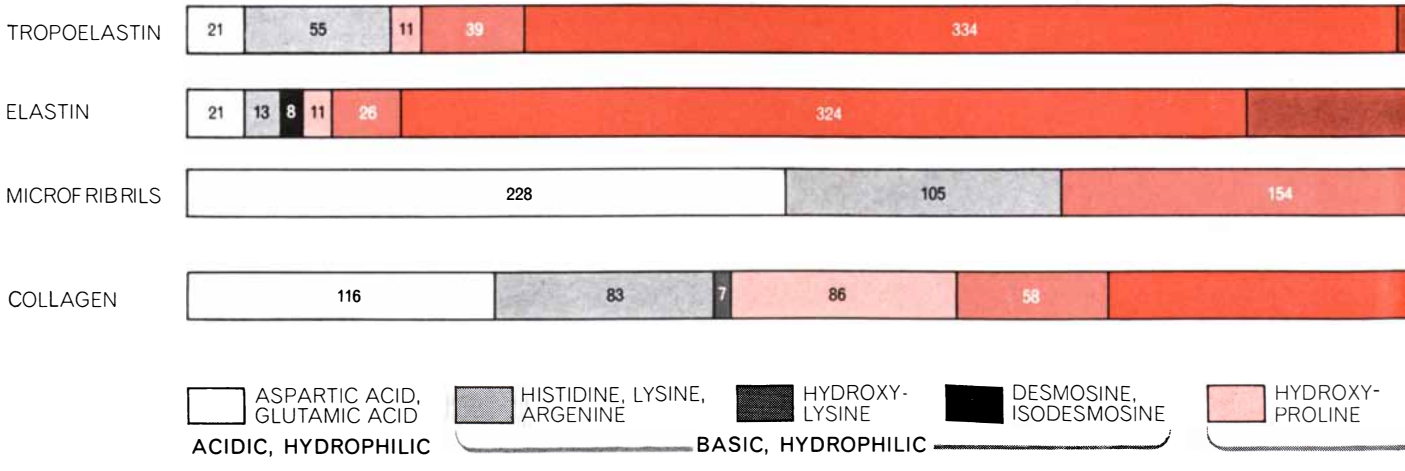


DEVELOPMENT of an elastic fiber is shown at two stages. The immature fiber (*left*) is an aggregation of microfibrils grouped in a long cylinder that lies along an infolding of the surface of a cell. At a later stage (*right*) a new protein, elastin (*color*), has been synthesized on the ribosomes (*black dots*) of the rough endoplasmic reticulum and has been secreted by the cell into the preformed cylinder of microfibrils. Thus the cell plays a part in forming the fiber, whose shape is determined by the microfibril cylinder.

ing in water or extraction with hot dilute alkali it is possible to obtain a product possessing a reasonably consistent amino acid composition and the characteristic look of elastin under electron-microscopic examination. Such a preparation often contains traces of the microfibrillar component of the elastic fiber and other impurities, however, and it was clearly impossible to ensure removal of all contaminating substances by such procedures without risking chemical alteration of susceptible regions of the elastin molecule. We therefore turned to a more effective two-step process. The first step isolated the elastic fiber, in purified and intact form, by the use of a denaturing extractant such as a concentrated solution of guanidine and enzymes that specifically break down collagen. Then, to separate the microfibrils from elastin, we took advantage of the fact that the microfibrillar protein contains a large amount of the amino acid cystine, whereas in elastin this amino acid is almost completely absent. By breaking the disulfide bond (S–S) of cystine we made the microfibrils soluble and thus separated them from elastin.

On analysis of the two proteins it turned out that the microfibrillar protein was markedly different from elastin. In amino acid composition they bore no relation to each other [*see bottom illustration on these two pages*], so that one of our questions had a categorical answer: The protein of the microfibrils in elastic fibers is definitely not a precursor of elastin.



AMINO ACID ANALYSIS of elastin, tropoelastin (its precursor), microfibrils and collagen establishes relations and differences among the four proteins. Results are given here in number of amino acids per 1,000. (Some asparagine and glutamine, which are neutral, inevitably contribute to the fraction analyzed as aspartic acid and glutamic acid in all four proteins.) Elastin is clearly different from the microfibrillar protein: it has a large proportion of hydrophobic amino acids, a low content of charged amino acids

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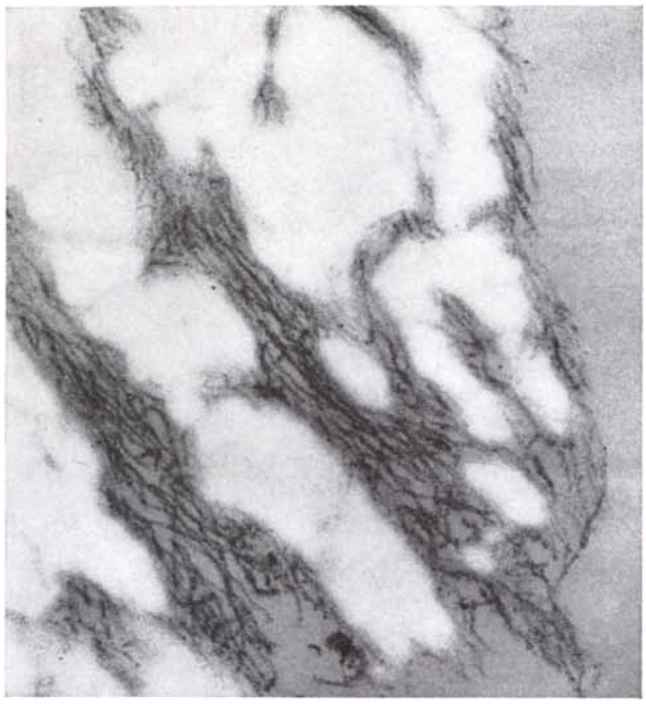
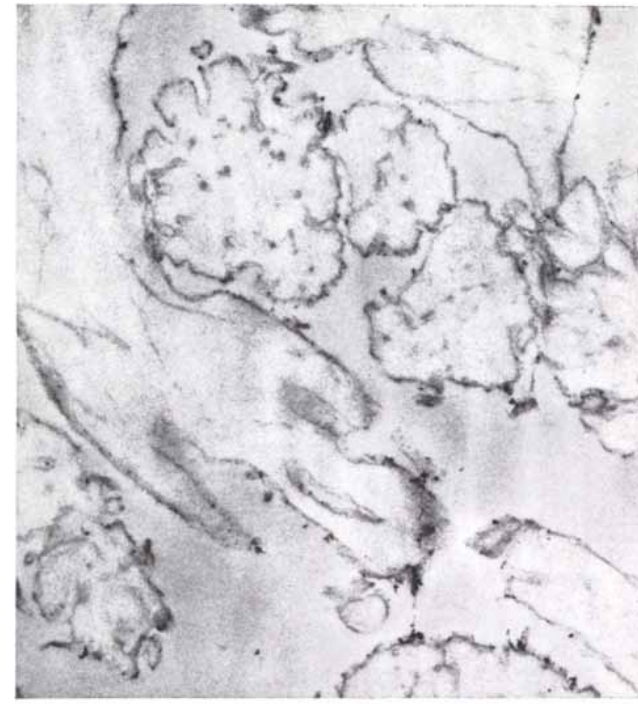


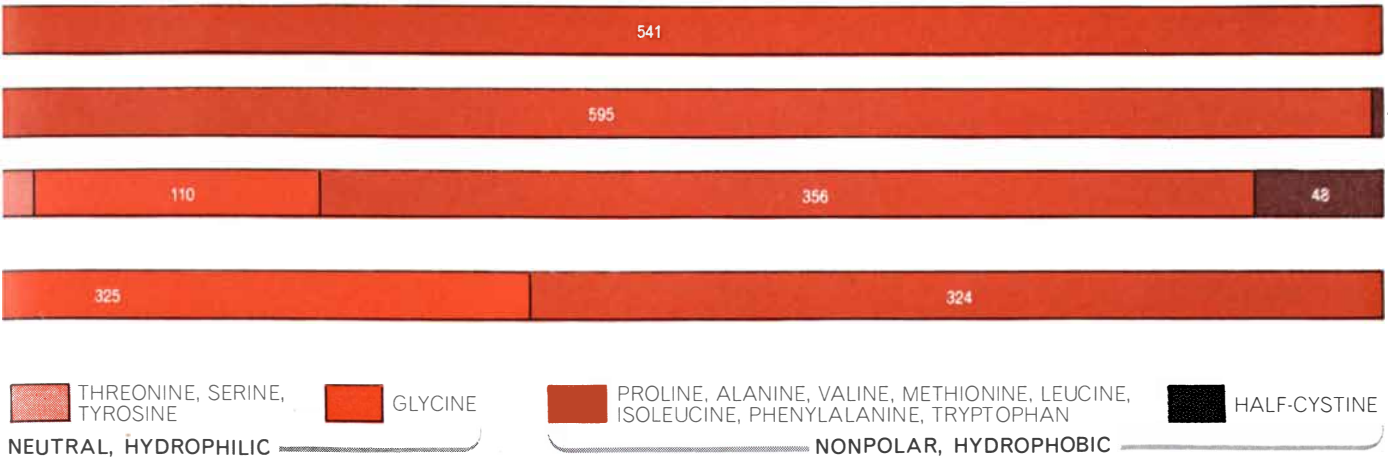


SEPARATION of the two components is seen in these electron micrographs of purified preparations of elastic fibers from elastic ligament in a calf fetus. The intact fibers (*left*), enlarged 50,000 diameters, include the microfibrils and the amorphous-appearing elastin. The microfibrils are dissolved by an agent that breaks the disulfide bonds of protein, leaving elastic fibers (*right*) that consist only of the amorphous component. It is possible to recover the two protein components and do an amino acid analysis of each.

We come now to another important question: How is the elastin polymer constructed? The key to the answer has been found in a special protein bond that was discovered only recently. Up to a decade ago the only known covalent mechanism for tying protein chains together was the disulfide bond. Since cystine, the amino acid supplying this bond, is not present in any appreciable amount in elastin or in collagen, the question of what kind of cross-link might be involved in polymerizing either of these substances was an enigma. Over the past 10 years the investigations of many biochemists, working in various laboratories in the U.S. and Britain, have combined to produce the answer.

The first clue was unearthed by S. M. Partridge and his associates at the Agricultural Research Council in Cambridge, England. They discovered that elastin incorporated two previously unrecognized amino acids, which they named desmosine and isodesmosine (from an original Greek root word meaning "bond"). These two amino acids were found to perform cross-linking functions in elastin. Other investigators proceeded to show that the desmosines were synthesized from four units of the amino acid lysine and that there were other lysine-derived cross-links in elastin that represented the condensation products of two or three lysines.

Details of how the cross-links are formed were then deduced from various experimental findings. In 1966 one of us (Bornstein), in collaboration with



and little or no cystine. (What cystine does appear may be a contaminant.) Tropoelastin is very similar to elastin, as befits a precursor. The significant difference is that elastin contains desmosine, which is made up of most of the lysine in tropoelastin (*see illustration on next page*); four lysines in the tropoelastin go into the formation of each desmosine in the elastin. Collagen is similar to elastin in its glycine content, but it is characterized by a higher content of hydroxyproline and by the presence of hydroxylysine.

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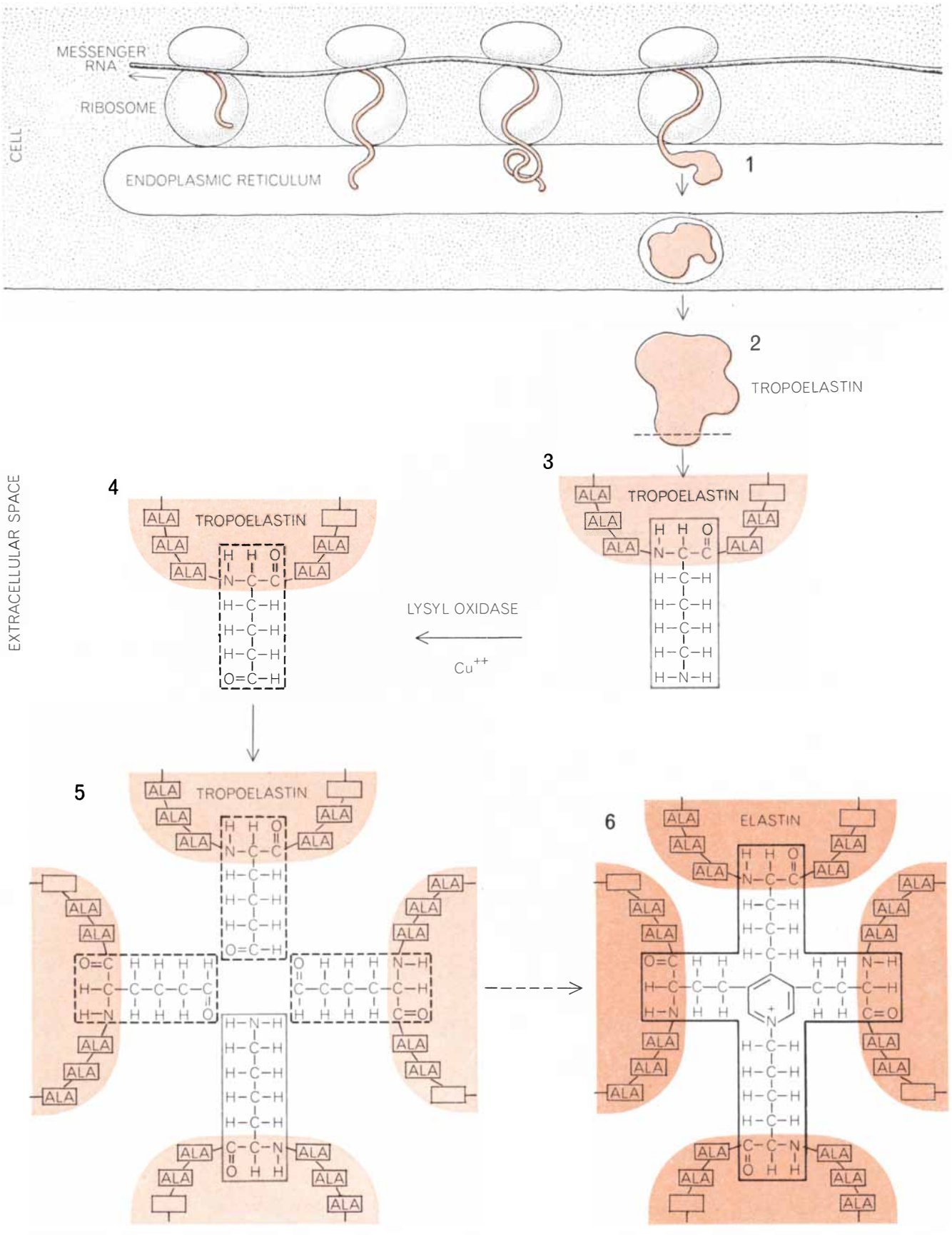

SYNTHESIS OF ELASTIN involves the formation of a special amino acid, desmosine (and its isomer, isodesmosine). Elastin's precursor, tropoelastin, is synthesized in the cell (*1*) and is then secreted into the extracellular space (*2*). A short segment of the peptide chain constituting tropoelastin is shown (*3*), containing a lysine (*gray outline*) surrounded by alanines. Such lysines are converted by the enzyme lysyl oxidase, in the presence of copper, into lysine-derived aldehydes (*broken outline, 4*). The apposition of three aldehydes and a lysine (*5*) leads in a series of reactions to formation of the desmosine (*black outline*) of elastin (*6*).

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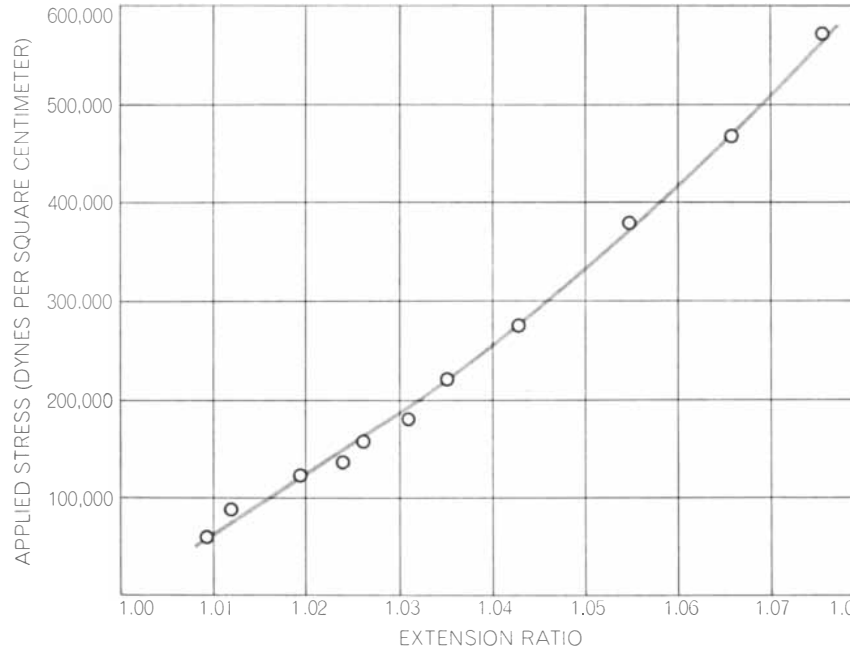
K. A. Piez of the National Institutes of Health, unraveled the manner of formation of an interchain cross-link in a soluble fraction of collagen. We found that the link was produced by a reaction between two aldehydes, derived from lysines on adjacent polypeptide chains. It was soon shown by several groups of investigators that insoluble collagen fibrils also contained lysine-derived cross-links, some of which resembled those identified in elastin. Further studies showed that the synthesis of the cross-links in elastin and in collagen is initiated by means of an enzyme, lysyl oxidase, that catalyzes the formation of the aldehydes. These highly reactive aldehydes, once formed, are thought to unite to produce a link whenever they come close together on neighboring molecules. In the case of the elastin precursor, which is presumed to have a globular shape, apparently four lysine-derived units commonly join to form the four-pronged desmosine link tying four elastin chains together [*see illustration on opposite page*].

Additional information on the construction of elastin, and identification of its precursor, came from studies of a disorder arising from inhibition of the enzyme lysyl oxidase. One form of this disease, called osteolathyrism, can be produced experimentally in animals by administering aminonitriles and related compounds. In osteolathyrism the inhibition of cross-links in elastin and collagen brings about structural abnormalities in the connective tissues, particularly those of blood vessels and bone. Inhibition of formation of the cross-links can also be caused by severe copper deficiency. This deficiency often results in rupture of the aorta in animals.

A group at the University of Utah has investigated the pathologic consequences of severe copper deficiency in young pigs. It found that the elastic fibers in the wall of the aorta developed structural defects because they contained a markedly subnormal amount of elastin and had an unusually large accumulation of microfibrils at their periphery. In the course of these studies L. B. Sandberg and his collaborators extracted from the defective aorta tissue a soluble protein that clearly had the properties of the long-sought precursor of elastin, and this substance was accordingly named tropoelastin. Among other things, tropoelastin is marked by certain amino acid sequences, involving lysine and alanine, that undoubtedly represent the sites where cross-links are created during the polymerization of elastin.



STRESS-STRAIN BEHAVIOR of elastic fiber was determined by A. S. Hoffman of the University of Washington and D. P. Mukherjee of the Goodyear Research Laboratories. Beef ligament was purified to remove components other than elastic fibers. Applied stress is the weight of a load parallel to the fibers divided by the unstressed cross section. Extension ratio is length under load divided by unstressed length; above about 1.03 essentially all fibers were under stress. The behavior of the samples was typical of a rubbery material.

Tropoelastin has an amino acid composition much like that of elastin, with two significant exceptions: it contains no desmosine and has a much higher content of lysine than elastin does. This situation is precisely what one would expect in view of the general hypothesis that the precursor is converted to elastin, the insoluble end product, by means of the formation of desmosine cross-links from lysine. The amount of lysine found in tropoelastin turns out to be in good agreement with the number of lysines that would be required for building the cross-links observed in elastin. Clearly the finding of recoverable amounts of tropoelastin and a subnormal amount of elastin in the aortas of these copper-deficient pigs indicates that the formation of cross-links for the conversion of tropoelastin to elastin was inhibited.

We can now put together a reasonable general picture of the process that produces the elastic fibers. Tropoelastin, elastin's precursor, is synthesized on the ribosomes within a cell. It is composed predominantly of amino acids (such as valine, alanine, glycine and proline) that are hydrophobic or uncharged, and so the molecule tends to be insoluble in water. It is possible, however, that tropoelastin contains enough lysine to form a hydrophilic (water-loving) "shell," so to speak, enclosing the hydrophobic amino acids within the body of the globular molecule. The charged and hydrophilic lysine shell may make the molecule soluble. After its synthesis tropoelastin is transported outside the cell and arrives at the surface of a growing elastic fiber. There, with the help of the enzyme lysyl oxidase, most of the lysines in the tropoelastin molecule are converted into aldehydes, which condense in combinations to form cross-links. As a consequence of the conversion and tying up of the hydrophilic lysines, the resulting elastin molecule asserts its predominantly hydrophobic constitution and becomes insoluble. The protein then constitutes an aggregate of subunits possessing the chemical and physical properties necessary for elasticity. It does not have the structure, consisting of chains entwined in a totally random manner, that is characteristic of rubber. Instead its structure is a syncytium (fused mass) of easily deformable corpuscles. In combination the corpuscles act as an elastic body in much the same way that an array of small, interconnected springs would.

How do the microfibrils of the elastic fiber fit into this picture? Apparently their role is to shape the elastin into a fibrous configuration. We have already noted that the microfibrils are the first structures to appear during elastic-fiber formation and that bundles of them are

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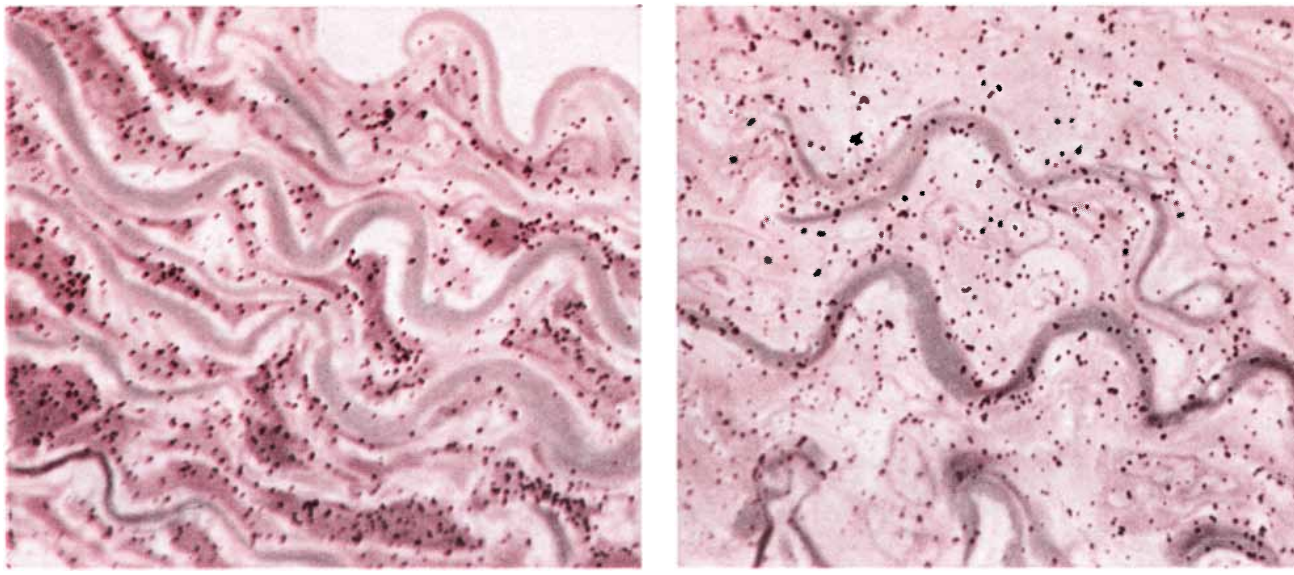

SMOOTH-MUSCLE CELLS were identified as the source of elastic fibers in arteries by autoradiography. A radioactive amino acid (proline) was fed to young rats. Sections of developing aorta were prepared after 30 minutes (*left*) and four hours (*right*). The sections were washed to remove free proline and exposed to photographic emulsion. Dark specks represent grains of emulsion exposed by the radioactivity of proline incorporated into protein. The photomicrograph at the left shows that protein synthesized in smooth-muscle cells is present in them at 30 minutes. The micrograph at the right shows that after four hours most of the labeled protein has left the cells and has taken its place either in the darkly stained, wavy elastic fibers or in collagen fibers between the cells.

aligned longitudinally in hollows close to the cell surface. Elastin itself would presumably not have a tendency to form a fiber. Conceivably the microfibrils, which are negatively charged, interact with the positively charged tropoelastin molecules and orient them in the shape of a fiber during the construction of polymeric elastin.

We have finally to answer the question regarding the birthplace of the elastic fibers. What cells synthesize the components of these fibers? For the elastic fibers of ligaments and tendons the answer is obvious. Their construction must originate in the fibroblasts, the cells that give rise to these connective tissues. For the elastic fibers in artery walls the answer was not quite so clear. It seemed reasonable to suppose that the most likely place for the generation of these fibers was the middle layer of the artery wall, which is the richest in elastic fibers and contains only smooth-muscle cells. To investigate whether or not these cells actually produce the components of elastic fibers one of us (Ross) and Seymour J. Klebanoff used the technique of autoradiography, which makes it possible to follow the biosynthesis of a large molecule by tracing the fate of a building block labeled with radioactive atoms. We used the amino acid proline as the tracer and fed it to a young growing rat. Tracing the incorporation of this labeled material in proteins by the smooth-muscle cells, we found that these cells did indeed synthesize the three major constituents of connective tissue: collagen and the elastic fiber's two components, the microfibrils and elastin.

Changes in the smooth-muscle cells of the artery wall and the connective-tissue components that surround them play a central role in diseases of the arteries, such as arteriosclerosis. Further study of each of these components should help in learning how such changes in blood vessels may lead to vascular disease.

SITES OF SYNTHESIS in the smooth-muscle cell are localized in this electron-microscope autoradiograph. The labeled protein, represented by the black curlicues, is in the rough endoplasmic reticulum, where proteins are synthesized, and in the Golgi complex.

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We want to be useful ...and even interesting

The pumpernickel looks better in color

Bakers not only outnumber astronomers but are more widely appreciated. Astronomers study the stars while undermining their own position by denying that the stars should be consulted about important matters like love affairs and investments. Pumpernickel and kuchen are more digestible than pulsars and quasars. It's a wonder astronomy has survived at all.

* * *

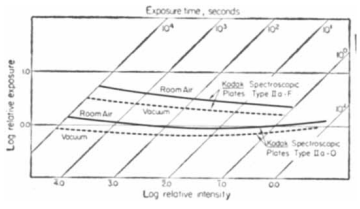
Astronomers make terrible customers for photographic manufacturers. Financially insignificant as consumers, they wheedle incessantly for better than the best that can be done. And you give it to them. Otherwise they'll crawl right into your emulsion kettles. What goes on therein may not long stop minds that can deduce the chemistry of stars.

* * *

The astronomer Schwarzschild noted that photographic response was not strictly the mere product of intensity and time but tended more toward It^p, where p seemed to be a constant other than unity. The late Emery Huse and colleagues at the Kodak Research Laboratories thought they'd better look into that. When the time scale was extended from days down to split milliseconds, p proved dependent on t. Microseconds were hard to come by in 1925. Later Huse went to Hollywood, where for many years he did glorious work selling our film to the motion picture industry.

* * *

We still study the failure of time and intensity to maintain reciprocity. This very year a paper* by T. A. Babcock, W. C. Lewis, and T. H. James –successors in interest to Huse *et al*–reports that an exposure requiring 2¾ hours on KODAK Spectroscopic Plates, Type IIa-F, takes only 1⅔ hours if room air is evacuated down to 10^{-6}–10^{-7} torr. Other than astronomers, only a small part of our market will thrill at this news from Rochester.



* * *

The speed advantage of evacuating the plateholder diminishes at more popular exposure times. Yet our scientific attention to reciprocity failure remains undiminished. We pour man-years into our vacuum sensitometer. We note that in certain experimental emulsions, the vacuum that prevents low-intensity reciprocity failure actually increases high-intensity failure, i.e. the microsecond is devalued. We note that dry O_2 restores some low-intensity failure. (Failure restored, hooray!) Masters of photosensitizing dyes, we note that the *desensitizing* dye phenosafranine may act as a good sensitizing dye in vacuum! Such dyes appear to act as transient traps for photoelectrons. This interference in the combination of electrons with silver ions increases the probability that oxygen will intercept those electrons and permanently remove them from participation in latent-image formation. Perhaps the process of electron trapping, silver atom formation, and silver atom dissociation is cyclic. It may take many cycles to form a stable product.

Theory and practical results continue to vitalize a product brewed from old bones. (Where else would the gelatin come from?)

* * *

Modern color film contains three different emulsions, each with its sensitizing dyes, each with its reciprocity effects. The people who have to get the film on the cable by 6 p.m. need know nothing about reciprocity. Not that kind.

* * *

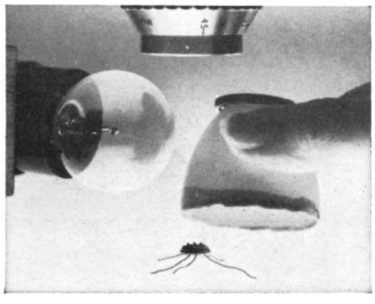
For TV, extreme localization impends. Hollywood is no longer the only place to sell professional motion picture film. Local entrepreneurs are getting on local cable systems, showing their neighbors their wares. The pumpernickel should look attractive.

Those who explore the universe may also help sell kuchen.

**Photographic Science and Engineering 15*:75 (1971)

Modest photography

When a picture is to be seen by 50 million people beyond the immediate neighborhood, one doesn't begrudge the shooting of an extra piece of film for good luck, or even the cost of potent equipment, or even, for that matter, the cost of rare skills long in building. That kind of photography is not covered in the new Kodak data book, "Basic Scientific Photography." Emphasis on "basic." As a good diffuser for photomacrography, for example, it recommends an eggshell, an inexpensive product not of our manufacture. That's the spirit of the book. Photographic dealers sell it.



The egg must be raw. A boiled egg will crack.

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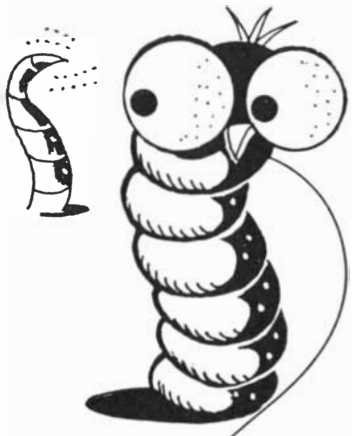
If you owned a graphite worm



that spun fiber smaller than a human hair . . . but could be

- **stronger than titanium**
- **stiffer than steel**
- **lighter than aluminum**

what would you teach it to do?

CONTEST RULES: Tell us how you think graphite fiber could be used in place of metal in your business using 37 words, more or less. All entries become the property of Hercules Incorporated and none can be returned. Employees and advertising agency people are not eligible so you might have a better chance. Contest offer not valid where prohibited by law and all entries must be postmarked by July 4. Decision of the judges will be based on originality of thought. More product information on Hercules graphite fiber gladly sent on request.

PRIZES: For the 63 most logical and coherent suggestions, we will send you a genuine "Graphite Worm Medal" which you may use instead of your Phi Beta Kappa pin to hold down your tie, hold together your keys, or hold in your shirt. XP71-2

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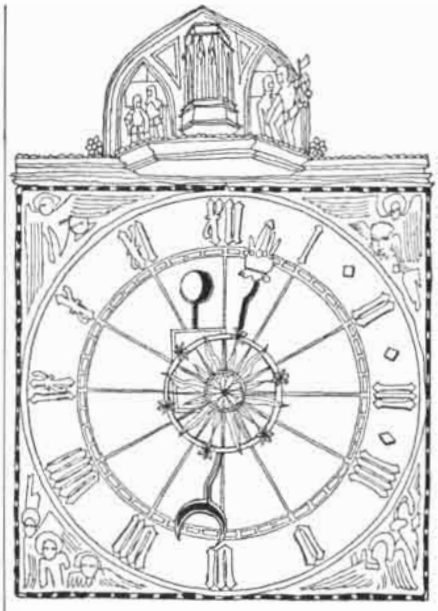

The Advance of Nuclear Power

Within 10 years nuclear power plants generating some 150,000 megawatts of electricity are likely to be in operation, providing about a fourth of all the electricity used in the U.S., according to the Atomic Energy Commission. In its annual report for 1970 the AEC says that nuclear plants are now being selected over conventional units purely on the basis of cost competition in situations where the higher capital cost of a nuclear plant is offset by potential savings from lower fuel costs. During 1970 five new nuclear power plants went into operation, in Illinois, South Carolina, Connecticut, Wisconsin and Minnesota (and a unit of the Enrico Fermi Power Plant in Michigan resumed operation after a shutdown since 1966, when an accident melted its fuel elements). There was a significant increase in orders placed by utility companies for new power reactors. Fourteen reactors, with a capacity of about 15,000 megawatts, were put under contract. At the end of 1970, 108 central-station nuclear power reactors with a net capacity of 86,100 megawatts were operable, under construction or under contract in 28 states and Puerto Rico. The growth has continued since the end of the year. As of the end of April the totals were 121 plants and 99,100 megawatts. Of this total, 21 plants (8,400 megawatts) were in operation, 56 plants (47,199 megawatts) were under construction and 44 plants (43,504 megawatts) were on order.

The nuclear power industry as a whole has come a long way since the first demonstration station went into operation at Shippingport in Pennsylvania in 1957. The AEC estimates that some 155,000 people in the U.S. are employed in Government-owned and private facilities at some 40 locations in 16 states. They are engaged in the manufacture of power-plant components, the production of uranium and the preparation and processing of fuel elements.

Vulnerable Uniformity

Hardy, high-yield varieties of major food crops, carefully crossbred and highly selected, are the success story of modern plant genetics, but they may carry the seed of their own destruction. The more successful a variety is, the more likely farmers are to choose its hybrid seed, and an entire society may come to depend on one highly selected variety. Then a new or mutant form of a pest or disease arrives to which the favored crop has no inbred resistance, and entire crops may be decimated. That happened last summer when a mutant fungus destroyed about 10 percent of the U.S. corn crop. Now a Committee on the Genetic Vulnerability of Major Crops has been established by the National Research Council in an effort to help forestall such outbreaks.

The committee will evaluate the breeding and seed-production practices that have shaped major U.S. crop varieties, with separate subcommittees to study individual major crops. They will try to learn how narrow the genetic base of each crop has become, and to what extent they are therefore susceptible to new diseases. The committee hopes to indicate particular crops that are so highly selected as to be particularly vulnerable and to suggest ways in which other varieties with a broader genetic base can be developed.

Experimental Cosmology

The question of how and where the heavy elements originated is one that has long vexed astrophysicists and cosmologists. It has been suggested, for example, that the heavy elements that went into the making of the early solar system had their origin in the primordial "big bang," which according to some theories marked the birth of the entire

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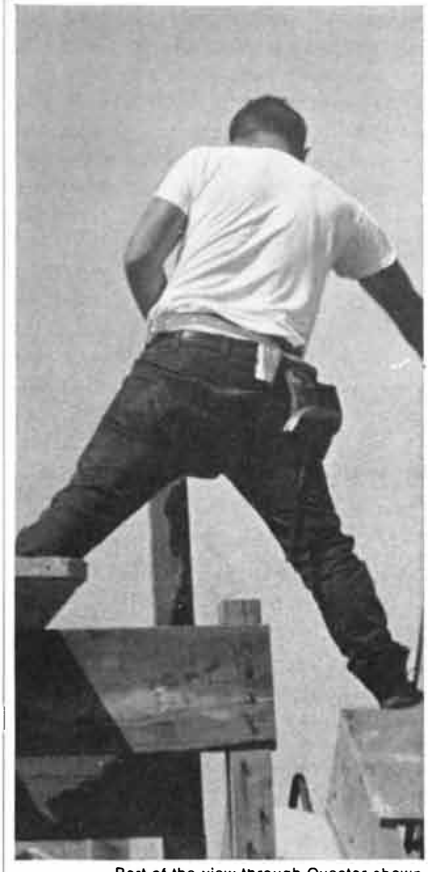
THE CITIZEN

universe some 10 billion years ago. Now a laboratory experiment carried out by a group of investigators at the University of California at Berkeley has provided strong indirect evidence that at least one heavy isotope, the radioactive plutonium 244, was in the process of being synthesized "only" five billion years ago in the supernova explosion that preceded the formation of the sun and the rest of the solar system. This discovery is regarded as being particulary significant because plutonium is heavier than the ordinary elements found in nature and can be produced only when lighter atoms are bombarded in an intense rain of neutrons; such conditions (which are created artificially in a nuclear reactor) would occur naturally in a supernova explosion.

Since plutonium 244 has a half-life of 82 million years, its former existence can only be inferred from the decay products of its extinct radioactivity: four kinds of xenon atoms, each characterized by a different atomic weight. All traces of such "nuclear fossils" were long ago removed from readily available terrestrial rocks by geological processes, but over the years characteristic complements of xenon atoms that could have originated in plutonium fission have been detected in certain stony meteorites; this observation has been accepted by some workers as tentative evidence for the synthesis of plutonium in the early matter of the solar system since, in order to be available when solid meteorites were formed, plutonium would have had to have been created within the time allowed by its disintegration cycle—only a few hundred million years at best.

What the Berkeley experimenters have done is to duplicate the entire plutonium-244 decay process in the laboratory, using a tiny sample of plutonium 244 artificially prepared at the Oak Ridge National Laboratory. The experimental procedure employed was described at a recent meeting of the American Geophysical Society by Emmit C. Alexander, Jr., of the Berkeley department of physics. Other members of the group are John H. Reynolds and Roy S. Lewis, both physicists at Berkeley, and Maynard Michel, a nuclear chemist at the university's Lawrence Radiation Laboratory.

In the first stage of the experiment the



Part of the view through Questar shown at lower left of photograph below

Another of those "impossible" views with a Questar —

the world's finest, most versatile small telescope, photo-visual, priced from $865. Our booklet, with more than 100 photographs by Questar owners, describes it. Send $1 for mailing anywhere in North America; by air to South America; $2.50; Europe and North Africa, $3.00; elsewhere, $3.50.

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The construction industry is not the only one discovering how easy it is to keep an eye on things with Questar's sharp closeups. Doesn't this suggest a need that you might have for safe, convenient maintenance inspection or supervisory control from ground level? Questar not only does this sort of job well, but is a lot of fun to use in its off hours.

Questar's new price catalog discusses, among other things, the demand for these superb optics in many special applications. The following, for example, are all in the day's work for Questar: closed-circuit television, autocollimation, laser sending and receiving, motion detection, solar research, star simulator, satellite tracker, site testing, bore sighting, surveillance (day and night), and biomedical studies, to mention just a few.

And if you haven't seen the recent price catalog you may not have heard the news about the **Questar Autocollimator, Questar TV Camera,** and the **Questar Cinema Model,** designed especially for the Arriflex 35, which is taking the professional cinematographers by storm. Of course, the 16-mm. buffs will want it, too.

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plutonium-244 sample was kept undisturbed in the Berkeley laboratory for almost two years, during which time the process of radioactive decay would be expected to yield a few trillionths of a cubic centimeter (or about 100 million atoms) of xenon gas. In the next stage the experimenters heated the plutonium-244 sample to more than 3,600 degrees Fahrenheit in order to drive out the tiny amount of xenon, then separated the xenon atoms by weight and calculated their relative abundances in a mass spectrometer.

In summarizing their findings the Berkeley team reports that "the mass spectrum from spontaneous fission in a laboratory sample of plutonium 244 is precisely what meteoriticists predicted it would be, completing a web of proof that the nuclide is a *bona fide* extinct radioactivity of galactic origin, that [this type of] nucleosynthesis was ongoing in the galaxy at the time of the birth of the Sun, and that the early meteoritic abundances of plutonium 244, heretofore tentative, can be utilized with confidence in models for the chronology of galactic nucleosynthesis."

The Berkeley group plans next to look for the xenon evidence of extinct plutonium in rocks retrieved from the moon and also to search for an explanation of other "anomalous" patterns of xenon in some meteorites. One theory concerning these unexplained patterns is that they may be evidence for the primordial existence of extinct superheavy elements with atomic weights beyond those of any known natural or artificial element.

$2^{19,937}-1$ Is Prime

The largest known prime number (a number divisible only by itself and 1) and the largest known perfect number (a number equal to the sum of its divisors, including 1 but not itself) have been discovered by Bryant Tuckerman, a mathematician with the International Business Machines Corporation. His achievement, announced at a recent meeting of the American Mathematical Society, took nearly 40 minutes on a System/360 Model 91 computer, the largest IBM machine in common use today.

The two newly determined numbers are huge. In exponential form Tuckerman's new prime is $2^{19,937}-1$. The even perfect number derivable from it is $(2^{19,937}-1)(2^{19,936})$. Written out in full, the new prime is 6,002 digits long, whereas the associated perfect number is almost exactly twice as long: 12,003 digits.

Tuckerman's discovery represents the 24th known Mersenne prime number, which is defined as a particular instance of a Mersenne number (a number of the form 2^n-1) for which n itself is prime. Both are named after the French mathematician Marin Mersenne, who in 1644 gave a list of the values of the exponent n, up to 257, that he thought yielded primes. Several errors were later found in Mersenne's computations, and the corrected list has been extended considerably in recent years, mainly by computer. The three Mersenne primes preceding the 24th, discovered in 1964, have as their exponents 9,689, 9,941 and 11,213.

The pattern of occurrence of Mersenne numbers, Mersenne primes and perfect numbers continues to mystify number theorists. For example, even a seemingly simple question such as whether or not there are any odd perfect numbers is still undecided. This question has also been studied by Tuckerman, who showed several years ago that there are none smaller than 10^{36}.

Anesthesia by Dissociation

Over the past decade new anesthetic agents have been prepared and tested that produce a different type of surgical anesthesia than conventional agents do. "Dissociative anesthesia," as it is called, has two main advantages. When properly induced, it does not depress the patient's respiratory and circulatory systems. And because it does not result in flaccid relaxation of the tongue or throat it does not interfere with the patient's normal airway. The advantages apparently stem from the mode of action of the new agents. Conventional anesthetics, primarily hydrocarbons and barbiturates, depress the lower and more primitive brain centers, and specifically the reticular formation. The dissociative agents appear to leave these centers largely unaffected and to depress the "association" areas of the brain: the connections between the cortex and the midbrain.

In an article in *The Journal of the American Medical Association* John W. Pender of the Palo Alto Medical Clinic in California reviews the history of the dissociative agents, what is known of their pharmacology and their clinical effects and side effects. Three such agents have been developed and tested in man. After intensive investigation one of them, ketamine hydrochloride, has been approved for general use and is available commercially. The dissociative agents such as ketamine are administered intravenously. They produce analgesia and amnesia, the basic objectives of anesthesia, but they do not induce the "collapse" of the patient into the nonresponding state that is characteristic of the hydrocarbons and barbiturates. Instead they produce catalepsy: the body is in a state of "waxy rigidity" rather than being flaccid. The eyes may remain open; slow nystagmus, or motion of the eyeball, may make it appear that the patient is still looking about. The patient usually exhibits small purposeless movements that are not the result of any painful stimuli. Pender points out that the anesthesiologist, who is accustomed to regarding any movement by the patient as evidence of inadequate anesthesia, must learn to differentiate these catatonic movements from motion caused by perceived pain. Conventional agents can be administered along with the ketamine to inhibit any movement that interferes with the surgical procedure.

Earmarked

Physiological differences between human beings, for example blood type, the presence or absence of color blindness and the ability to taste the substance phenylthiocarbamide, are so randomly distributed that they are almost useless in defining the races of man. A much less familiar difference—the fact that earwax is either wet or dry—proves to be a surprisingly reliable means of distinguishing between the Mongoloid strain of mankind and all others. This is the result of a little-known genetic fact: possession of numerous lipid-secreting apocrine sweat glands, the source of the wax, is a recessive characteristic among Mongoloids but a dominant characteristic in nearly everyone else.

Analysis of the earwax from various donors in the Far East suggests that the smaller the degree of mixture between Mongoloid and other human stocks in a given population, the larger the proportion of individuals with dry wax. The lowest frequency of wet wax is found among northern Chinese (less than 5 percent). A sampling of the Tungus people of eastern Siberia came close to this (less than 6 percent). Koreans are next (less than 8 percent), followed by the Khalkha people of inner Mongolia (less than 10 percent). The Japanese average is about 16 percent.

Interbreeding with populations of southeast Asian origin raises the wet-wax percentage. The Hakka, a minority population of southern China, have wet wax in 35 percent of the individuals sampled; the Li, a people of the island

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VEGA KAMMBACK. IT'S A WAGON AND THEN SOME.

The Vega Kammback wagon is three things. It's a Vega. It's a Kammback. And it's a wagon.

Let's start backwards. As you can see by the wagon-like shape, the Vega Kammback is a wagon. The back end lifts up. The back seat folds down. And while it's no giant, it'll easily hold plenty of groceries and rose bushes and antiques and cub scouts.

But the Vega Kammback wagon is more. It's a Kammback.

Kammback is not just another fancy word. It refers to the aerodynamic shape of our little wagon. A shape that contributes meaningfully to both the stability and the handling of the Kammback.

Which means you may feel the desire to forget the rose bushes and the cub scouts and just go for a ride. Just for the fun of it.

Our clincher: the Vega Kammback wagon is also very much a Vega. So without even asking, you'll get an overhead-cam aluminum engine, front disc brakes, front bucket seats and lots lots more.

The Vega Kammback wagon. It's a lot more than you bargained for.

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Buckle your seat and shoulder belts.
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of Hainan, have it in 55 percent. Micronesians score higher: more than 70 percent of the inhabitants of Ponape have wet wax. Both whites and those of aboriginal white stock score higher still: 86.7 percent of the Ainus of Japan and 97 percent of a German group in Westphalia have wet wax. Limited sampling among blacks suggests that 99 percent have wet wax.

Among American Indians, whose ancestors were of exclusively Mongoloid stock, the proportion with wet wax today generally ranges between 25 and 80 percent. Among some Central American groups, however, the proportion rises above 90 percent. This finding has been cited as evidence that wet wax may be selectively advantageous to inhabitants of tropical environments.

Change of Pace

With an estimated 50,000 Americans now wearing artificial cardiac pacemakers to help maintain their natural heartbeat, the potential danger that external electromagnetic radiation may interfere with the proper functioning of these sensitive electronic devices is coming under closer scrutiny by U.S. public health officials. According to a report issued recently by the Bureau of Radiological Health of the Public Health Service, studies of the susceptibility of implanted pacemakers to external interference have established that apparatus commonly used in the hospital environment, such as diathermy and electrocautery equipment, can disrupt pacemaker function. In addition isolated cases of pacemaker malfunction have been observed outside the hospital in the vicinity of radio stations, gasoline-engine ignition systems, radar sites and certain household appliances.

The latest source of concern—and the main topic of the recent report—is the increasing use of microwave ovens in residences, hospitals and commercial establishments. Spurred by a letter to the editor of *The Journal of the American Medical Association* describing a case in which two pacemaker patients exhibited symptoms of heart malfunction in the vicinity of an operating microwave oven, Paul S. Ruggera and Robert L. Elder of the Bureau of Radiological Health undertook an investigation "to determine the relative danger presented by the microwave oven in comparison with other potential known sources of interference."

Taking into consideration such factors as the frequency of the energy radiated from commercially available microwave ovens, the efficiency of various pacemaker components as receiving antennas for external signals and the shielding capability of the human body at the given frequency, Ruggera and Elder found that "the probability of interference cannot be dismissed." Moreover, they added, "it is known that the output waveforms from microwave ovens are modulated. Therefore, the peaks would possess much more energy than the average ... and the probability of pacemaker malfunction would be greater."

On the basis of these findings the bureau decided late last year to issue warnings by letter through professional channels "to those most capable of informing the pacemaker wearer of the overall interference problem." The warnings, distributed to more than 10,000 hospital administrators and selected physicians, mention several potential sources of cardiac-pacemaker interference, including microwave ovens. The letters point out that any interference signal entering the circuitry of a noncompetitive, or synchronous, pacemaker that mimics the electrical signal corresponding to a normal heartbeat "may be interpreted by the pacemaker as a normal heartbeat and cause changes in the pacemaker's output. The patient's response to these effects on his pacemaker will depend on the mode of operation of the pacemaker, his individual cardiac condition and whether the pacemaker is implanted or external." In certain cases, it is stated, the effect "can be hazardous to the patient who is totally pacemaker-dependent." The letters add that "it is important to recognize that the pacemaker is not damaged by electrical interference and will resume its previous performance when the patient is removed from the source of interference."

Chicken Little

The favorable economics of dwarfism, exploited by plant geneticists in high-yield wheat and rice, is being extended to animal husbandry. Selective breeding of fowl, utilizing a sex-linked dwarfing gene, has now produced a laying hen of the Leghorn type and a hen that produces broiler chickens; each is only two-thirds normal size. The standard cage that holds two normal laying hens will house three of the dwarf Leghorns; each can be expected to produce 200 eggs of standard size per year, compared with 240 for normal birds, for an investment of the same 160 pounds of feed per cage. This offers the poultryman a production gain of more than 20 percent at no increase in feed cost. The hens that produce broiler chickens offer the same kind of feed economy to the broiler industry.

The application of the dwarfing gene in selective breeding was first reported by F. B. Hutt of Cornell University. Experimental work continues at Cornell, the University of Oregon, the University of Tennessee and Texas A & M University. Meanwhile dwarf hens that produce normal-size broilers are being marketed by at least one commercial breeder in Pennsylvania, and dwarf egg-layers are being sold by Hy-Line Poultry Farms of Des Moines, Iowa, at the rate of nearly a million birds per year. Hy-Line researchers are examining the possibility of exploiting a similar dwarfing gene in beef cattle.

Here We Go Again

It is well established that the prehistoric inhabitants of North America often killed buffaloes by driving a herd of them into a steep ravine or over a cliff (see "A Paleo-Indian Bison Kill," by Joe Ben Wheat; SCIENTIFIC AMERICAN, January, 1967). It seems that the overhanging lip of a canyon wall west of San Antonio, Tex., was so well suited to this method of hunting that it was used on two occasions some thousands of years apart. This is the conclusion drawn by David S. Dibble of the University of Texas from two superimposed deposits of bison bone unearthed at the Bonfire Shelter kill site in Val Verde County. Dibble and his colleague Dessamae Lorrain excavated the site on behalf of the National Park Service in 1963. Under an extensive bed of bison bones at the foot of the canyon wall, evidently the remains of an Archaic Indian jump-kill sometime between 650 and 750 B.C., they found the butchered remains of some 120 bison of an extinct species. A single charcoal sample from an adjacent hearth was available for carbon-14 analysis; the result suggested that the earlier kill dated back to about 8000 B.C.

Writing in *Plains Anthropologist,* Dibble reports that two additional charcoal samples from the same Bonfire Shelter hearth have now been analyzed. The new dates agree almost exactly with the earlier finding; this agreement, taken together with the fact that the bison are of an extinct species and that two kinds of Paleo-Indian projectile point ("Plainview" and "Folsom") were present, confirms Dibble's view that some 7,000 years before the Archaic hunters stampeded a bison herd to its death a Paleo-Indian group had used the cliff for the same purpose.

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TWO-MILE-LONG ELECTRON ACCELERATOR at the Stanford Linear Accelerator Center (SLAC) was used to obtain the experimental results reported in this article. The electron beam is raised to a maximum energy of 21 billion electron volts (GeV) as it travels down a vacuum pipe lined with klystron tubes and focusing magnets. Near the end of its trip the electron beam passes through a "beam switchyard" before reaching the target areas, which are located inside the two large buildings in the foreground.

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The Structure of the Proton and the Neutron

The way ultrahigh-energy electrons are scattered by protons and neutrons suggests that these "elementary" nuclear particles have a complex internal structure consisting of pointlike entities

by Henry W. Kendall and Wolfgang K. H. Panofsky

Sixty-five years ago Ernest Rutherford observed how alpha particles are scattered by thin metal foils and concluded that the atom is not a homogeneous body but consists of negatively charged electrons surrounding a small, massive, positively charged nucleus. Since that time physicists in many laboratories have conducted scattering experiments with particles of ever increasing energy in an effort to probe the structure first of the atom, then of the nucleus and now of the basic constituents of the nucleus: the proton and the neutron. Are these "elementary" nuclear particles homogeneous? Recent investigations with electrons brought to an energy of 21 billion electron volts by the two-mile accelerator at the Stanford Linear Accelerator Center (SLAC) strongly suggest that history may be repeating itself on a scale 100,000 times smaller than that of the atom. It turns out that ultrahigh-energy electrons are scattered by protons and neutrons in ways that no one had predicted. The tentative conclusion is that the nuclear particles have a complex internal structure consisting of pointlike entities now called partons. And there is evidence that partons share some of the properties assigned earlier to those hypothetical particles named quarks.

Knowledge of the internal structures of the proton and the neutron may provide the key to understanding the "strong" force that holds the atomic nucleus together and endows the universe with its stability. The strong force makes its presence known in the nuclear reactions that fuel the stars and that, on a more modest scale, provide the energy for nuclear power and nuclear explosives. Although the exploitation of the strong force has become a commonplace in technology, the nature and origin of the force is still poorly understood.

In addition to exhibiting the strong force, protons and neutrons also respond to the electromagnetic force, which is some 100 times weaker. Both nuclear particles behave like tiny magnets and both comprise electric charges (although the neutron's net charge is zero). Whereas the strong force operates only when the interacting particles are very close together (a distance roughly equivalent to their own diameter: about 10^{-13} centimeter), the electromagnetic force has an infinite range, falling off in strength with the square of the separation. Since the neutron and the proton respond to the electromagnetic force, they scatter electrons aimed at them. It is the pattern of the scattering that provides clues to their structure.

Since the Stanford experiments are fundamentally the same as Rutherford's it will be useful to briefly review his techniques and results. He placed a natural emitter of alpha particles (particles with a charge of +2, later identified as helium nuclei) in an evacuated box equipped with a collimator so that a well-defined beam of particles would strike a target consisting of a metal foil [*see top illustration on page 63*]. The box was also provided with a zinc sulfide screen that would scintillate when it was struck by an alpha particle. The screen could be moved to intercept particles scattered at any angle, and the scintillations were counted one at a time with the aid of a low-power microscope. Two of Rutherford's collaborators, Hans Geiger and Ernest Marsden, soon noticed that alpha particles were being scattered at large angles far more often than one would have predicted on the basis of the then current ideas of atomic structure. The electric charge in atoms was believed to be diffusely distributed and hence should not have exhibited the concentrated electric fields needed to produce such large particle deflections.

Rutherford concluded that "the positive charge associated with an atom is concentrated into a minute center or nucleus, and that the compensating negative charge is distributed over a sphere of radius comparable with the radius of the atom." He also worked out the mathematical law describing how one point of electric charge would be scattered by another point charge [*see bottom illustration on page 63*]. The force between two charged particles was assumed to be given by Coulomb's law. Knowing the charge and mass of the interacting particles, Rutherford combined Coulomb's law with Newton's laws of motion to relate the probability of scattering through a given angle to the energy of the incident particle. The probability of scattering by a single target atom is the "scattering cross section," defined as the area of the incident beam within which the influence of the target atom gives rise to the process observed—in this case scattering. The cross section is not necessarily related to the "true" physical size of the target particle but rather represents a measure of the force exerted on the incident particle by the target particle.

The cross section is experimentally determined for different angles (measured from the axis of the incident beam), and the results can be compared with theoretical predictions. Rutherford's formula predicts the scattering cross section from the mass m and charge of the incident particle, the mass and charge of the target particle, the velocity v of the incident particle and the scattering angle θ. The formula depends directly on the particular combination of these variables that describes the vector difference, q, between the initial momentum and the final momentum of the scattered particle: $q = 2mv\ (\sin \theta/2)$. Another term for

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q is "momentum transfer" [*see top illustration on page 64*]. The formula assumes that the interacting particles are mathematical points, having neither size nor shape. In general, however, a scattering cross section will depend not only on the details of the forces (for example exactly how their strength varies with distance) and on the laws of motion of the particles (which may involve non-Newtonian, or relativistic, considerations) but also on whatever internal structure the particles may have.

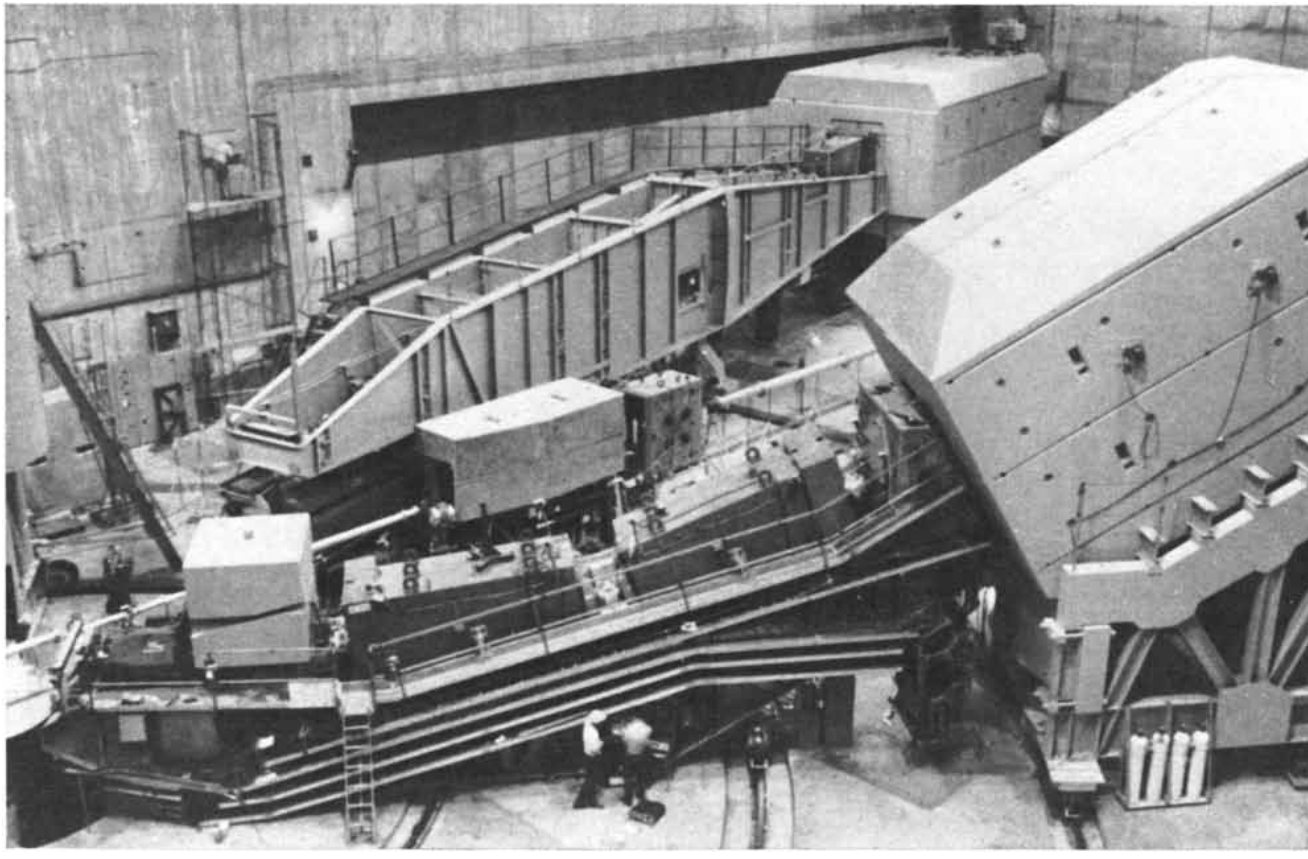
In scattering processes described by quantum mechanics the momentum transfer plays a central role, because it determines the scale of what is being studied. In quantum mechanics a particle that has a certain momentum p also has associated with it a certain wavelength λ. The formula that relates these properties is $\lambda = h/p$, where h is the extremely small number (6.6×10^{-27} erg-second) known as Planck's constant. The accuracy to which a particle can be located is limited by the associated wave; the probability of finding the particle at a given point is governed by the behavior of the "wave packet" describing the particle's motion. To locate one particle with another, the two have to interact (that is, the experimenter must scatter one from the other), and this involves a transfer of momentum between the two. Thus it is reasonable that the accuracy Δx to which the details of an unknown structure can be examined is governed by the momentum transfer q experienced in the collision; the resulting relation is $\Delta x = h/q$ [*see bottom illustration on page 64*]. This formula implies that our ability to distinguish fine detail in the target particle depends on making q as large as possible in order to make the wavelength λ as small as possible. (Momentum is the product of mass times velocity; at the energies of interest to physicists engaged in high-energy electron scattering the mass increases with increasing energy while the velocity remains essentially constant at the velocity of light.)

In scattering experiments of the type performed at Stanford momentum is measured in units of GeV/c, where "GeV" stands for giga (10^9, or one billion) electron volts and c is the velocity of light. An electron of 20 GeV lacks only one part in three billion of traveling at the velocity of light. Under these conditions the particle energy expressed in GeV and its associated momentum expressed in GeV/c are essentially equal.

Two Kinds of Scattering

The scattering of electrons can be either "elastic" or "inelastic." In elastic scattering the target particle recoils much as if it were a billiard ball, remaining in the same internal state it was in before the collision. In inelastic scattering the target particle either disintegrates or is left in an excited state, a state different from its original condition. There is a trade-off between the two processes: one robs the other. Both processes tell a good deal about the structure of the target particle. We shall discuss elastic scattering first.

Rutherford's formula does not adequately describe the elastic scattering of high-energy electrons for two reasons. First, the velocities are so great that one must use relativistic quantum theory to describe the wave nature and behavior of the incident and target particles. Second, electrons have "spin," that is, they have a unique angular momentum, as if they rotated around an internal axis. The



LARGE MAGNETIC SPECTROMETERS in one of the experimental areas at the SLAC site are used to separate and classify the scattered electrons emerging from the target and to funnel them into a system of detectors. Three spectrometers, each consisting of a complicated array of magnetic lenses and bending magnets, are installed around a common pivot point in this area; two are visible in this view. The scale of the instruments can be appreciated by noting the two men standing near the "middle-sized" device.

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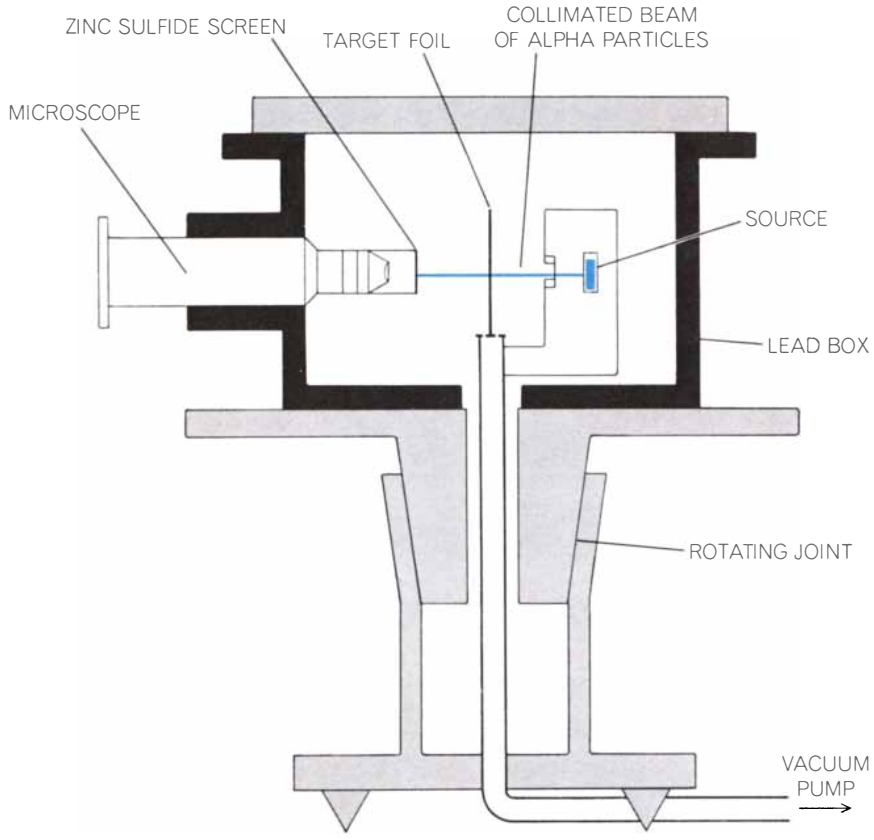
more precise formula that must be used is known as the Mott cross section. Except for the term that accounts for the spin of the electron, the Mott equation can be reduced directly to Rutherford's equation in those cases where the velocity of the incident particle is much smaller than the speed of light, as was true in Rutherford's experiments [*see top illustration on page 65*]. Since Rutherford did not know that quantum mechanics governed his scattering experiments, it is only a happy accident that his formula correctly describes low-energy scattering. We now know that Newton's "classical" laws of motion can be successfully applied only when scattering is attributable primarily to those forces whose strength varies inversely with the square of the distance, as the electrical Coulomb force does.

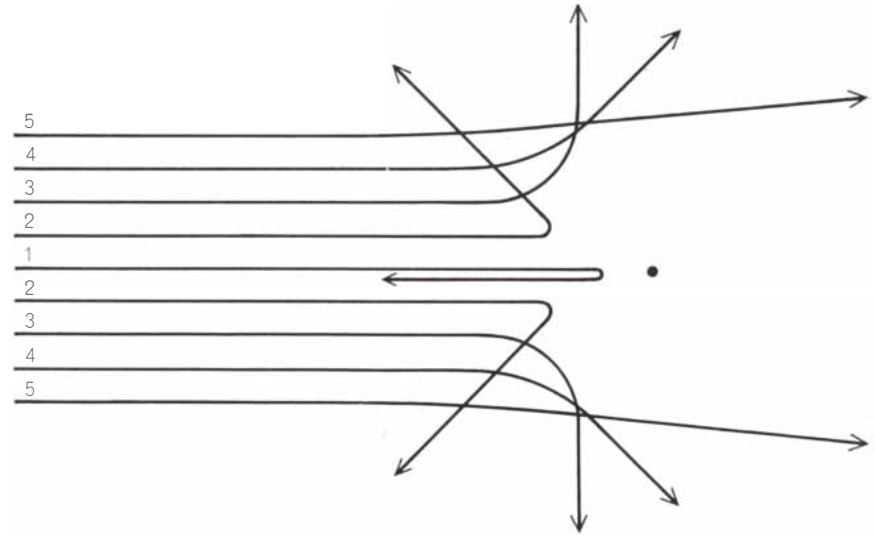
The Mott formula itself must be modified if the electron is scattered not by another point charge but rather by an object of finite dimensions [*see bottom illustration on page 65*]. In that case each segment of the electron wave front is diffracted separately by each subunit of charge within the target particle. The individual wavelets scattered by the subunits then recombine to form an outgoing wave that describes the scattered electron. As one might expect, some of the wavelets add constructively and some interfere, thereby canceling one another. The elastic-scattering cross section from a charged particle of finite size is therefore generally less than the cross section from a point charge. The factor by which the scattering is decreased below that from a point charge is given by the square of a number called a form factor, designated F.

The formula for the form factor is obtained by tracing the extra length each wavelet has to travel when it is scattered by charged subunits within the target particle. The formula depends solely on the momentum transfer, q, which is the vector difference in momentum between the ingoing and the outgoing electron. Given a sufficiently high value of q, the form factor will be sensitive to details of the target's structure; if q is too small, the experiment will reveal little.

If the target particle is a nucleon (a proton or a neutron), one would like to study its structure at distances smaller than its own radius, which is known to be about .8 fermi (one fermi is 10^{-13} centimeter). To have a resolution of, say, .1 fermi would require a momentum transfer of 2 GeV/c. In the present experiments the practical limit is about 5 GeV/c and is therefore small enough to



ORIGINAL APPARATUS used by Ernest Rutherford and his co-workers to study how alpha particles are scattered by thin metal foils is shown in this illustration, which was adapted from a diagram published in *Philosophical Magazine* in 1913. A natural emitter of alpha particles was placed in an evacuated box equipped with a collimator so that a well-defined beam of particles would strike the target foil. A zinc sulfide screen that would scintillate when struck by an alpha particle was moved to intercept particles scattered at any angle and the scintillations were counted with the aid of a low-power microscope. It was on the basis of observations made with this device that Rutherford concluded that the atom consists of a massive, positively charged nucleus surrounded by negatively charged electrons. All later scattering experiments are essentially variations of this basic technique.



ACCORDING TO RUTHERFORD, the scattering of one point of electric charge by another point charge could be described by a mathematical law that combined Coulomb's law (for the force of attraction or repulsion between two charged particles) with Newton's laws of motion to relate the probability of scattering through a given angle to the energy of the incident particles. In this diagram of the Rutherford scattering process the amount of scattering can be seen to depend also on the position of the incident particle's trajectory.

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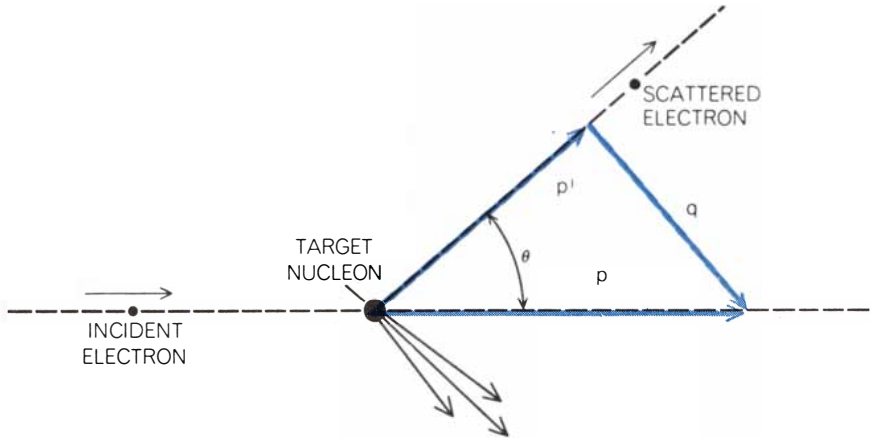


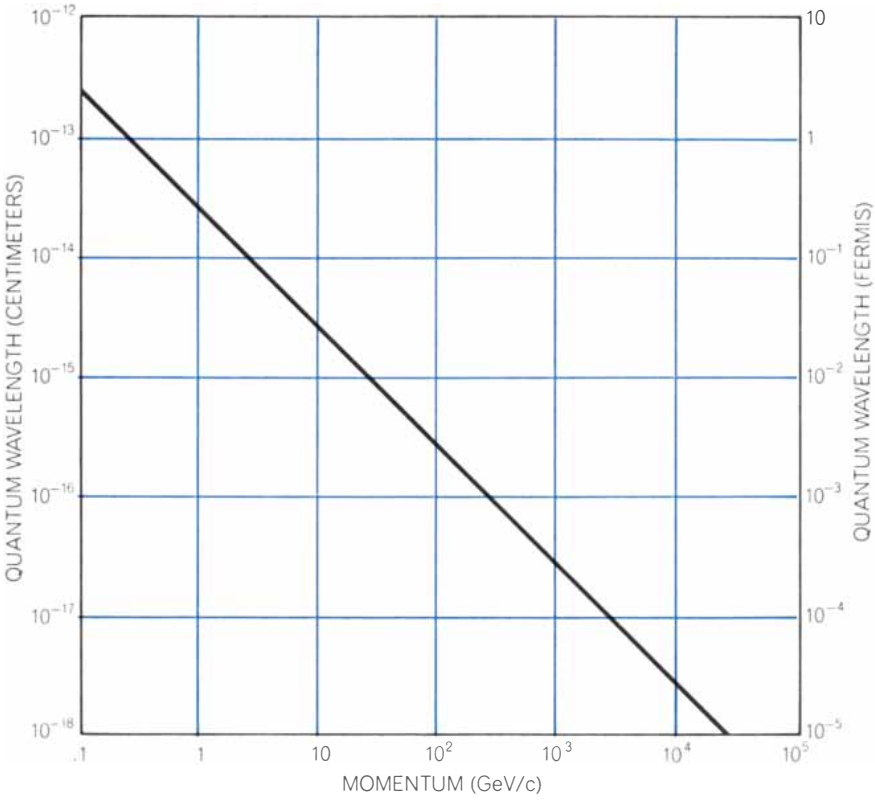
MOMENTUM TRANSFER, an important concept in the theoretical treatment of the scattering process, is defined as the vector difference (q) between the initial momentum (p) and the final momentum (p') of the scattered particle. The formula that expresses this relation is $q = 2mv\,(sin\ \theta/2)$, where m is the mass of the incident particle, v is its velocity and θ is the scattering angle. In elastic scattering the target nucleon simply recoils; in inelastic scattering it either disintegrates to form other particles or it is left in an excited state.

provide substantial information about the proton. If the form factor were known for a wide range of values of the momentum transfer, the charge distribution in the target particle could be reconstructed.

The task of computing the distribution of charge within a particle such as a proton from electron-scattering data closely resembles the task of reconstructing the structure of a crystal from the complex diffraction pattern produced when it is bombarded by X rays. The electron-scattering problem is much more difficult, however, particularly when the velocity of the recoiling proton approaches the velocity of light. The effects of relativity on the motion of the proton introduce ambiguities that complicate our attempts to reconstruct the spatial distribution of the charge.

A further complication is introduced by the proton's spin, which produces a magnetic moment. As a result the incident electron can interact with the proton's magnetization as well as with its electric charge. Since the magnetization can also have a finite distribution in space, it gives rise to a second form factor, designated F_m to distinguish it from the electric form factor F_e. The effect of these complications is to modify Rutherford's original formula to take account of the following facts: Both the incident and the target particle carry spin, the target particle is extended in space, the collision velocities are so high that relativistic effects are introduced, and the motion of both particles is described by wave mechanics rather than by classical mechanics [*see illustration on page 66*].

This somewhat elaborate discussion should not detract from the basic simplicity of the electron-scattering process. The process enables one to explore the unknown structure of subnuclear particles with the known forces of electromagnetism. This is in contrast to those experiments (interesting for other reasons) in which two particles of unknown structure collide, for example in proton-proton or pion-proton scattering. As far as is known to date, electrons behave like point charges and interact in scattering experiments only through the force of electromagnetism. (It is true, of course, that electrons also interact through the "weak" force, which plays a role in radioactive decay processes, but since the weak force is roughly 10^{10} times smaller than the electromagnetic force it can be ignored in electron-scattering experiments.) The laws of electricity and magnetism as they are now embodied in the equations of quantum electrodynamics represent the one and only area in physics where a single quantitative description has proved valid over the entire range of experiments for which it has been tested, from cosmic dimensions down to 10^{-15} centimeter. Thus the assumption that these particular forces are understood seems well justified.



POSSIBILITY OF LOCATING A PARTICLE of momentum p is governed by its associated wavelength λ according to the relation $\lambda = h/p$, where h is Planck's constant (6.6×10^{-27} erg-second). In this graph of the relation momentum is measured in units of GeV/c, where "GeV" stands for giga (10^9) electron volts and c is the velocity of light. The quantum wavelength of the incident particle is given in both centimeters (*left*) and fermis (*right*).

The Two-Mile Accelerator

Before discussing the results of elastic- and inelastic-scattering experiments obtained with the Stanford electron accelerator, we shall briefly describe the facility and the techniques involved. The

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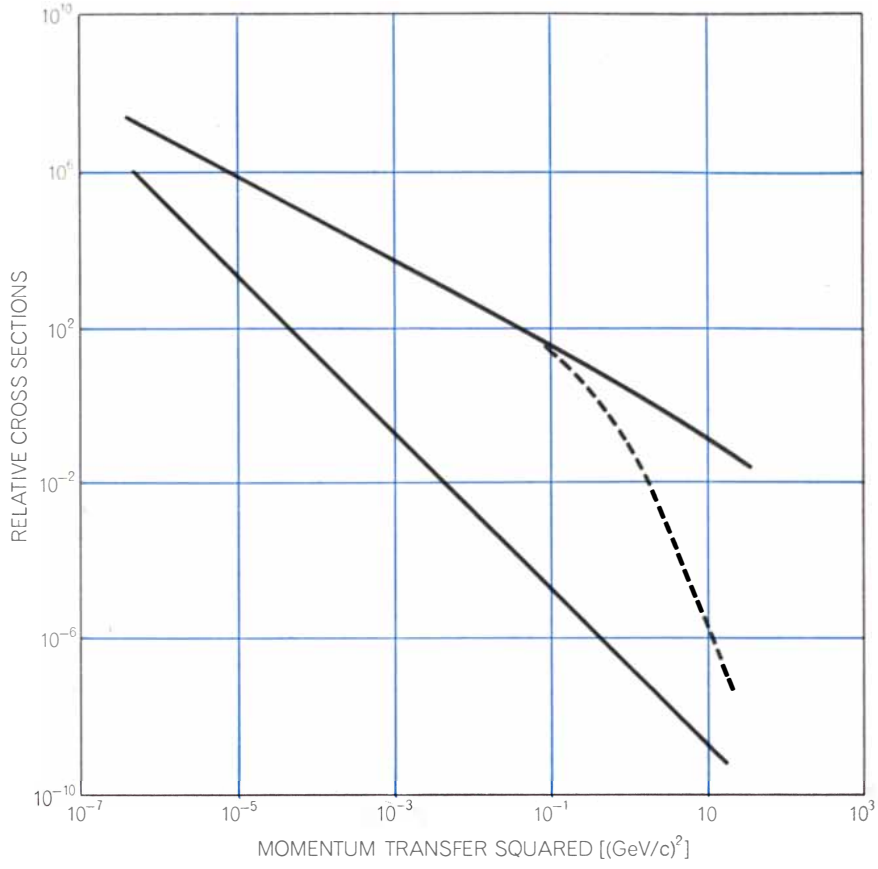
electron beam is raised to a maximum energy of 21 GeV as it travels down a two-mile evacuated pipe lined with 245 klystron tubes that pour electromagnetic energy into the beam. During its two-mile trip the beam is kept tightly focused by magnetic "lenses" spaced every 100 meters. At the end of its trip the beam passes through a final "purgatory" of magnets and slits that closely define the width and energy range of the electron beam that reaches the target. A typical scattering experiment requires a target containing hydrogen or deuterium and a means for selecting and identifying electrons scattered at different angles and measuring their momenta in the presence of many other particles produced by the collisions of electrons and nuclei.

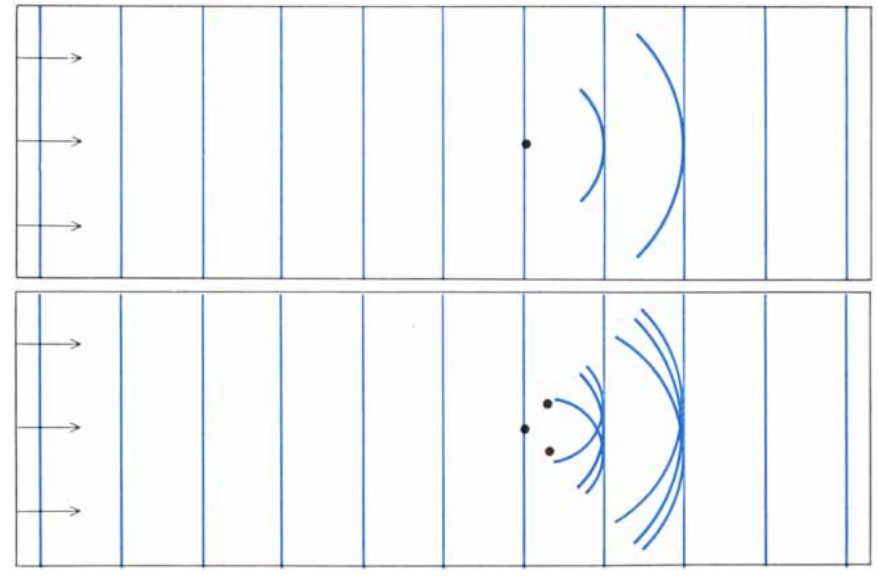
A vessel containing liquid hydrogen provides the target protons; the nucleus of ordinary hydrogen consists of a single proton. Using liquid deuterium, or heavy hydrogen, is the next best thing to having a target of free neutrons; the deuterium nucleus consists of a proton and a neutron. To a good approximation the scattering from deuterium nuclei is simply the sum of the scattering from neutrons and protons. Because the beam striking these liquefied gases is very intense they must be cooled continuously by means of a heat exchanger, not simply to prevent boiling but to minimize changes in density that would throw off the results.

To separate and classify the electrons emerging from the target the Stanford installation is equipped with three magnetic spectrometers, which funnel the electrons into a system of detectors. They were designed and constructed as a collaborative effort by physicists from the California Institute of Technology, the Massachusetts Institute of Technology and the group at SLAC. Very high resolution in both energy and angle is required, since we must be able to distinguish between elastically and inelastically scattered electrons and to resolve the detailed structure in the spectra of electron energies produced by inelastic scattering.

In the inelastic scattering one or more pions can be produced in the scattering collision. Since the energy required to create a pion is 139 MeV (million electron volts) the resolution needed must be considerably better than the ratio of 139 MeV to the incident energy, which can exceed 20 GeV. A resolution of better than .7 percent in energy is therefore needed. A similar analysis of the collision kinematics indicates that the resolution in angle should be a fraction of a milliradian, which is about three minutes



SCATTERING CROSS SECTION, defined as the area of the incident beam within which the influence of a target atom gives rise to a certain kind of interaction, is given here for the scattering of an electron by a target nucleon according to the Rutherford formula (*bottom line*) and according to the Mott formula (*top line*). Except for the term that accounts for the spin of the electron, the Mott formula reduces directly to Rutherford's as the energy and the velocity of the incident electron become small. The broken curve shows Mott scattering from a finite proton. The curves are drawn for a scattering angle of 20 degrees.



MODIFICATION of the scattering formula is required if the electron is assumed to scatter not from another point charge (*top*) but rather from an object of finite dimensions (*bottom*), represented here as composed of three point constituents. In the latter case each segment of the electron wave front is diffracted separately by each subunit of charge. The individual wavelets scattered by subunits then recombine to form an outgoing wave that represents the scattered electron. The amount by which the scattering cross section from a charged particle of finite size is reduced below that from a point charge is called the form factor (F).

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of arc. What counts is the precision in *relative* angle and in *relative* energy between the incident and the scattered electrons; therefore these requirements for the resolution of both angle and energy apply equally to the incident beam and to the spectrometers analyzing the scattered beam.

The spectrometers are large and complicated machines [*see illustration on page 62*]. They consist of magnetic lenses and bending magnets that deflect the scattered electrons vertically and then bring them to a focus. The amount of vertical deflection is a measure of the electron's momentum; the horizontal position is a measure of the scattering angle. Hundreds of counters, the equivalent of the zinc sulfide scintillation screen used in Rutherford's experiments, identify the momentum and angle of each electron. The counters are narrow bars of specially prepared transparent plastic that scintillate briefly when they are struck by a high-energy particle. Each bar is viewed by a photomultiplier tube that signals each tiny light flash.

The signals from the counters and other particle-identification devices are processed and passed on to a large computer. The computer is run "on line," storing data for later detailed analysis at the same time it is performing a simplified partial analysis. In addition to displaying such results the computer provides status information on the equipment and performs many routine "housekeeping" chores, such as adjusting currents in the spectrometer magnets and logging beam currents and other quantities of interest.

Nucleon Form Factors

The elastic-scattering experiments carried out by Cal Tech, M.I.T. and SLAC physicists have yielded measurements of the four elastic form factors that describe the structure of the proton and the neutron. The quality and quantity of these data, however, are quite variable. The most accurate measurements are those that give the magnetic form factor of the proton [*see illustration on page 72*]. The magnetic form factor of the neutron, obtained by subtracting from the deuterium scattering the scattering attributable to the proton, looks similar to the proton curve except that the errors are larger. The electric form factor of the proton resembles its magnetic form factor, but the electric curve has been determined for only a much smaller range of variables. The electric form factor of the neutron is known to be practically zero; the errors in the existing measurements, however, are large.

One might ask: Why are electrons scattered by the neutron at all, since the neutron has no electric charge? The answer has two parts. First, the neutron's spin produces a magnetic moment; this alone would show up in the scattering described by the magnetic form factor. Second, the electric current that gives rise to the neutron's magnetism can produce localized accumulations of charge within the particle even though the particle's net charge is zero. Such accumulations give rise to electric scattering whenever the values of momentum transfer exceed zero. Thus elastic electron scattering not only responds to the overall charge and magnetic moment of the neutron but also reveals what is going on inside.

The experiments indicate that the magnetic structures of the neutron and the proton are almost identical but that the magnitude of the scattering from each is proportional to the magnetic properties of each particle as found from static experiments. In other words, the magnetic form-factor curves of the two particles are identical in shape as far as we can tell from experiment. It is probably also significant that over the limited range accessible to experiment the electric scattering of the proton is proportional to the magnetic scattering. This suggests that the distribution of electric charge within the proton is directly related to the magnetic structure.

The scattered wavelets create a diffraction pattern similar to the shadow pattern formed when parallel rays of light strike the edge of an object. If the object has a sharp edge, the pattern will consist of alternate dark and light bands. Similarly, if the proton were an object with a sharply defined surface, one would see much more structure in the form-factor curve than is in fact seen. Evidently, therefore, the proton has a fuzzy boundary. Details of the curve give the proton's average radius: about .8 fermi, or $.8 \times 10^{-13}$ centimeter.

RUTHERFORD CROSS SECTION

$$\sigma_R = \frac{(2e^2\ m)^2}{q^4}$$

MOTT CROSS SECTION

$$\sigma_M = \frac{(2e^2\ E'/c^2)^2}{q^4} \cdot \frac{E'}{E}\left(\cos^2\frac{\theta}{2}\right)$$

ROSENBLUTH CROSS SECTION

$$\sigma = \sigma_M\left(\frac{F_e^2 + \tau F_m^2}{1+\tau} + 2\tau F_m^2 \tan^2\frac{\theta}{2}\right)$$

e=ELECTRON
m=MASS OF ELECTRON
$q = 2\sqrt{pp'}\sin\theta/2$
p=INITIAL MOMENTUM OF ELECTRON
p'=FINAL MOMENTUM OF ELECTRON
θ=SCATTERING ANGLE OF ELECTRONS
E=INITIAL ENERGY OF ELECTRON
E'=FINAL ENERGY OF ELECTRON
c=VELOCITY OF LIGHT
F_e=ELECTRIC FORM FACTOR
F_m=MAGNETIC FORM FACTOR
$\tau = q^2/4M^2c^2$
M=MASS OF NUCLEON

INCREASING COMPLEXITY is introduced to the scattering equation as one proceeds from the Rutherford formula to the Mott formula to the Rosenbluth formula (*left*). The final equation takes into account the following facts: both the incident and the target particle carry spin, the target particle is extended in space, the collision velocities are so high that relativistic effects are introduced, and the motion of both particles is described by wave mechanics rather than by classical mechanics. Symbols are defined in key at right.

Particles Real and Virtual

One of the most surprising findings to physicists is the fact that the curve representing the magnetic form factor of the proton, shown on page 72, is smooth over an enormous range of experimental variables. The observed scattering cross section, which varies as the square of the form factor multiplied by the Mott formula for point scattering, falls off by 10^{12} over the range of variables for which measurements have been made. The cross sections associated with the lowest part of the curve are extremely small: the smallest cross section measured was about 2×10^{-39} square centimeter per steradian, which under the conditions of the experiment means that only one out of every 10^{18} electrons was scattered into the detector. The scattering decreases as the fourth power of the momentum transfer. This rapid falling off is one of the current puzzles in high-energy physics. To understand how the

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We decided not to make a big case out of it.

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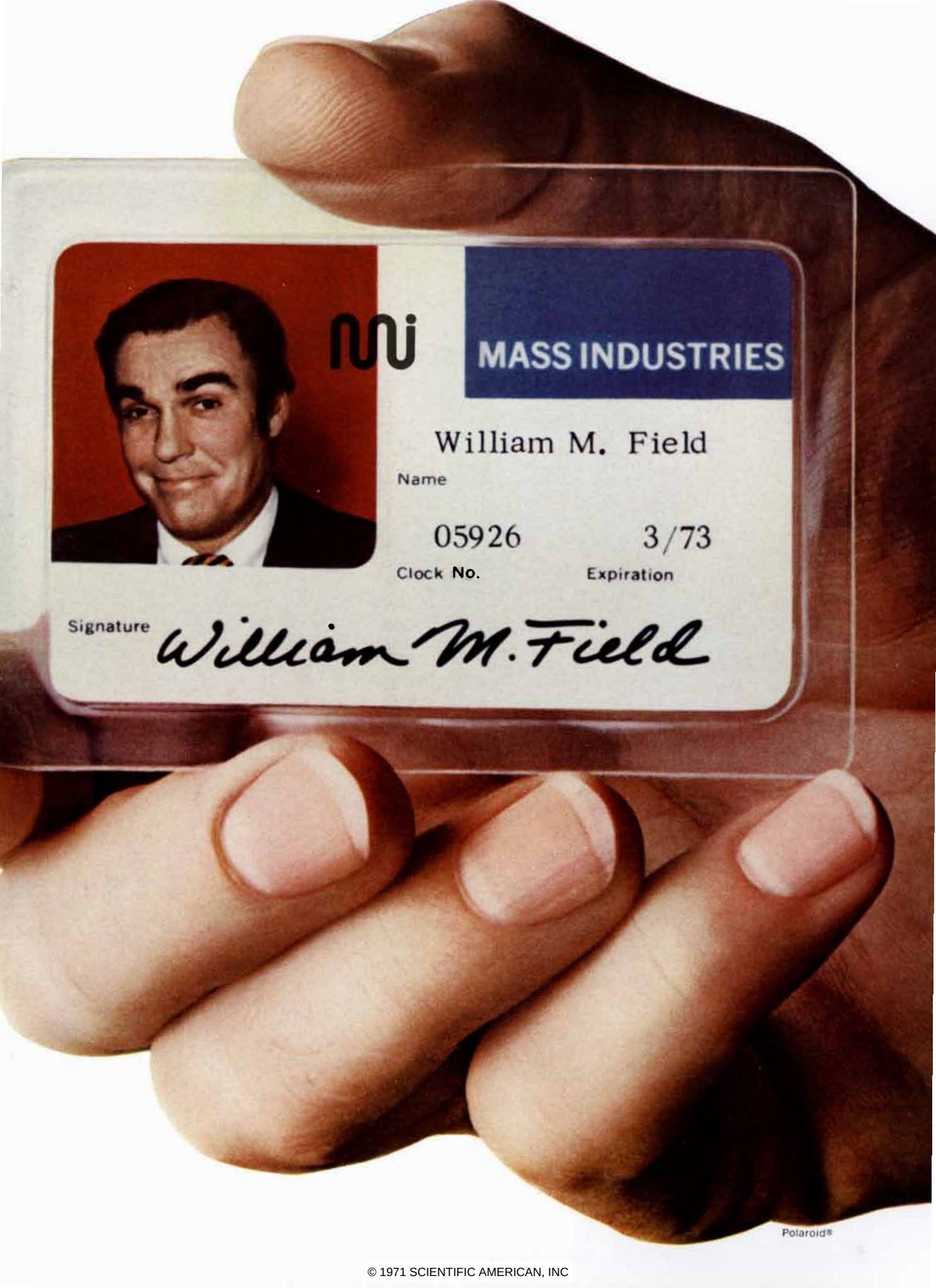

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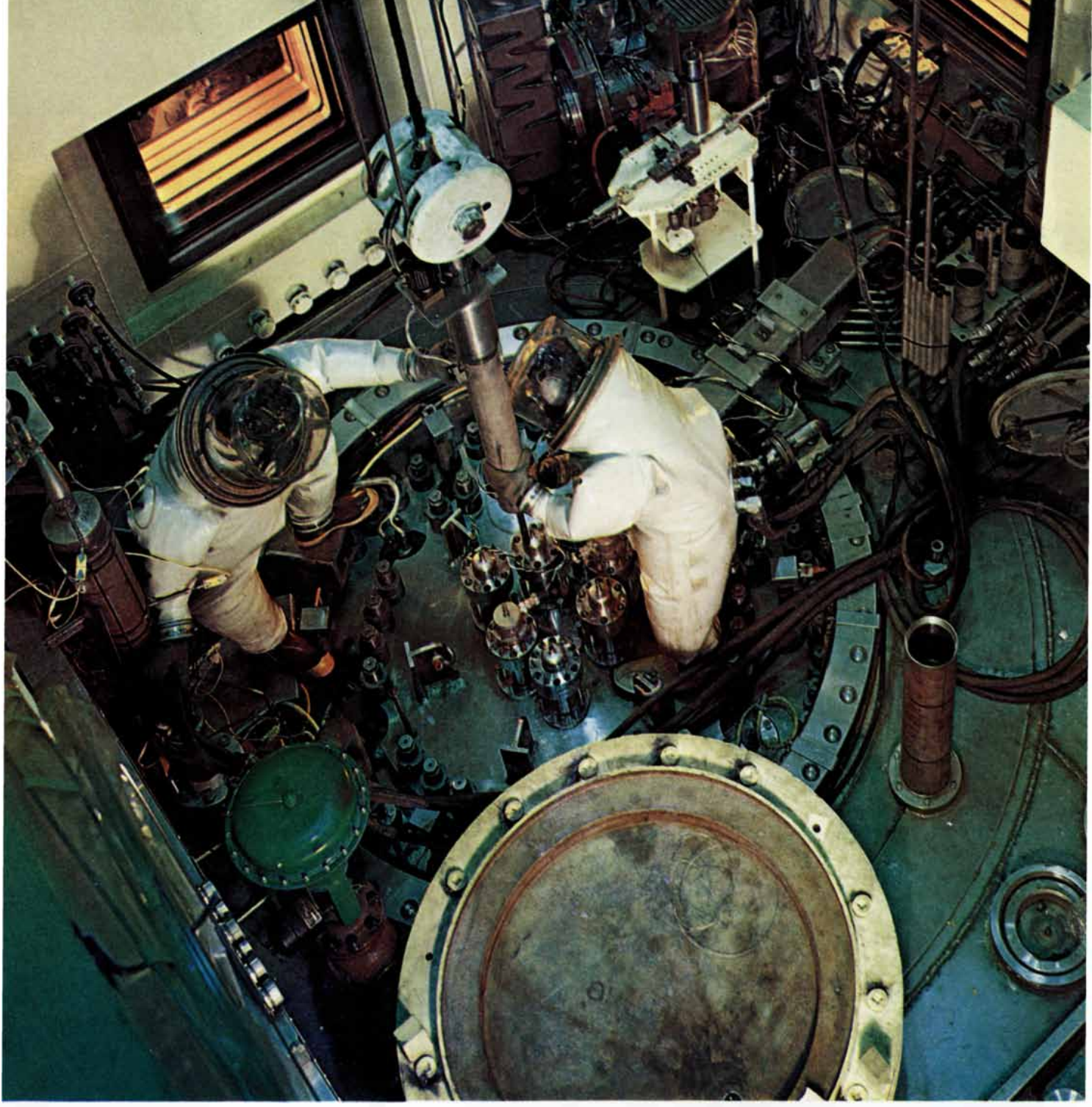

Technicians charging a fast breeder reactor

D'AREZIEN/SHOSTAL

The September issue of **SCIENTIFIC AMERICAN** will be devoted to

ENERGY and POWER

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puzzle arises and how it may be explained it is necessary to dwell briefly on the concept of "virtual particles."

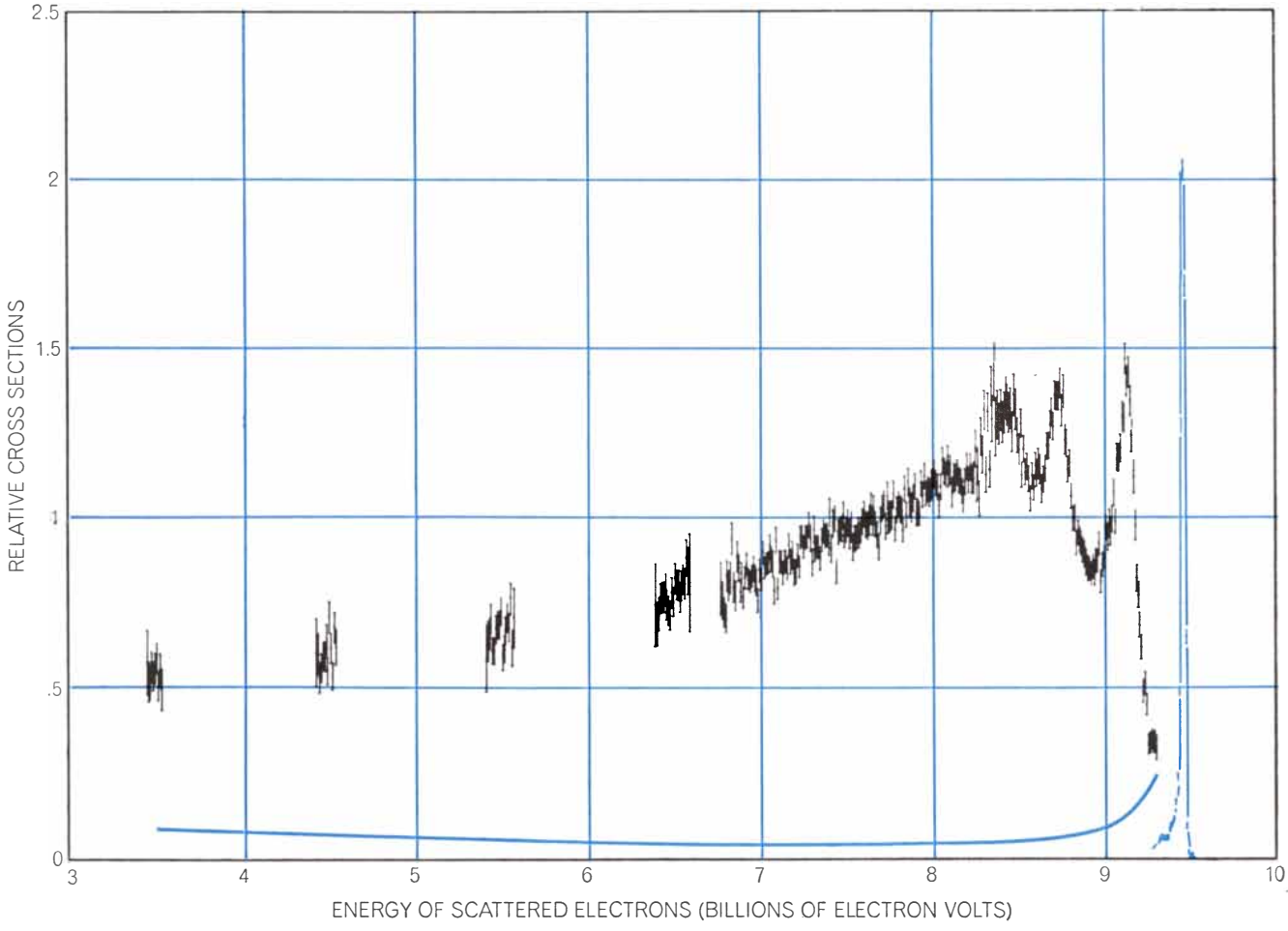
The concept of virtual particles is related to the uncertainty principle enunciated by Werner Heisenberg more than 40 years ago. In the wave description of matter it is impossible to determine simultaneously a particle's wavelength and its momentum. Heisenberg's principle relates the uncertainty in the measurement of the particle's wavelength, Δx, with the uncertainty in the particle's momentum, Δp. The product of the two uncertainties is proportional to Planck's constant h ($\Delta p \cdot \Delta x \simeq h$). Equivalently one can relate the uncertainty in the particle's measured energy, ΔE, to the uncertainty in the time, Δt, within which the measurement was made, in which case $\Delta E \cdot \Delta t \simeq h$.

Now, in relativity theory mass and energy are equivalent, as expressed by Einstein's relation $E = mc^2$. One can imagine, therefore, that for a very short time Δt any given amount of energy ΔE can be converted into a mass m equivalent to the rest mass of some particle, provided that the product of ΔE and Δt does not exceed h. In other words, without violating the uncertainty principle one or more particles can appear in a system and exist for immeasurably brief periods. In a sense their existence is "hidden" by an irreducible uncertainty in our knowledge of the system. Particles that appear in this way are called virtual particles; they cannot be observed directly as real particles can.

Most models that describe the interaction between the electron and the proton visualize the photon (the quantum of light) as the carrier of the electromagnetic force. It too can be real or virtual. Real photons are the packets of waves that carry energy from a radiating source (such as a star) to an absorber (such as the pigments in the eye). In quantum electrodynamics the electromagnetic forces that act between two (or more) moving charges are attributed to the emission and absorption of virtual photons. Hence in electron scattering a virtual photon emitted by the electron interacts with, and is absorbed by, the electric charge and magnetism within the proton. Virtual photons can carry energy and momentum in any proportion, unlike real photons, whose energy and momentum are uniquely related.

Although it may seem that virtual particles violate fundamental conservation laws, the violation is closely delimited to those areas where the uncertainty principle applies. It does not apply, for example, to the conservation of electric charge. Thus it is not possible for a single virtual electron to appear in a vacuum; it must always be accompanied by a particle of opposite charge, the positron.

There is a class of unstable particles,



TYPICAL SCATTERING SPECTRUM produced by an electron beam with an energy of 10 GeV colliding with stationary protons includes both elastic events (*color*) and inelastic events (*black*). The elastic peak at right has been reduced in height by a factor of five; the asymmetry of its tail arises because the electrons can emit "soft" X rays that "rob" various amounts of energy and thus blur out the elastic peak on the low-energy side. The smaller peaks or bumps in the inelastic spectrum correspond to excited states of the proton; they are called resonance excitations, or simply resonances. To the left of these bumps is a smoother continuous spectrum called the continuum. As one goes to higher incident energies the resonances tend to disappear but the continuum remains.

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the neutral vector mesons, whose members resemble photons in many ways, with two important exceptions: they have mass and they exhibit the strong force. The most prominent is the rho meson, which has a mass equivalent to about 750 MeV. (The mass of the proton is equivalent to 939 MeV.) Rho mesons can be created as real particles in the laboratory, and their decay products can be detected. Neutral vector mesons can also be created as single virtual particles by photons propagating in a vacuum—and the photons that create them can be either real or virtual. In a sense the photon is a vector meson a tiny fraction of the time.

Because vector mesons are massive they become a significant factor in modifying photon processes only in experiments at very high energies, such as those we are describing. In addition, as carriers of the strong force, the vector mesons play an important role when real photons of very high energy interact with nucleons.

Before the recent scattering experiments were conducted theorists thought they could predict how the vector mesons would participate in both elastic and inelastic scattering at high energies. In particular they predicted that if elastic scattering is dominated by vector mesons, the form-factor curve should fall off as the inverse square of the momentum transfer. Instead the curve decreases as the inverse fourth power. Clearly the simple model does not work.

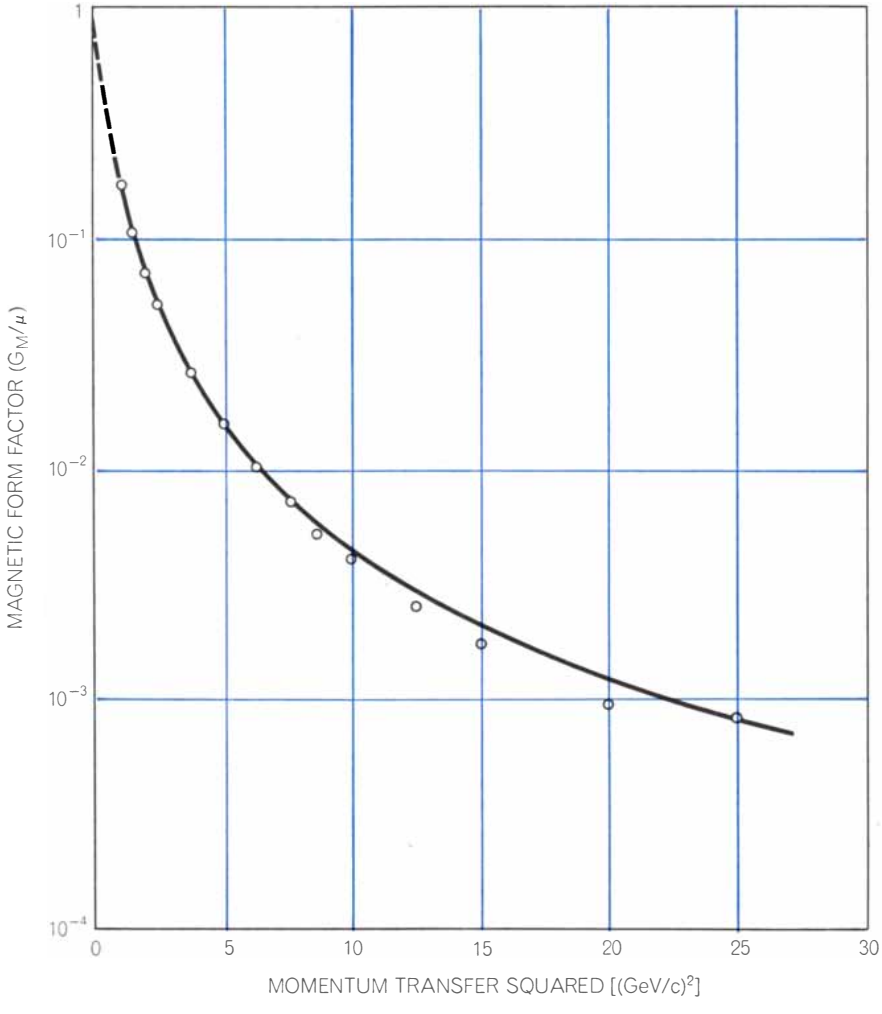
Inelastic v. Elastic Scattering

In a collaborative program of measurements carried out by workers at M.I.T. and SLAC very large cross sections were discovered for the inelastic-scattering processes. When one looks at a typical scattering spectrum produced by electrons of 10 GeV colliding with protons, one sees first of all a broad peak with an asymmetric tail [*see illustration on preceding page*]. The peak represents elastic scattering; the asymmetry of the tail results from the fact that the electrons can emit "soft" photons (X rays) that steal various amounts of energy and so blur the elastic peak on the low-energy side.

In addition, the scattered-electron spectrum contains two features produced by inelastic processes. First one sees a number of bumps that correspond to excited states of the proton. They are often called resonance excitations, or simply resonances. The position of the bumps corresponds to now well known excited states of the proton, identified in many high-energy experiments. Four specific resonances have been identified in inelastic electron scattering; the size of the associated bumps depends strongly on the magnitude of the momentum transfer to the proton. The bumps shrink rapidly in size as the momentum transfer increases. The shrinkage occurs just about as fast as the shrinkage of the elastic-scattering peak itself. From this we conclude that the radial dimensions of the excited states represented by the bumps are comparable to the dimensions of the proton itself in its unexcited condition. This implies that in some way most of the nucleon structure is involved when it is in a resonance, or excited, state.

The second feature of the scattered-electron spectrum produced by inelastic processes is called the continuum: the smooth distribution in the energies of those scattered electrons that do not fall in the resonance peaks. Physicists regard the continuum as perhaps the most exciting and puzzling part of all the recent Stanford results. As we go to larger scattering angles or to higher incident energies the resonances tend to disappear but the continuum remains.

When the inelastic-scattering program was formulated, theorists had believed that the continuum cross sections would decrease nearly as rapidly as the elastic cross sections when the momentum transfer was raised. Instead the results show that for incident electron energies ranging from 4.5 to 19 GeV the inelastic-scattering cross sections more closely resemble those that would be produced by point targets [*see illustration on page 75*]. In one comparison the best predictions available before the experiments turned out to be low by as much as a factor of 40 [*see top illustration on opposite page*]. The factor of error is even



MAGNETIC FORM FACTOR OF PROTON was found by the Cal Tech–M.I.T.–SLAC group to be unexpectedly smooth over an enormous range of experimental variables. (The square of the magnetic form factor is the amount by which the scattering cross section attributable to the magnetization of a charged particle of finite size is less than that of a point charge.) The fact that the form factor decreases as fourth power of the momentum transfer, which is faster than theorists had predicted, is a current puzzle of high-energy physics.

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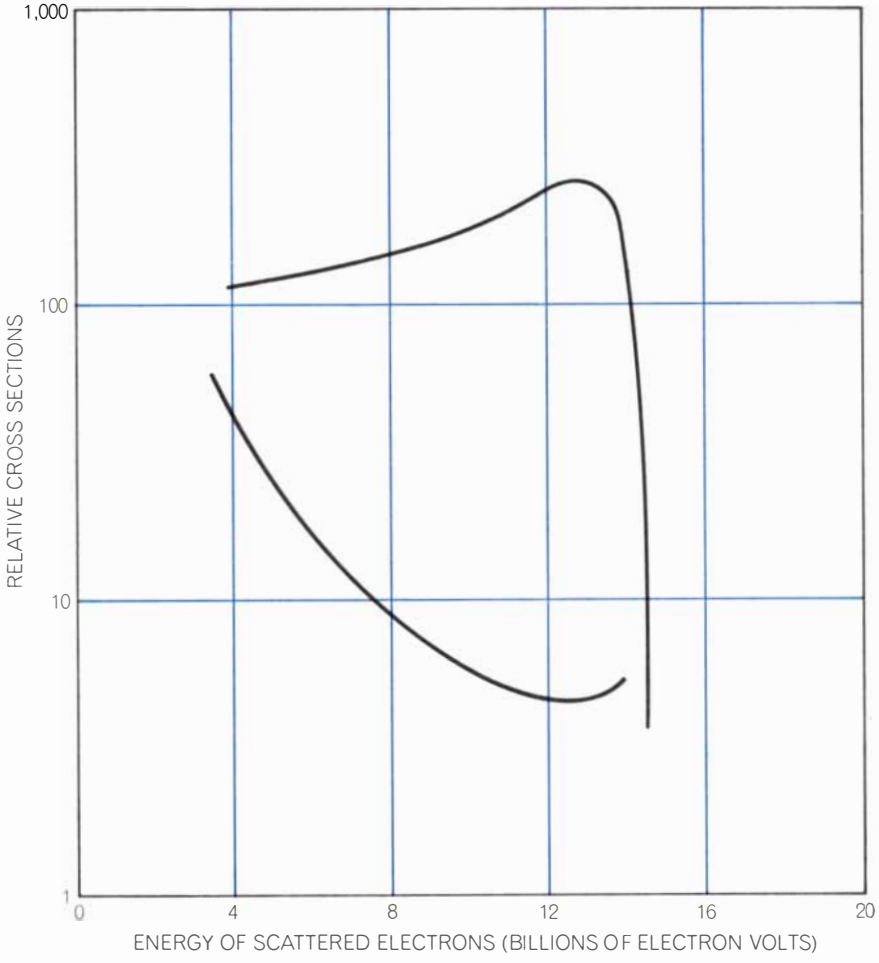
higher in other spectra. The tentative conclusion is that the internal structures from which inelastic scattering takes place are much smaller than the nucleons either in their ground state or in their excited state.

The Parton Model

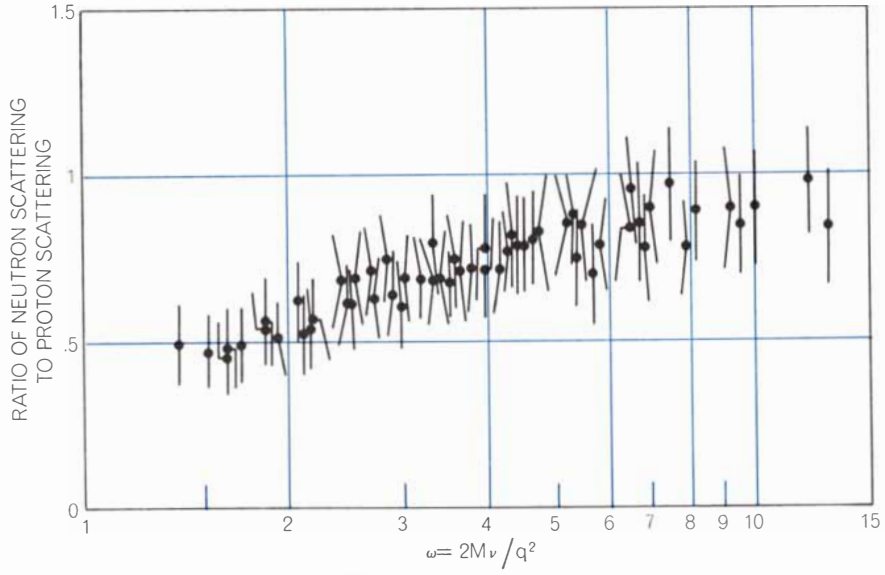
Richard P. Feynman of Cal Tech has been developing a theoretical model of the nucleon that may explain the inelastic-scattering results. He has given the name "parton" to the unknown constituents of the proton and the neutron that inelastically scatter high-energy electrons. Feynman assumes that partons are point particles. He and others have examined the possibility that partons may be one or another of the great array of previously identified subnuclear particles. The mesons that contribute to the "clouds" of nucleonic charge are obvious candidates, but there is strong experimental evidence that partons, if they exist at all, do not exhibit the known properties of mesons.

It has also been suggested that partons may be identical with the hypothetical entities known as quarks, the curious particles proposed independently in 1964 by Murray Gell-Mann and George Zweig of Cal Tech. Quarks are unlike all known particles in having a fractional electric charge: either $+2/3$ or $-1/3$ ($-2/3$ or $+1/3$ for antiquarks). Gell-Mann and Zweig suggested that mesons could be assembled from a quark and an antiquark. Nucleons and other particles with similar properties (that is, the baryons) would have to be assembled from three quarks. No real particles with fractional charge have yet been observed, in spite of long and continuing searches. Nevertheless, a fairly detailed picture of the nucleon's properties, as exhibited in inelastic scattering, can be constructed mathematically by arbitrarily assuming that the hypothetical partons have the properties formerly assigned to the equally hypothetical quarks.

Conceptual models such as the parton model represent the theorist's effort to describe the nucleon's internal structure in accordance with the most advanced information provided by high-energy experiments. The theorist tries to solve the mathematical problems that arise when the model is used to "predict" the properties observed in experiments that have already been completed; he also suggests further measurements to test the validity of the model. Models fail either because the mathematical difficulties cannot be overcome or because their



EVIDENCE that the internal structures of the proton and the neutron from which inelastic scattering takes place are much smaller than the nucleons either in their ground state or in their excited state is summarized in this graph, which covers a portion of the spectrum recorded by the M.I.T.-SLAC group in which the predicted scattering cross section (*bottom curve*) is lower by a factor of 40 than the observed cross section (*top curve*). The data were obtained at a scattering angle of six degrees; the energy of the incident electrons was 16 GeV.



ANOTHER UNEXPECTED RESULT of the scattering experiments is that inelastic scattering from the proton is distinctly different from inelastic scattering from the neutron. In this graph the ratio of the inelastic-scattering cross sections of the two types of nucleon is plotted as a function of a new variable, ω, which is defined as the ratio of the square of the momentum transfer (q) to the difference in energy of the electron before and after scattering.

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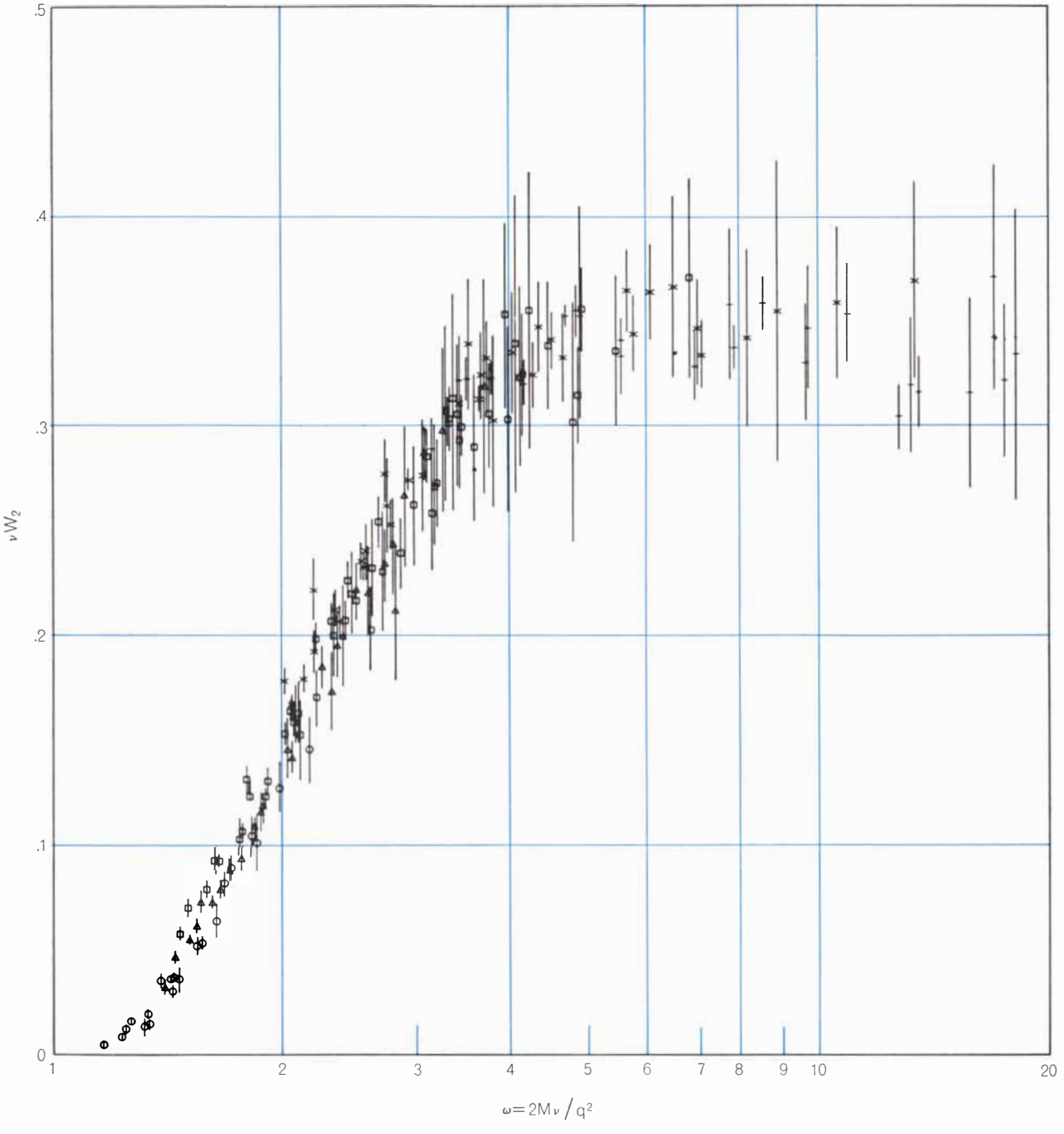
predictions do not agree with experiment. The verification of a model, such as occurred with Rutherford's nuclear atom, can greatly extend the range and scope of the physicist's understanding. It is through the interplay of observation, prediction and comparison that the laws of nature are slowly clarified.

Another unexpected result is that inelastic scattering from the proton is distinctly different from inelastic scattering from the neutron [*see bottom illustration on preceding page*]. It turns out, however, that the electron-scattering results can be greatly simplified if one introduces a variable representing the ratio of the square of the momentum transfer to the difference in energy of the electron before and after scattering. If the various observations are plotted as a function of this simple ratio, the data recorded over a large range of scattering angles and initial and final energies coalesce into a single curve for the proton and a single curve for the neutron [*see illustration below*]. This unexpected coalescence has a simple explanation if one assumes that



"UNIVERSAL CURVE" results when the inelastic-scattering data taken over a large range of scattering angles and initial and final energies are plotted as a function of the new variable ω introduced in the bottom illustration on the preceding page. This coalescence into a single curve (one for the proton and one for the neutron) is consistent with the idea that the scattering of the high-energy electrons actually takes place from pointlike objects within the individual nucleons. The physical nature of these objects, which have been called "partons," remains uncertain. The coalescence illustrated by the curve has been given the name "scaling." This kind of relation, involving the square of the momentum transfer, occurs naturally in the kinematics of scattering from pointlike particles.

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NASA needed simplicity of operation. (Aren't there times when you, too, want to concentrate on your subject, not your equipment?) The 500 EL offered electrically-driven automatic film advance and cocking of shutter.

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It has an oversized shutter release button for the same reason.

And a longer handle on the magazine slide for the same reason again.

And a safety lock to prevent the film back from floating off into space during weightlessness.

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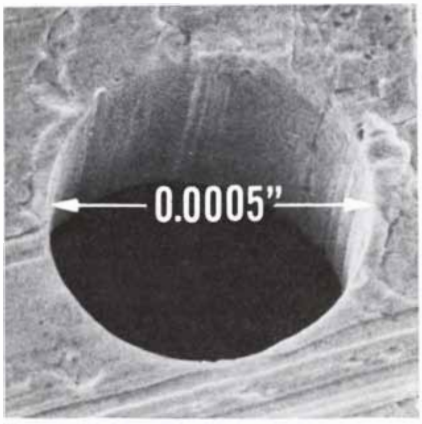

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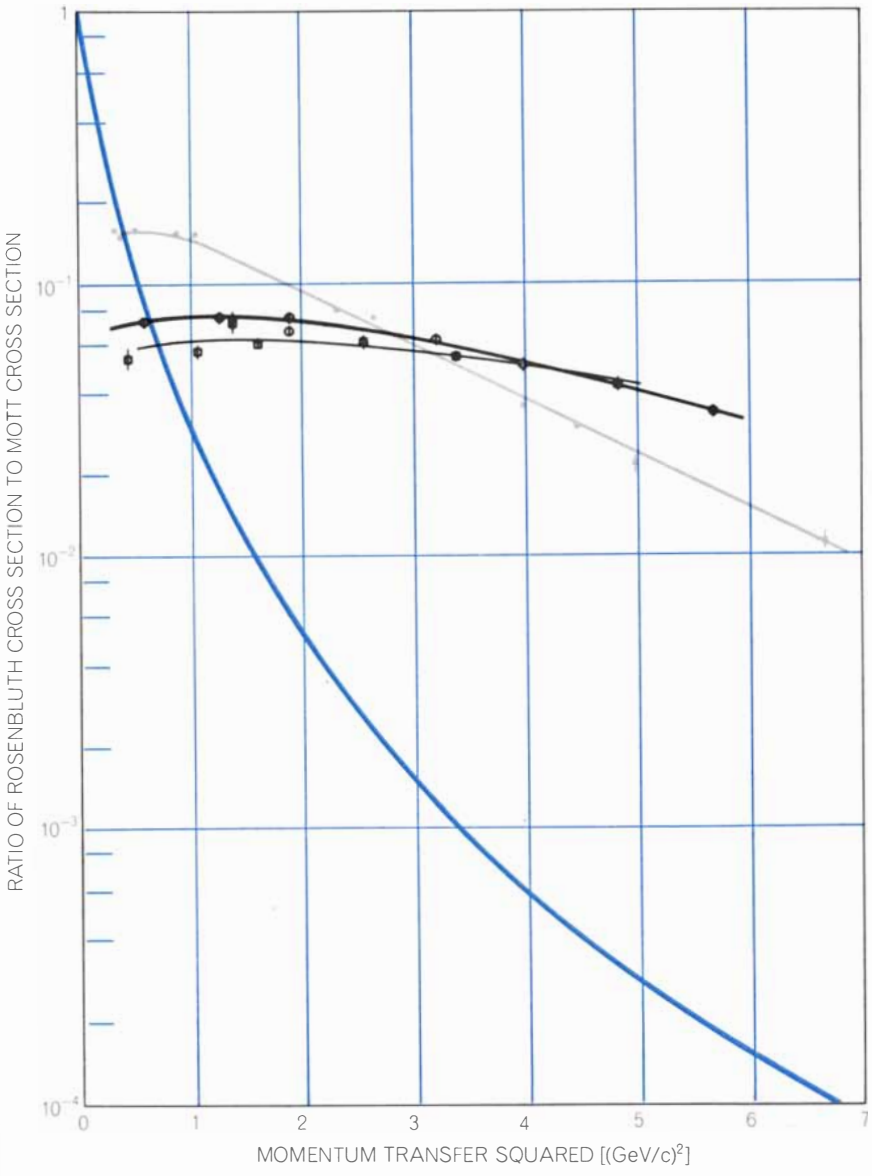
the scattering is produced by individual partons, since a "scaling" relation involving the square of the momentum transfer arises naturally in the kinematics of scattering from point particles. In addition the difference between neutron scattering and proton scattering can be accounted for qualitatively by the different configurations of the three quarks needed to produce protons and neutrons.

Because the partons, whatever they may be, are so intertwined with one another their individual properties are difficult to determine. Paradoxically the problem becomes simpler if one conceives of a cloud of partons moving in a frame of reference at nearly the velocity of light, so that the entire nucleon is relativistically contracted into a flat disk. Here the virtual photon that carries the electromagnetic force exerted by the scattered electron interacts with only one of the partons; the parton (owing to the relativistic dilation of time) exists as a free object long enough for it to retain its individual character. Therefore the theoretical analysis of events in the rapidly moving frame can be made with some degree of confidence and transformed back to the laboratory frame. In this way theory can be compared with experiment. Although the parton model is qualitatively quite successful in explaining the scattering results, its quanti-



FURTHER EVIDENCE that the observed inelastic-scattering cross sections may be produced by point targets is presented in this graph, in which the ratio of Rosenbluth scattering to Mott scattering is given for elastic electron scattering (*colored curve*) and for three different portions of the inelastic-scattering spectrum (*black curves*). Before these results were obtained it had been assumed that the inelastic-continuum cross sections would decrease as rapidly as the elastic cross sections when the momentum transfer was raised.

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tative predictions are not uniformly reliable. There is evidently a need both for more experimental information and for more theoretical studies.

Even though the parton model is incomplete, it has already been used to interpret experimental results from other particle reactions, and it has supplied the motivation for several experiments now in the planning stage. At the Italian nuclear research center in Frascati an intense beam of high-energy electrons circulating in a storage ring has been made to cross a counterflowing beam of positrons. A certain fraction of the positrons and electrons interact and annihilate each other, frequently giving rise to two or more pions. The cross sections for annihilation and pion production turn out to be much larger than was expected. Electron-positron annihilation and the "deep" inelastic scattering of electrons observed at Stanford are directly related phenomena; in a fundamental way they can be regarded as inverse reactions of each other. Hence the large cross sections at Frascati support and confirm the large scattering cross sections at Stanford. A further related result is that neutrino beams from the huge accelerator at CERN (the European Organization for Nuclear Research) have initiated inelastic reactions whose cross sections too are unexpectedly large. Again the parton model provides the best available explanation for the observations.

Several related experiments are now being planned. One calls for a comparison of neutrino and antineutrino scattering (which one expects to have equal cross sections). Another involves a search for positron-electron annihilation at high energies to yield a proton and an antiproton in addition to pions (a reaction that may also exhibit a pointlike cross section). A third experiment is being designed to measure the highly inelastic scattering of real photons (which one expects to show large cross sections similar to those observed in electron scattering).

The unpredicted electron-scattering results obtained with the two-mile linear accelerator at Stanford have stimulated a fresh wave of theoretical speculation and experimental study. It is still too early to say whether the parton model will lead to an understanding of the nucleon's structure or whether entirely new ideas may be required. Whatever the case, it seems likely that a full explanation of the electron-scattering studies will clarify not only the nature of the nucleon's constituents but also the nature of the strong interaction and the families of particles that are governed by it.

WHAT DOES IT TAKE TO PRODUCE A $1000-BILLION GNP?

The Editors of SCIENTIFIC AMERICAN have prepared a wall chart, based upon the latest Federal input/output table, displaying the interindustry flows of raw materials, intermediate products and business services required to carry the U.S. economy to the benchmark Gross National Product of $1000 billion.

Input/output tables provide management, government administrators, economists and market analysts with a powerful new tool for forecasting and measuring the indirect as well as the direct interindustry relationships that structure our industrial economy.

This handsome and informative wall chart (70" x 46", in eight colors) offers a unique entry into the rapidly developing discipline of interindustry (or input/output) analysis. Based upon input/output tables issued by the Office of Business Economics of the U.S. Department of Commerce, the chart can be used as a teaching tool and for study of practical and theoretical questions about the U.S. economy.

The chart presents an interindustry matrix of 99 rows and 99 columns; each of the nearly 10,000 cells in the matrix shows (1) the direct input/output coefficient, (2) the "inverse" coefficient and (3) the interindustry dollar flow for a $1000-billion Gross National Product. The input/output coefficients as published by OBE have been recomputed by the Harvard Economic Research Project to reflect gross domestic output. The 370 sectors of the detailed tabulations have been selectively aggregated to 99 sectors to provide maximum feasible detail for the wall chart. Where the ratio of input to output exceeds 1/100, the cell is tinted in the color-code of the industrial bloc from which the input comes. This device, combined with triangulation of the matrix, brings the structure of interindustry transactions into graphic visibility.

Offprints of five SCIENTIFIC AMERICAN articles on the technique of input/output analysis, accompany the chart. The articles are:

Input/Output Economics
by Wassily L. Leontief

The Economic Effects of Disarmament
by Wassily W. Leontief and Marvin Hoffenberg

The Structure of Development
by Wassily W. Leontief

The Structure of the U.S. Economy
by Wassily W. Leontief

The Economics of Technological Change
by Anne P. Carter

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MAGNETIC BUBBLES

A magnetic material is divided into regions that are magnetized in different directions. These "domains" can be formed into small "bubbles" that can be utilized in a new kind of computer memory

by Andrew H. Bobeck and H. E. D. Scovil

Electronic computers and other data-processing devices are largely limited in performance by the speed, capacity and reliability of their memory systems. The speed, capacity and reliability of memory systems, in turn, are largely a function of what one is willing to pay. The fastest and most flexible memory systems are those built either from tiny ring-shaped ferrite cores strung on a mesh of fine wires or, more recently, from transistor circuits laid down on tiny chips of silicon. At the moment cores are cheaper: about one cent per bit (binary digit) of storage capacity. Even this low cost, however, mounts up swiftly. A core memory to duplicate the estimated capacity of the human brain—perhaps 10^{10} bits—would cost 10^8 dollars. The requirements of an electronic telephone central office are more modest: around 10^7 bits, for which a core memory would cost 10^5 dollars. Considering that a central office may need twice this capacity to assure reliability, one can appreciate why the telephone company, among others, would like to find a less expensive all-electronic system.

A promising alternative, now under development at the Bell Telephone Laboratories, exploits a new technology in which data bits are stored in the form of magnetic "bubbles" moving in thin films of magnetic material. The bubbles are actually cylindrical magnetic domains whose polarization is opposite to that of the thin magnetic film in which they are embedded. The bubbles are stable over a considerable range of conditions and can be moved from point to point at high velocity.

The evidence available at present indicates that magnetic-bubble memories should be substantially cheaper than core memories and up to 10 times faster than magnetic-disk memory systems now widely used for high-capacity storage. These systems depend on the mechanical movement of a storage medium below a "head" that can read out data that were previously entered or write in fresh data. In the higher-performance magnetic-disk systems the several disks, with many tracks per disk, spin continuously under as many read-write heads as there are tracks. Thus the disk systems can provide access, limited only by the time it takes for data to be cycled under the read-write heads, to any sequence of stored data. A serious drawback of such systems is that one cannot manipulate the stored information without reading it out and writing it in again, a process that can take appreciable time. Moreover, since disk systems are mechanical, they are not as reliable as the all-electronic components now being installed in telephone switching offices, which are designed to operate for 40 years.

Magnetic-bubble memories now under development are in many ways all-electronic analogues of magnetic-disk memories, but there are also important differences between the two. In both systems information is stored as states of magnetization on (or in) a thin magnetic film. In a disk memory the film is moved mechanically at high speed; in a bubble memory the bubbles move at high speed through the film. In a disk memory the information is rigidly fixed and passes the read-write head in only one dimension. In bubble devices the information can travel in two dimensions, that is, anywhere in the film. In bubble devices one can also perform many logical operations on the stored data without reading them out and writing them back in again. Finally, since bubble devices have no moving parts they should work reliably for many years. This, of course, has yet to be demonstrated.

The development of magnetic-bubble devices has required combining the insights of magnetic theory, dating back more than 50 years, and skills more recently developed in the tailoring of magnetic materials to meet precise specifications. The key to theoretical understanding is the magnetic domain, foreshadowed by James Clerk Maxwell's concept that "a magnet is built up of particles each of which is a magnet." He and his 19th-century contemporaries attempted to explain the bulk properties of ferromagnetic materials on the basis of simple electromagnetic interactions among individual magnetic "particles" of molecular size. Although this approach was astute, it failed to account for certain fundamental properties of magnets.

In 1907 Pierre-Ernst Weiss suggested that the inadequacies of the theory would be removed if one assumed that within a ferromagnetic material there are powerful "molecular fields" capable of aligning molecular magnets parallel to one another. Weiss calculated that the magnitude of the field needed to accomplish this alignment was about 10 million oersteds, a field much stronger than any continuous field yet produced by laboratory electromagnets. Weiss was unable to explain, however, how such an intense field could arise. With the advent of quantum mechanics 20 years later it was recognized that Weiss's "molecular field" is generated by exchange forces among ferromagnetic atoms and that the individual molecular magnets are the atomic magnetic moments associated with the spin of the electron.

Even without this knowledge Weiss perceived that the molecular magnets need not line up throughout the entire body of the magnetic material. He suggested that only small volumes, or "domains," would be spontaneously magnetized. At first it seemed plausible that in a material consisting of many small

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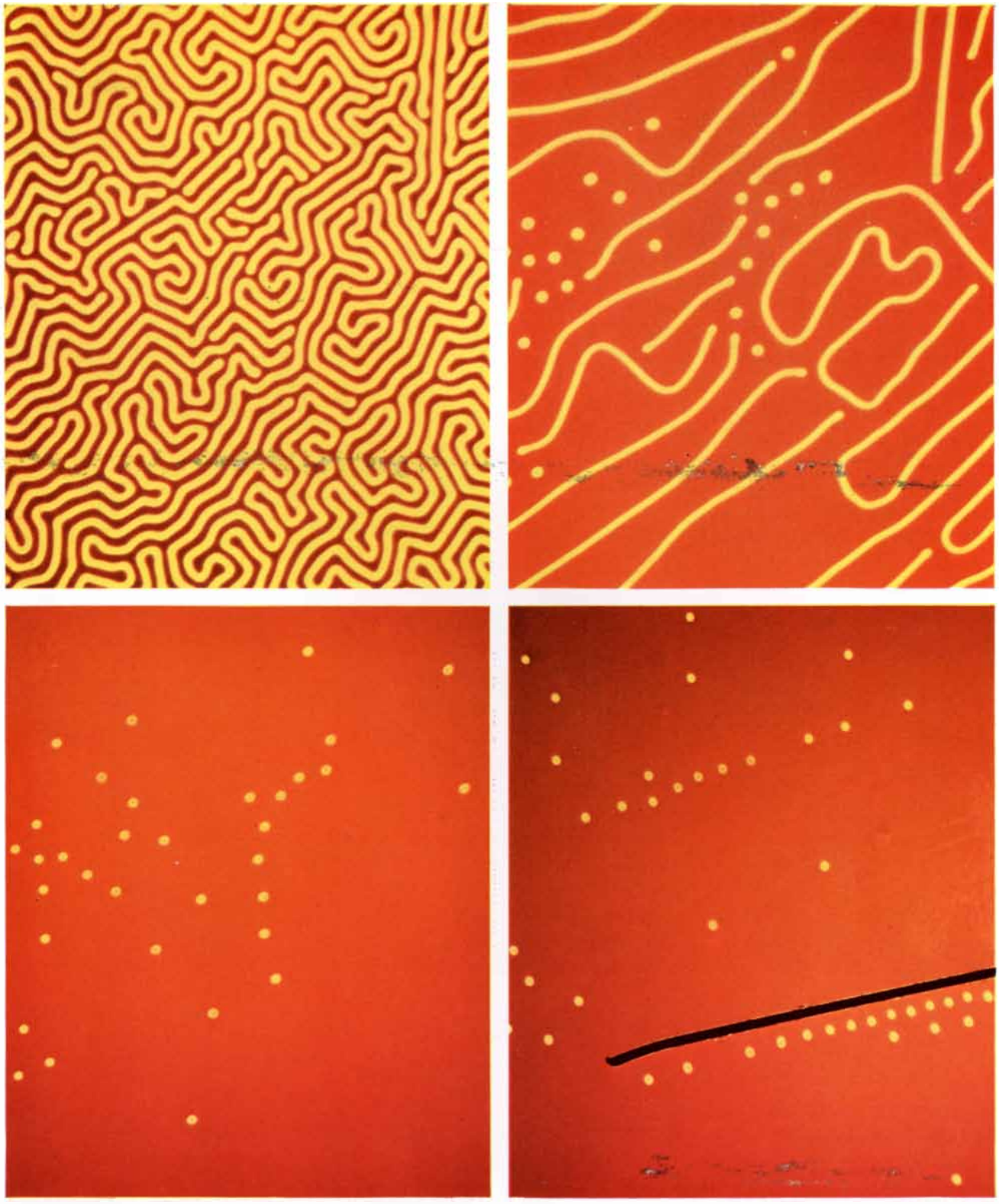

EMERGENCE OF MAGNETIC BUBBLES in a thin wafer of magnetic garnet is demonstrated in this sequence of photomicrographs taken at the Bell Telephone Laboratories. The magnetic domains in the specimen rotate polarized light in different directions depending on whether the internal magnets in the crystal point up or down. By adjustment of a polarizing filter domains with the same orientation can be made to look either bright or dark. When no external magnetic field is present (*top left*), the domains form serpentine patterns, with domains of opposite magnetization occupying equal areas. (The apparent departure from equality here is an artifact of the exposure.) When an external magnetic field is applied perpendicularly to the specimen (*top right*), the domains that are magnetized in the opposite direction shrink and in a few cases contract into bubbles. Although these circular domains are called bubbles, they are actually stubby cylinders viewed from the end. A further increase in the external bias field (*bottom left*) converts all the remaining "island" domains into bubbles. With a "soft" magnetic wire whose magnetization is polarized by the external field one can move the bubbles around freely (*bottom right*). Because the bubbles repel one another they tend to maintain a certain minimum separation. Nevertheless, they can be packed with a density of more than a million per square inch.

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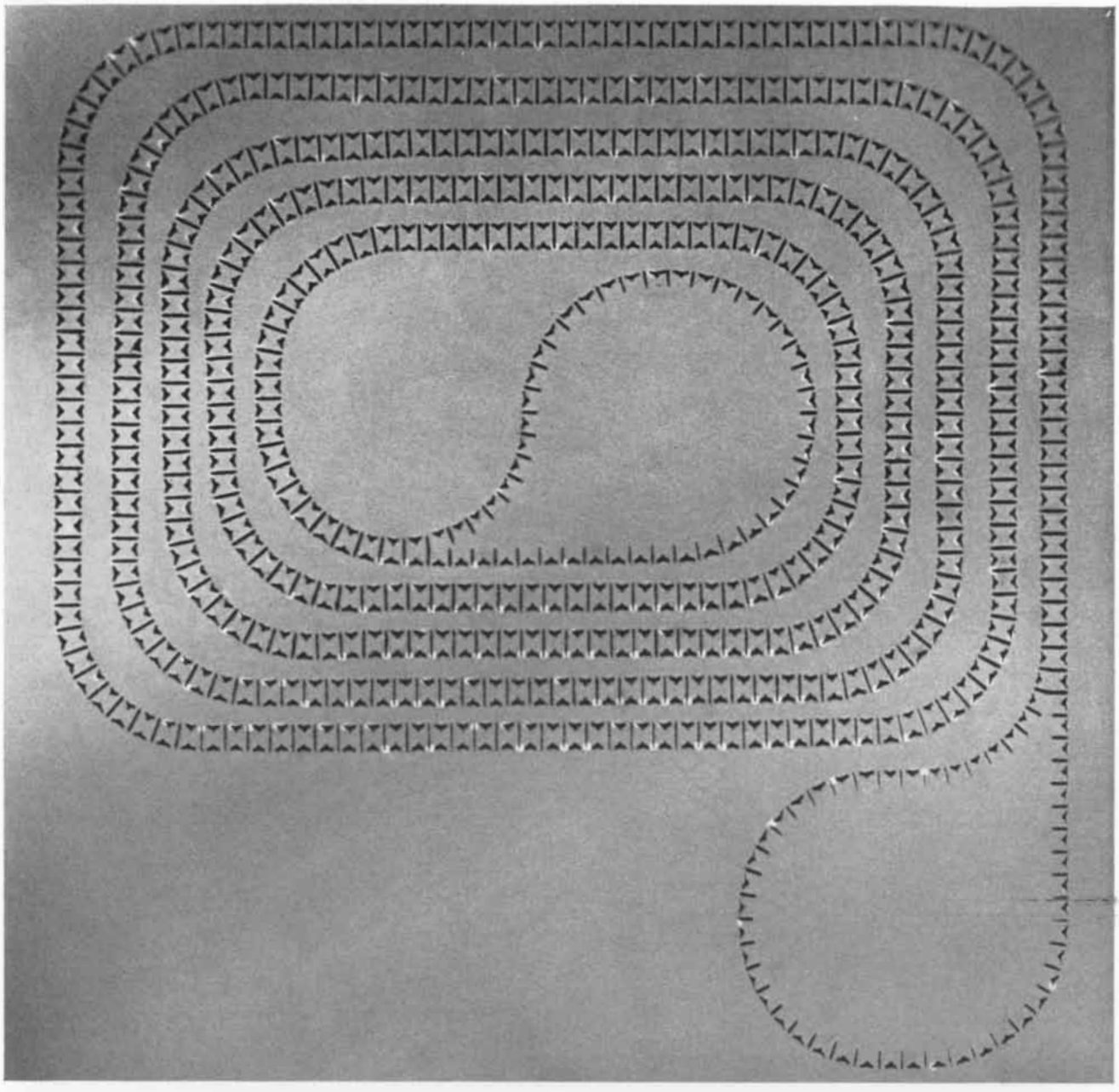
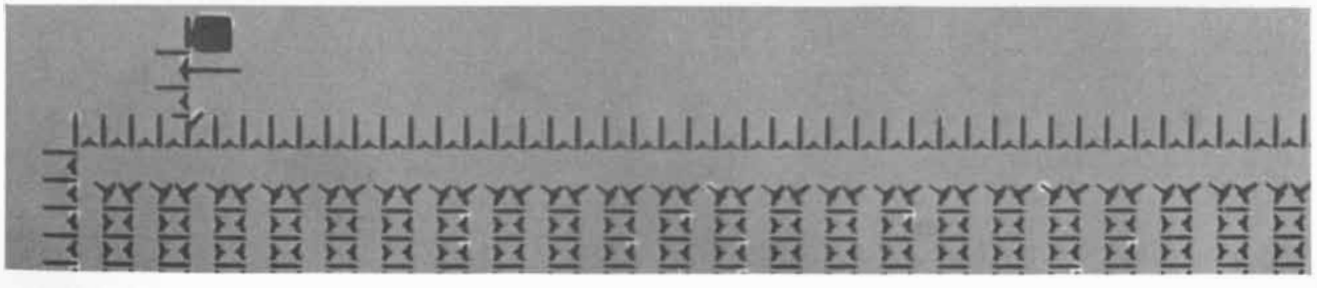


BUBBLE MEMORY REGISTER resembling an ultraminiature toy-train system was built as a prototype at Bell Laboratories. Magnetic bubbles are guided through the system by Permalloy (soft-magnet) elements deposited on the surface of the magnetic wafer in the form of stubby *Y*'s and thin bars. Each *Y*-bar pair constitutes one step in the register; there are 1,074 steps in all. A rotating magnetic field applied in the plane of the register keeps the bubbles circulating. They are turned around by the reverse loop in the center and by the external loop at the lower right. Each bubble is capable of representing one binary digit of information.



TEN-THOUSAND-STEP REGISTER is contained on a chip a tenth of an inch on a side. Only about 7 percent of the complete register appears in this micrograph. As in the small register shown at the top of the page, the bubbles are guided by a Permalloy pattern of *Y*'s and bars. The bubbles are barely visible as light-toned dots resting in the gaps between the two kinds of structure. The bubbles are injected into the register by a bubble generator (*square black shape at the upper left in the micrograph*). A sensing element, which does not appear in the micrograph, can read on command binary data that has been encoded in the flowing stream of bubbles.

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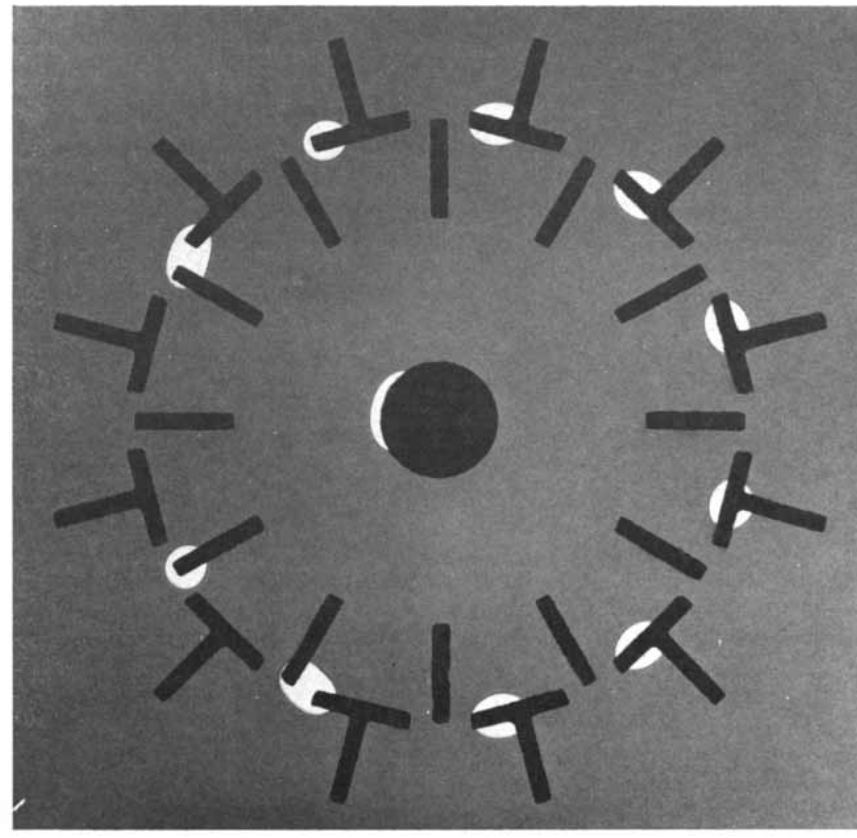
crystals these domains might consist of the individual crystals. When domains were subsequently observed in single crystals, this hypothesis was disproved. Now we know that the size and shape of the domains are chiefly determined by a balancing of several forces that minimizes the sum of the magnetic energy, the exchange energy and the magnetocrystalline energy [*see illustrations on next two pages*].

Since domains are at the heart of the new bubble technology we shall describe this minimization process more fully. The strong exchange force that aligns the magnetic moments of atoms is essentially isotropic, that is, it has no preferred direction. The crystals of actual magnetic materials, however, have internal fields that make it "easier" for the magnetic moments to line up in preferred directions, specifically in directions along the axes of the crystal lattice. If the crystal is subjected to an external magnetic field that does not coincide with one of these "easy" directions, the magnetic moment will line up in an intermediate direction that depends on a balancing of the internal and the external forces.

Still a third force is at work, however: magnetostatic fields, which arise from any discontinuity in magnetization. Magnetostatic fields are produced, for example, by physical boundaries. They always oppose the magnetization and in doing so they reduce not only the overall magnetization of the ferromagnet but also their own magnitude. For this reason they are called self-demagnetizing fields. These fields are always present, even in seemingly perfect crystals, and they make their presence known by creating domains.



STRIP DOMAINS AND BUBBLES can be compared in this micrograph and the one on the cover of this issue of SCIENTIFIC AMERICAN. The pattern of *T*'s and bars is a variation of the pattern that can be seen in the registers on the opposite page. The picture on the cover shows how domains of opposite magnetization occupy equal serpentine areas in the absence of an external magnetic field. The thin walls that separate the domains are also faintly visible. In the picture above an external magnetic field has reduced the strip domains to bubbles. They are made to circulate around the pattern by a rotating in-plane magnetic field.

Domains are readily visible as wavy strips if a ferromagnetic crystal is cut in a thin section perpendicular to its easy axis and viewed through a polarizing microscope. The domains rotate the plane of polarization of the polarized light in opposite directions depending on their magnetic polarity. By adjusting the polarizing filter on the microscope one can make half of the domains dark and the other half bright.

The boundaries separating adjacent domains are called domain walls. They too arise from a process of energy minimization. The domain wall is not a sharp line but is spread across several hundred planes of atoms in the crystal [*see illustration on page 83*]. This is a result of a compromise that minimizes the work needed to rotate the atomic moments against the exchange force (which acts to keep adjacent moments parallel) as well as the work needed to rotate the moments away from the easy axis of the magnetocrystalline field. The larger the exchange force, the thicker the domain wall; the larger the magnetocrystalline anisotropy, the thinner the wall. The energy absorbed in the formation of the domain walls limits the number of domain subdivisions.

Only in single crystals with few defects can one obtain domains of simple geometric form. Ordinary materials have small defects, inclusions, pores and stress points that generate highly localized magnetostatic fields and discontinuities that interact with a domain wall and keep it from assuming its minimum-energy position. These defects are desirable, however, if one is seeking a material with high coercivity and hysteresis, properties associated with permanent magnets. For the devices we are discussing, in which maximum mobility of domains is sought, the material's coercivity, or magnetic "hardness," should be low and controllable [*see illustrations on page 84*].

Now let us look at a thin wafer cut from a specially synthesized single crystal of magnetically anisotropic material. When the wafer is viewed by polarized light, with no external magnetic field present, one sees a pattern of wavy strips representing domains. In half of the strips the tiny internal magnets point up, in the other half they point down. Depending on the orientation of the polarizing filter, one set of the strips will look bright and the other dark. The two sets of strips occupy equal areas [*see illustration on page 79*].

Next let us immerse the wafer in an external magnetic field perpendicular to the wafer and observe what happens when we slowly increase the strength of the field. As the strength is raised the wavy strips whose magnetization is opposed by the field begin to get narrower. The process continues until at a certain field strength all the "island" domains (strips not pinned to the edge of the wafer) suddenly contract into the small circles we call bubbles. The bubbles are actually cylinders seen end on. Raising the external field still further causes the

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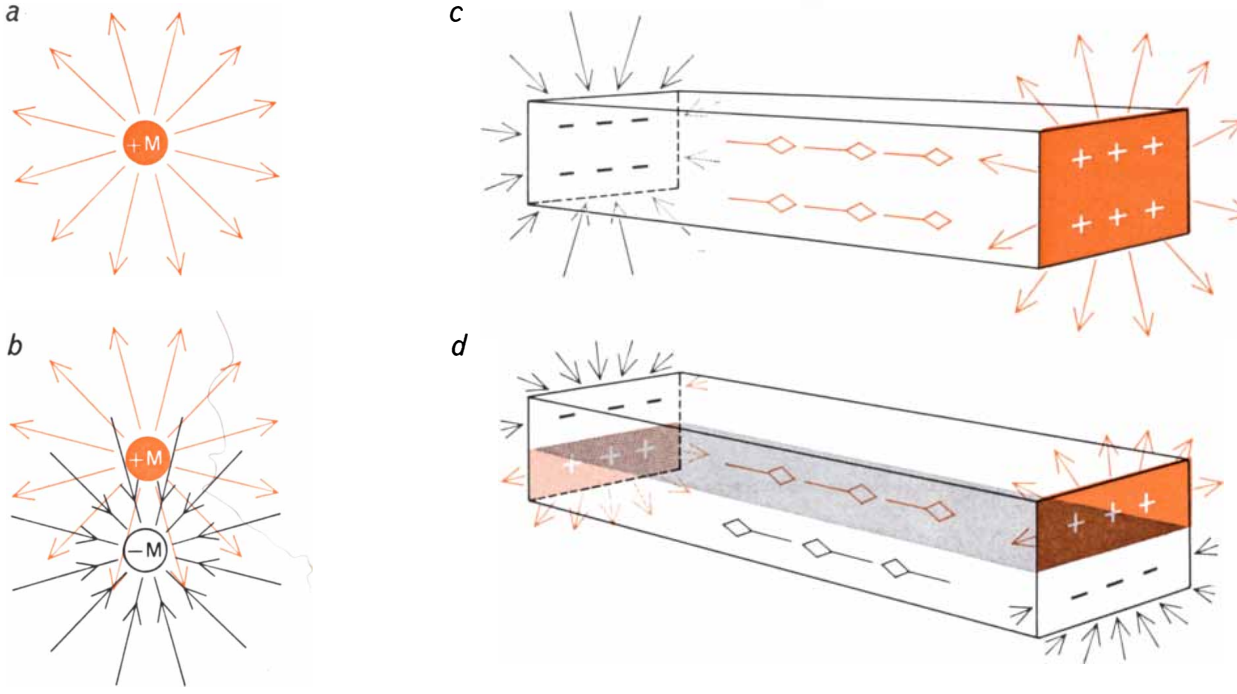
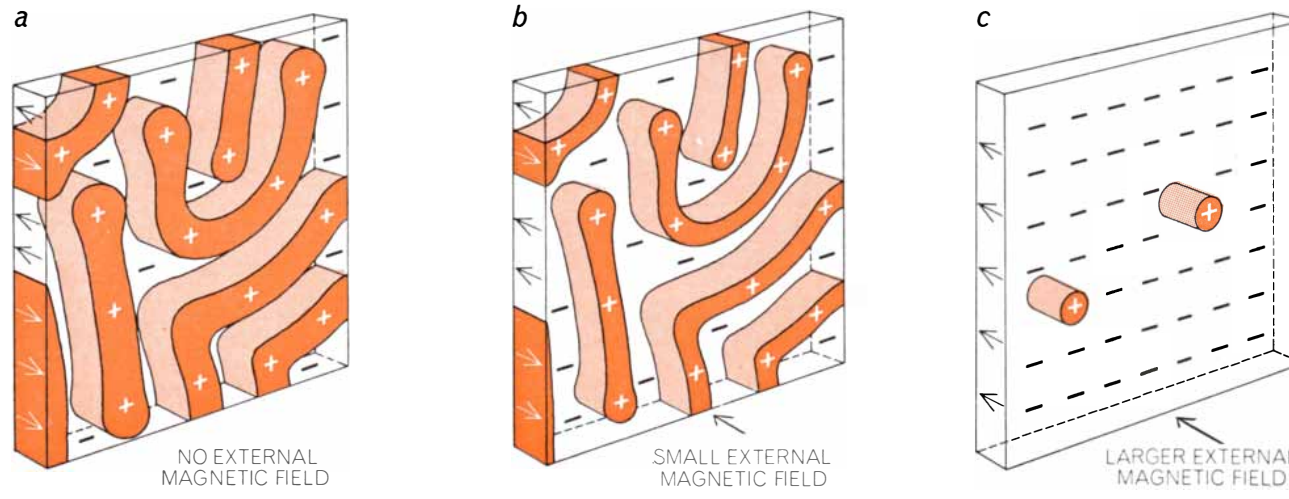
bubbles to shrink until finally they disappear altogether. Depending on the material, the bubbles have a diameter ranging from a few microns to several hundred. They are stable over a three-to-one range in diameter.

Each bubble acts like a tiny magnet afloat in the sea of a magnetic field of opposite polarity. The extreme mobility of the bubble can be demonstrated by moving a fine magnetized wire across the surface of the wafer while observing through the microscope how the bubbles respond. The bubbles can be pushed effortlessly in any direction. At the same time the bubbles repel one another and maintain a fairly uniform spacing because they are all similarly polarized. One can show that if the external field that produces the bubbles is held constant within a range of ±20 percent, the bubbles are completely stable and can be moved about indefinitely. Thus we have duplicated on a microscopic scale objects as



EFFECT OF DOMAIN WALLS is to reduce the amount of magnetostatic energy in a magnetic crystal. A magnetic field surrounds each small magnetic entity, for example the positive monopole shown in *a*. If it is placed next to a monopole of opposite polarity (*b*), the two external fields tend to cancel and thereby reduce the magnetostatic energy. If a single magnetic crystal in the form of a bar were uniformly magnetized (*c*), the poles would be widely separated and the magnetostatic energy would be maximized. If the magnetization were reversed in half of the bar, dividing the bar into two domains (*d*), the magnetostatic energy would be significantly reduced. The domain wall, the interface between the two domains (*gray*), introduces energy of its own, however. Thus the



STABILITY OF MAGNETIC BUBBLES is a consequence of applying a magnetic field that is perpendicular to a magnetic wafer that would otherwise reach a minimum energy state with domains in the shape of serpentine patterns (*a*). The wafer is cut so that the "easy" axis of magnetization is perpendicular to the surface. The external field changes the total energy of the wafer in such a way that domains whose polarity is opposite to that of the external field shrink (*b*) until only cylindrical configurations, or bubbles, remain (*c*). The curve at the right shows that three energy components (the domain wall, external field and magnetostatic ener-

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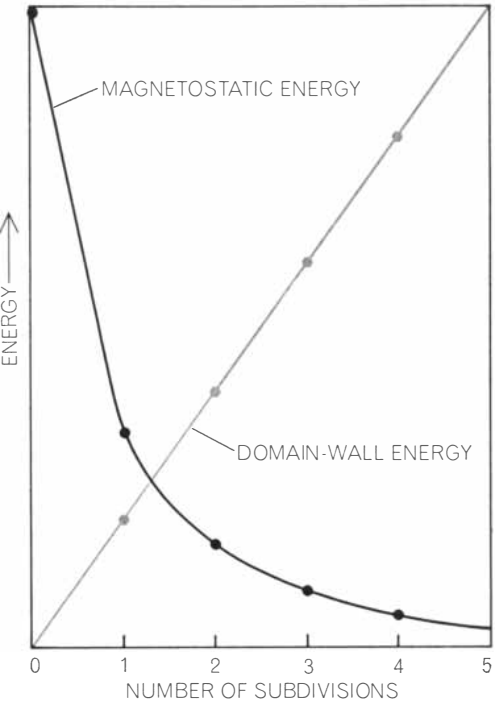
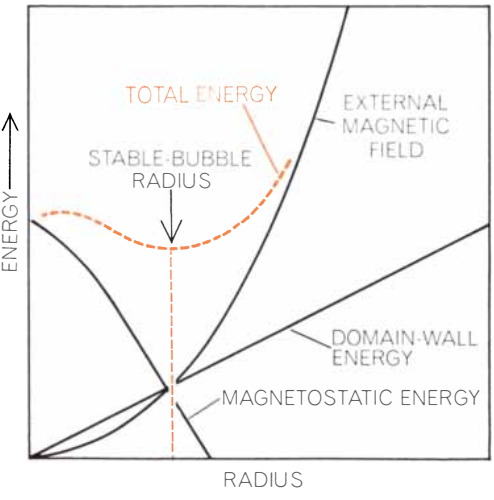
durable and as impenetrable as billiard balls, with the added advantage that they repel one another. Moreover, bubbles can be created anywhere they are desired, and they can be destroyed by techniques we shall describe below.

The first magnetic materials found to have the desired properties for studying the new bubble technology were orthoferrites, a special class of ferrites with the chemical formula $RFeO_3$, where R represents yttrium or one or more rare-earth elements. Samarium terbium orthoferrite is a good example. Orthoferrites can be grown as single crystals by mixing the ingredients with a suitable flux, melting the mixture in a crucible and allowing the melt to cool over a period of several weeks. At the end of that time a few crystals of good size will normally be found. Other crystal-growing methods have also been studied, and recently good wafers have been cut from single-crystal rods pulled directly from the melt.



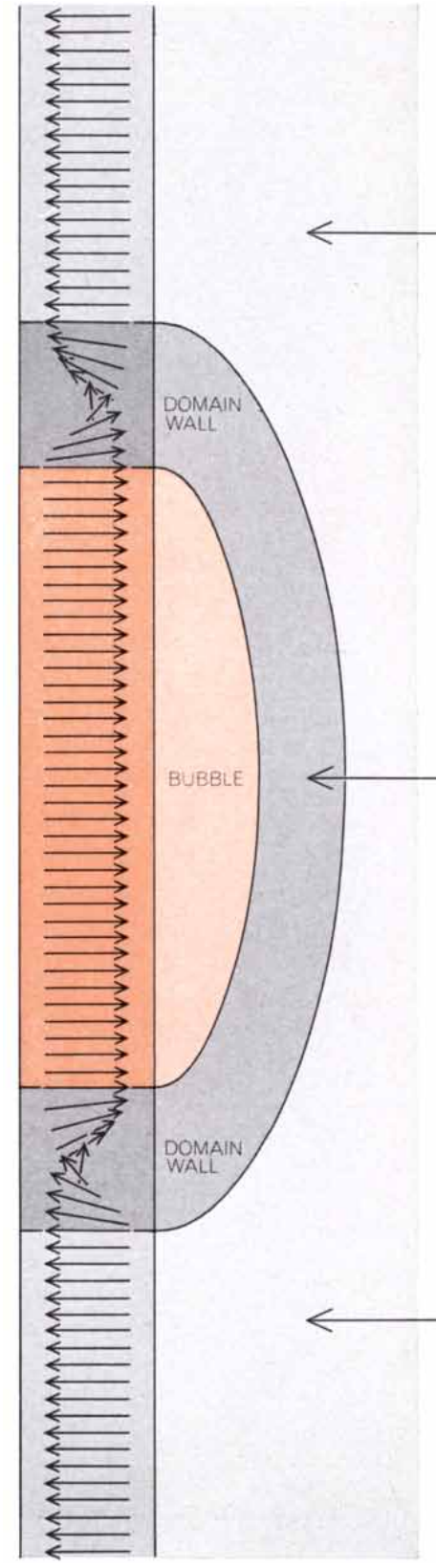
system tends toward a minimum energy state in which the reduction in magnetostatic energy is balanced by an increase in domain-wall energy. For the case illustrated here the minimum energy corresponds to one or two subdivisions (*curve at right*).



gies) add up to produce a total energy curve in the shape of a dish. The stable-bubble radius corresponds to energy minimum at bottom of the dish. Above a certain critical external field the bubble domain collapses.

Over the past several years we have examined hundreds of orthoferrite wafers of different composition in an effort to find materials that give rise to small bubbles that can be moved at high velocity. The minimum objectives have been to attain a packing density of a million bubbles per square inch and a mobility allowing a data-processing rate of a million bits per second. The best of the orthoferrites (samarium terbium orthoferrite) will satisfy the second of these objectives but fails to satisfy the first by a factor of nearly 10 because its bubbles are about three times too large: about 25 microns, or one mil, in diameter. (A practical separation between bubbles is four diameters from center to center.) One ferrite with a hexagonal crystal structure ($PbFe_{12}O_{19}$) produces the smallest bubbles yet observed, one micron in diameter, and hence would provide a packing density of about 70 million per square inch, but the bubbles move too slowly by a factor of more than 20.

After more than a year of searching we found the material we were looking for in synthetic garnets with the general formula $A_3Fe_5O_{12}$, where A can be yttrium, any of the rare earths or, at least in part, lanthanum or bismuth [*see bottom illustration on page 87*]. The garnets readily lend themselves to materials engineering and bubble parameters can be easily controlled. In the most satisfactory garnet samples the bubble diameter is about three microns, which allows the packing in of a million bubbles per square inch. Bubbles in these garnets can be moved stepwise at the rate of at least a million steps per second. The energy needed to move a garnet bubble four diameters is about 4×10^{-14} joule, or only about a 250th of the energy needed to switch the smallest transistor. Thus to switch a million bubbles a million times in a second, equal to 10^{12} op-



DOMAIN WALL is a transition zone through which the magnetization reverses direction. The force exerted by the domain wall combines with the force of the external field (*arrows at right*) in effort to reduce the diameter of the bubble domain.

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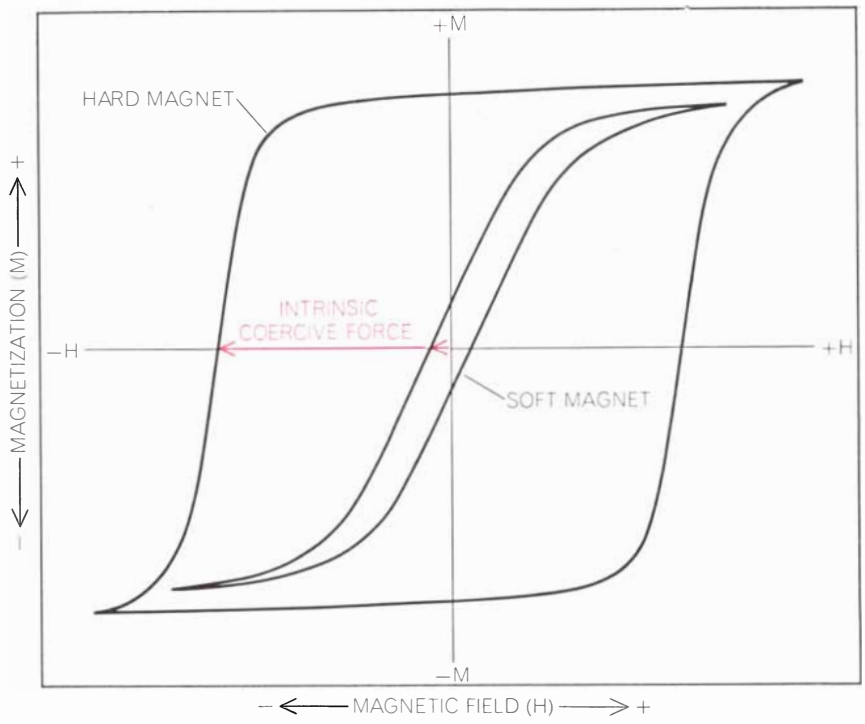
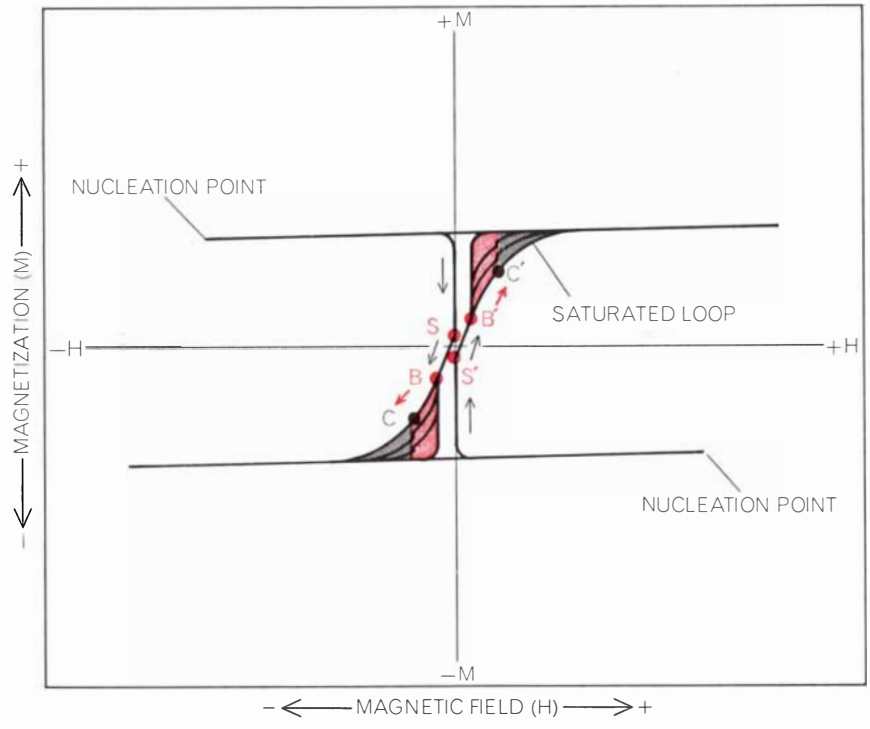


MAGNETIC MATERIALS respond differently to magnetizing and demagnetizing fields, depending on whether they are "hard" or "soft." Two types of response are reflected in these hysteresis loops. Hard magnets, with high coercivity, resist change in direction of magnetization. Soft magnets, with low coercivity, are easily magnetized and demagnetized.



MATERIALS FOR BUBBLES combine low magnetization (M) and low coercivity. If even a small region of the wafer can be caused to magnetize in the reverse direction, at either nucleation point, the entire wafer will quickly demagnetize. The neutral wafer will then break up into strip domains at S (or S'). If a small external magnetic field, $-H$, is applied, a bubble (or bubbles) will begin to form at B and persist until the field reaches the value C, whereupon the bubble will collapse. The exact path depends on the specific domain configuration. When the demagnetized wafer is driven in the opposite direction by a positive field ($+H$), the sequence moves up the hysteresis loop from S' to B' to C'.

erations, requires only 40 milliwatts compared with about 10 watts for 10^{12} transistor switching operations.

The concept of using magnetic particles to store data and to carry out logical operations seems obvious now that the properties of magnetic bubbles are well understood, but the first efforts to manipulate magnetic domains for this purpose took a quite different approach. The original notion was to create tiny "slugs," or regions of reversed magnetization, in a wire that had a preferred, or easy, axis of magnetization parallel to its length. Each slug would be isolated by a domain wall fore and aft. By wrapping the wire with driving coils it would be possible to move the magnetic slugs through the wire at high speed, much as oil is pumped through a pipeline. The presence of a slug could represent 1 in binary code, its absence 0. Suitable writing heads could put data into the pipeline by creating magnetic slugs with the spacing desired; reading heads located anywhere downstream could extract the data as they flowed by at high speed. Data-processing rates as high as 600,000 bits per second were demonstrated in the laboratory, and rates of a million bits seemed attainable.

The magnetic pipeline had many attractive features. Development was carried far enough to show that it could be manufactured with fairly simple machinery at low cost. One important drawback was that no practical way could be found to move slugs between wires except by reading a slug out of one wire and writing it into another. Therefore many storage systems that looked simple enough on paper became clumsy and costly on implementation. A more serious drawback was size. The domain walls at each end of a magnetic slug do not cut through the wire at right angles but extend fore and aft in the shape of two long cones. The length of a slug from tip to tip is about 100 times the diameter of the wire. With ultrafine wires it is possible to achieve a packing density of 20 bits or so per linear inch, but the practical density is more like 10 bits.

Faced with these limitations, we and our colleagues U. F. Gianola, William F. Shockley, P. C. Michaelis and R. C. Sherwood wondered if it might be possible to create compact domains inside sheets of magnetic material, rather than inside wires, and move them around in two dimensions. At this point some of us were acquainted with the fascinating variety of domain configurations familiar to those who deal routinely with magnetic materials. Yet even though we

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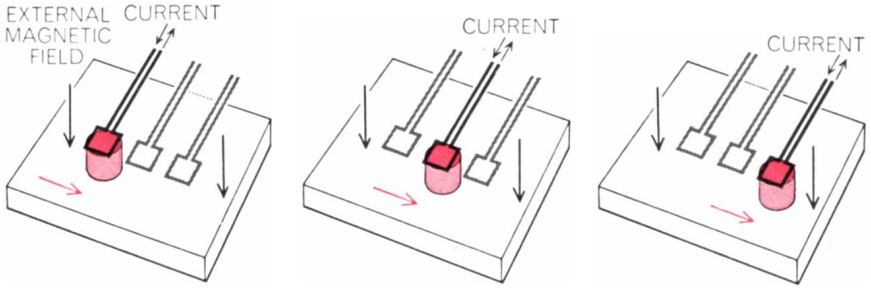
had occasionally seen under the microscope what we later called bubbles, it did not occur to us that such entities might serve as data-carriers. We spent several months devising schemes to create within sheets of magnetic material the hypothetical magnetic carriers we wanted before we realized that the magnetic bubble was hiding in our samples waiting to be exploited. Our excitement grew at learning that these frictionless particles are stable over a range of three to one in diameter, that they repel one another and can be made to dart around simply by exerting unbalanced forces on their domain walls.

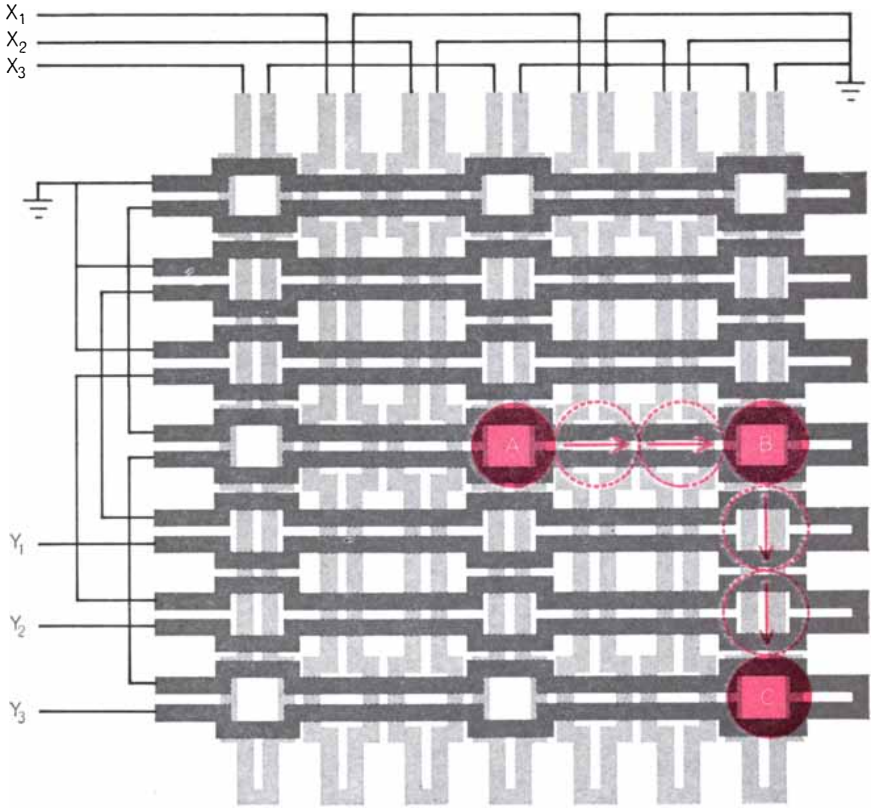
We shall now describe some of the techniques by which bubbles can be controlled for storing data and for performing logical operations. Control requires the creation of magnetic driving fields: magnetic fields with components in the plane of the wafer. Two general methods are available. The first employs conductors in which flowing currents generate the desired fields. This method is called conductor access. The second method, called field access, involves immersing the entire wafer in either a pulsating or a rotating magnetic field that acts on the bubbles by means of carefully placed spots of magnetic material that concentrate the field.

The conductor-access method calls for laying down on the wafer (by photolithographic techniques) a pattern of conductors incorporating loops each about the same size as the diameter of a bubble. The magnetic field generated by each loop is strong enough to attract a nearby bubble into its center [*see top illustration on this page*]. One can see that if a series of adjacent loops is energized in sequence, a bubble will be stepped along from one loop to the next. To ensure that a bubble will move in the intended direction the loops are energized by three independent drive circuits, with each circuit connected to every fourth loop. Thus a bubble "feels" the pull of loops No. 1, No. 2 and No. 3 in sequence and is drawn toward loop No. 4 at the same instant that loop No. 1 is energized again. In this scheme a bubble can lie under every loop and at each step in the cycle be pulled in only one direction one loop at a time. If an ordinary binary code is used, a bubble stands for 1 and the absence of a bubble stands for 0. Bubbles can readily be moved in two dimensions by adding a second set of loops at right angles to the first [*see bottom illustration on this page*].



ONE BUBBLE-MOVING SCHEME involves laying down a pattern of conductor loops on the magnetic wafer. The polarity of the electric current is chosen so as to decrease the magnetic-bias field within the conductor loop. This produces an attracting force on the bubble. When the loops are energized in sequence, the bubble moves from one loop to the next.

The trouble with conductor methods is that a great many accurately placed conductors whose dimensions are comparable to the size of bubbles must be interconnected with external-access circuits. This problem is greatly simplified by the field-access approach. One field-access method involves rhythmically raising and lowering the overall magnetic bias on the wafer so that bubbles alternately shrink and expand. Motion results if the wafer is provided with a pattern of closely spaced asymmetrical energy traps, for example a pattern of thin-film Permalloy arrowheads all pointing in the same general direction. When the bubble is at its maximum diameter, it is centered under one arrowhead and covers half of the arrowhead directly in front of it and half of the arrowhead directly behind it. When the magnetic bias is raised, the bubble contracts and its trailing edge slides forward in the direction of the arrowhead. When the bias is lowered again, the bubble expands and its leading edge moves forward onto the



ARRAY OF CONDUCTOR LOOPS makes it possible to move magnetic bubbles at right angles anywhere within a magnetic wafer. The wiring pattern is arranged so that all loops connected to the X_1 circuit are energized at one time, then all loops connected to the X_2 circuit and then all the loops connected to the X_3 circuit. Similarly, the Y_1, Y_2 and Y_3 loops are energized in sequence. If a magnetic bubble is at position *A*, the sequence X_1, X_2, X_3 will move it to *B*; the sequence Y_1, Y_2, Y_3 will then move it from *B* to *C*.

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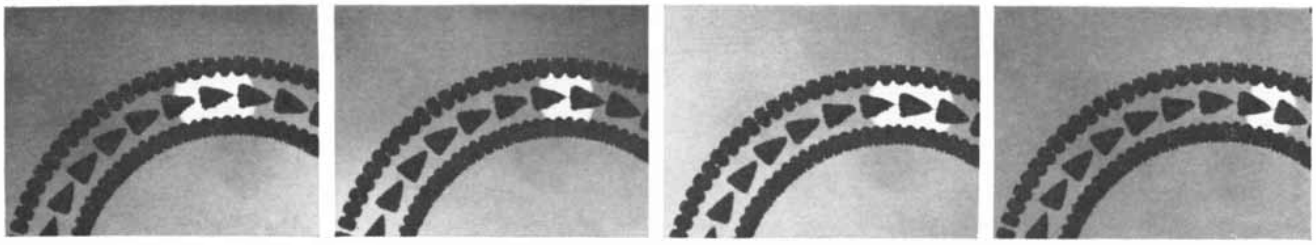
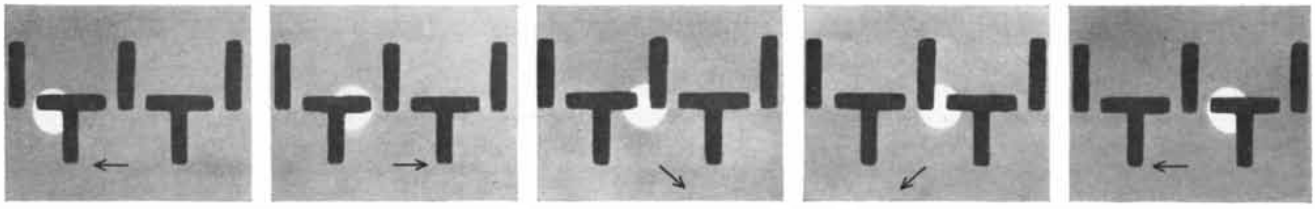
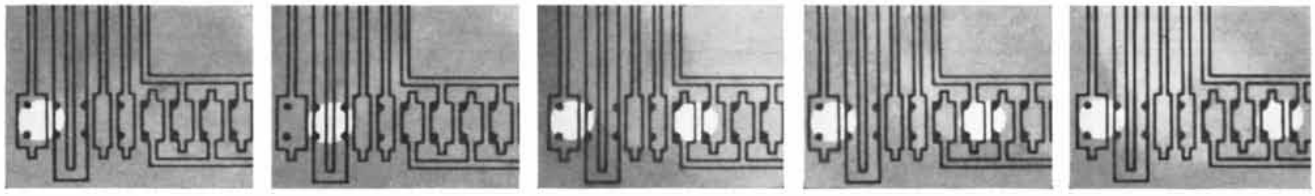


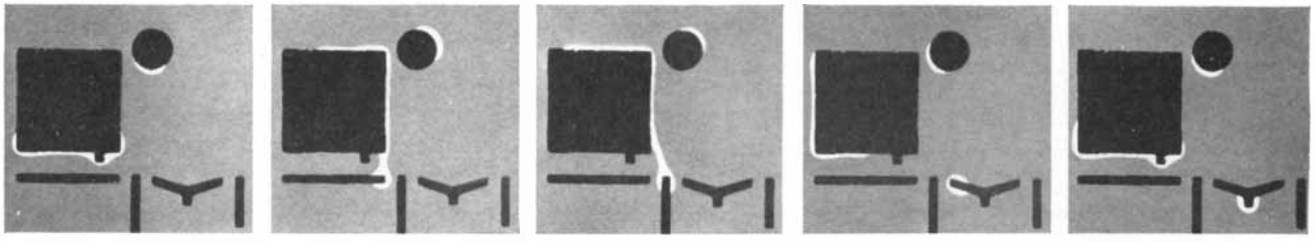
"ANGELFISH" BUBBLE-MOVER is classed as a "field access" propagation method because the bubbles move in response to changes in the external magnetic field rather than in response to electric currents passed through conductors. A pattern consisting of thin-film Permalloy structures is laid down on the bubble wafer to form a sequence of arrowheads, affectionately known as angelfish. The external magnetic field is raised and lowered rhythmically to make the bubbles alternately contract and expand. Each time a bubble contracts it slides off the tip of the trailing arrowhead. With each expansion the bubble slides onto the next arrowhead in line.



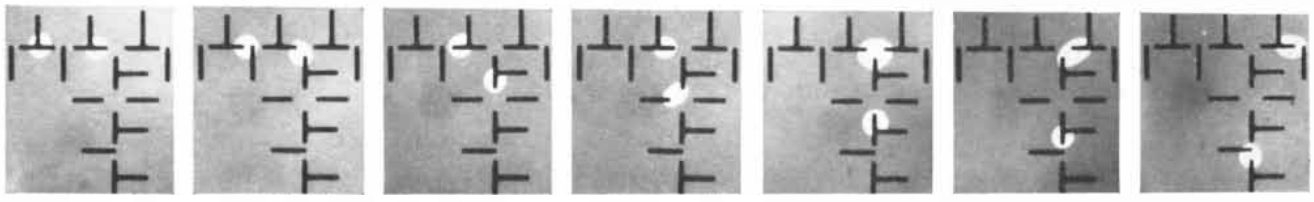
T-BAR BUBBLE-MOVER is another field-access scheme. Here the external magnetic field rotates clockwise 360 degrees in the plane of the wafer, as is shown by the black arrows. As the field rotates, different parts of the *T*'s and bars, made of Permalloy, are sequentially polarized plus and minus. Assuming that the top of bubble has a minus polarization, it will be attracted to plus poles as they progress to the right through *T*-bar pattern. Propagation with fields rotating at a million cycles per second has been demonstrated.



BUBBLE-SPLITTER consists of a special loop with an internal hairpin circuit that can be separately energized when a bubble is centered above it (*second frame from the left*). When current flows through the hairpin circuit, the bubble is split in two even faster than it can be photographed (a few millionths of a second). Subsequently one bubble of the new pair moves off to the right.



BUBBLE-GENERATOR is a field-access device that can create a new bubble every time an in-plane field makes one rotation. The domain appearing as a white crescent projecting from the black disk shows the field direction. The bubble originates as a filamentary strip that becomes circularized after it has split away from generator. Thereafter it is carried to right by modified *Y*-bar pattern.



DIVIDE-BY-TWO CIRCUIT employs an idler that traps every other bubble. Here two bubbles approach the idler from the left. The first bubble is diverted into the idler (located between the second and the third *T* from the bottom). Its presence in the idler forces the second bubble to stay in the horizontal track. The passage of the second bubble in turn forces the first bubble out of the idler.

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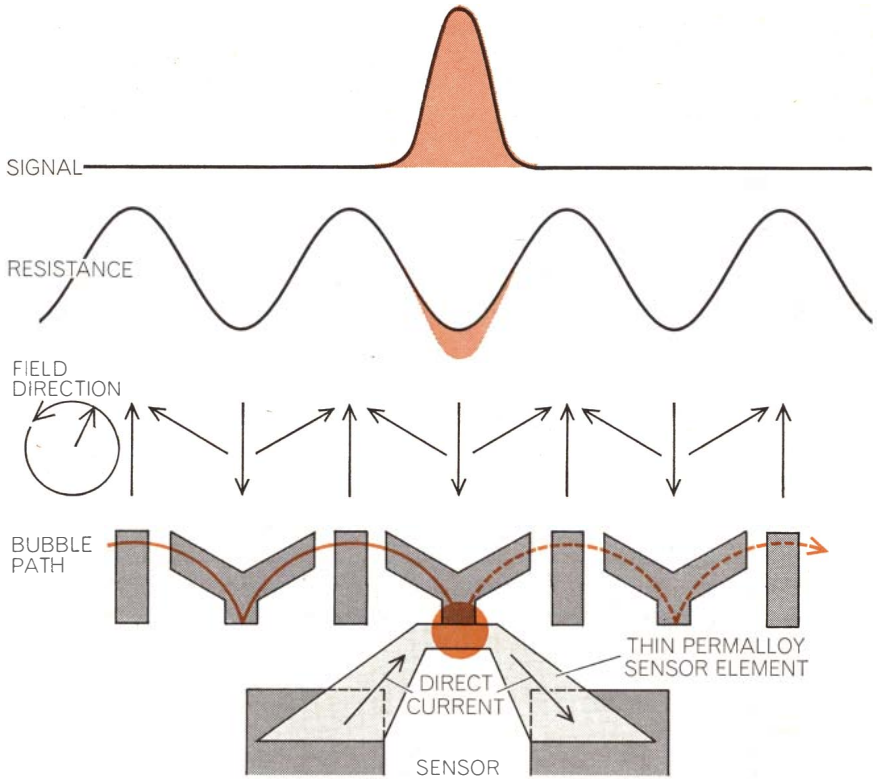
base of the arrowhead next in line [*see top illustration on opposite page*].

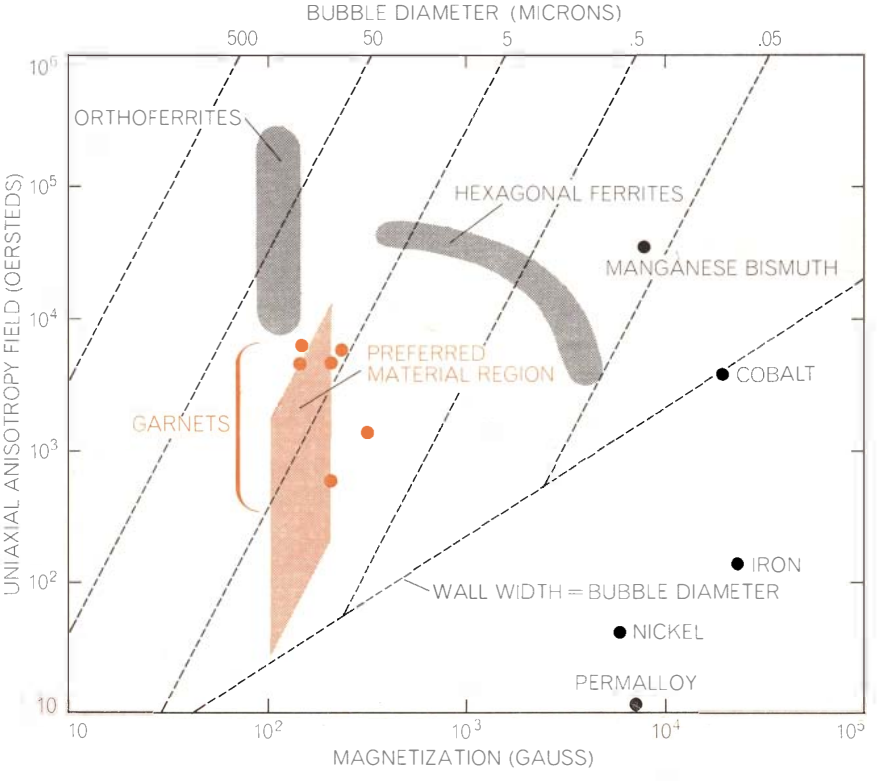
In a second field-access method, which seems more promising than the first, the bubbles remain the same size but are moved from point to point by a rotating magnetic field acting in conjunction with a pattern of thin-film Permalloy *T*'s and vertical bars. Although the field is rotating, one can think of it as pointing in succession to the four directions of the compass. If a *T* is placed in such a field, only the parts of the *T* parallel to the field at a particular time will be magnetized. Thus the horizontal member will be magnetized one way when the field is pointing east and the opposite way when the field is pointing west. Similarly, the vertical bar will exhibit two different polarities depending on whether the field is pointing north or south. A vertical bar placed in the same field will exhibit only north-south magnetization; when the field is pointing east and west, the bar will be essentially neutral. Now imagine an alternating sequence of *T*'s and bars so arranged that the bottoms of the bars line up with the tops of the *T*'s [*see second illustration from top on opposite page*]. If a bubble is introduced at the level of the top of the *T* at the left end of the row, and if the magnetic field is rotated clockwise, the bubble will move step by step to the right. In one full rotation of the field the bubble will travel from the center of one *T* to the center of the next. In the first practical devices, now under development, the field will rotate 100,000 times per second, corresponding to a serial data-processing rate of 100,000 bits per second. Higher rates will undoubtedly follow.

Each of the access methods can be designed to generate new bubbles. In the conductor-access scheme a new bubble can be produced by equipping one of the loops with a hairpin conductor that can be separately energized. If the hairpin is energized while a bubble is in the loop, the bubble is pinched at the waist and finally fissions into two bubbles, which repel each other and jump under the loops at each side [*see third illustration from top on opposite page*].

In the field-access scheme that employs a rotating field one can install a bubble-generator at the head of any row of *T*'s and bars. The generator consists of a Permalloy disk with a small horizontal projection. Under the influence of the rotating magnetic field a new bubble will be produced for every complete revolution of the field, and it will be propagated to the right [*see fourth illustration from top on opposite page*]. It is



BUBBLE-DETECTOR, OR SENSOR, employs the principle of magnetoresistance. The detector is a Permalloy junction whose resistance to a flow of direct current varies sinusoidally in response to the rotating magnetic field that moves the bubbles. When a bubble lands under the Permalloy junction, the resistance is reduced by an additional amount, giving rise to an output signal. The readout is nondestructive: the bubble continues on its way.



PREFERRED PROPERTIES of bubble materials fall within the colored area. It is essential, first, that the material be uniaxial: magnetizable only along a single axis. This is expressed by the uniaxial anisotropy field; the higher it is, the more stable the unique magnetic axis is. When this field is high, however, the bubbles tend to have too large a diameter. If the field is too low, there is a danger that zones of reverse magnetization will nucleate spontaneously. The garnets (*colored dots*) seem to cluster closest to preferred region.

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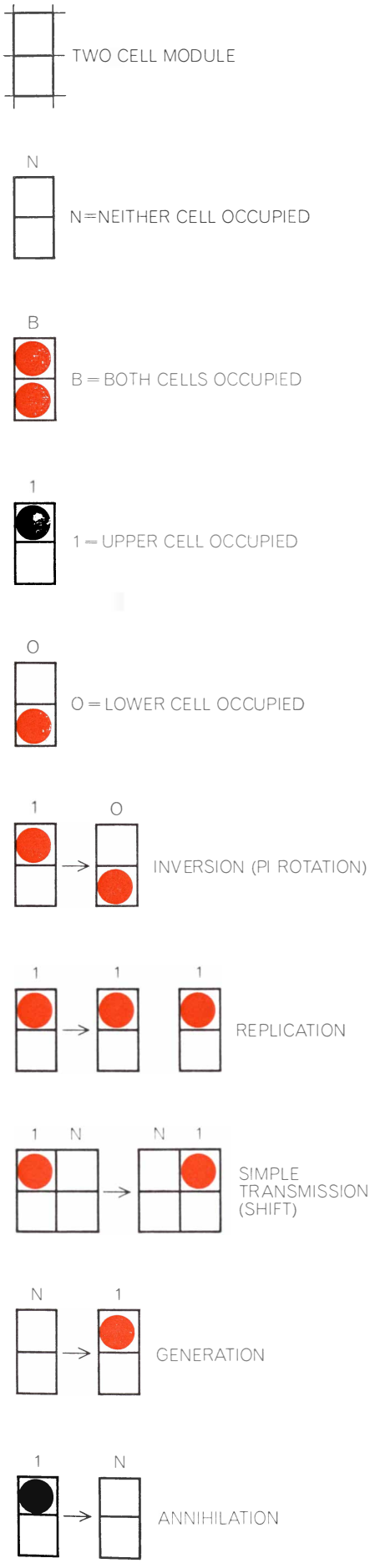

also a simple matter to divide any stream of bubbles by two by creating a little trap, or bypass, that shunts every other bubble to one side and removes it from the mainstream [*see bottom illustration on page 86*]. The bubbles removed can then be destroyed by an annihilator, or "bubble-eater": a region of high magnetic bias that shrinks the bubble to less than its minimum stable diameter.

Any digital system using bubbles requires, of course, a method for detecting the presence or absence of bubbles. The detection method can be either destructive or nondestructive. The bubble-eater, for example, might be made part of a destructive detector. Nondestructive reading techniques have been studied that are based on several physical principles, among them electromagnetic induction, the Hall effect, direct optical sensing and magnetoresistance.

In the electromagnetic-induction method the bubble serves as a tiny moving magnetic dipole that induces a weak electric current in a pickup loop located in the reading head. In the Hall-effect method a voltage appears across a tiny semiconductor slab carrying a direct current when the magnetic field of the bubble acts perpendicularly to the slab (at right angles to the current). Direct optical sensing is based on the same technique that makes domains visible under a polarizing microscope; the detector reacts to changes in the intensity of light caused by the passage of a bubble. The magnetoresistance method appears to be most compatible with the ultraminiature solid-state devices made possible by integrated-circuit technology. In this method the presence of a bubble lowers the resistance, and hence the voltage, as it is measured between two poles of a bridge circuit; the result is a small output signal [*see top illustration on preceding page*].

Now let us see how magnetic-bubble devices lend themselves to the requirements of memory systems. Information storage and processing in virtually all digital computers are done in the binary format. There are many reasons why binary, or bilevel, coding is used. Probably the most important single reason is that the most reliable computer storage and logic devices have just two stable states. The relay, the toggle switch, the transistor flip-flop and the ferrite core are examples. Electronic telephone-switching systems closely resemble large digital computers. In both it is necessary to store and manipulate large streams of digital data and provide the results for external utilization.

The topic of bubbles for binary storage and binary logic can be introduced by considering how one might use larger particles—say billiard balls—for such functions. In the simplest binary system the presence of a ball in an assigned position, or cell, could signify a binary 1 and its absence could signify a binary 0. A sequence of billiard balls and spaces would thus represent binary data.

For a logical operation we must have an interaction. Clearly two billiard balls interact; both cannot occupy the same position at the same time. This kind of interaction, which we shall define as a short-range interaction, allows all necessary operations except replication. Replication, which in a conventional semiconductor logic system is called "fanout," is the duplication of existing binary states. Since binary data are generally consumed within calculation centers, the ability to replicate the data for future manipulations is essential.

To make replication possible in our billiard-ball model the first modification required is to divide the basic cell into two cells, one above the other [*see illustration at left*]. This simplifies many of the basic operations. When neither cell is occupied (state *N*), we have empty areas through which particles can be moved and repositioned. When both cells are occupied (state *B*), we have a reservoir of particles. States corresponding to 1 and 0 are symmetrical and are defined arbitrarily: a particle in the upper cell signifies 1 and a particle in the lower cell signifies 0. Thus by simple inversion of the cells occupied, a 1 is converted into a 0 and vice versa.

Replication is achieved by introducing the concept of a long-range interaction. We assume that whenever a particle enters a cell immediately adjacent to an occupied cell, it pushes the occupant one cell to the right, so that there is always at least one empty cell between two particles. In other words, each particle has a sphere of influence equal to twice its diameter. We must stipulate

BASIC LOGICAL OPERATIONS needed in bubble devices are represented at the left. A bubble can occupy any cell of a basic grid (*top*). Various states of nonoccupancy or occupancy of a two-cell module can be described by four symbols whose meanings are explained pictorially: *N*, *B*, *1*, *0*. Five operations are depicted: inversion, replication, shift, generation and annihilation. It can be readily shown that replication requires a particle capable of interaction at a distance (*see top illustration on opposite page*).

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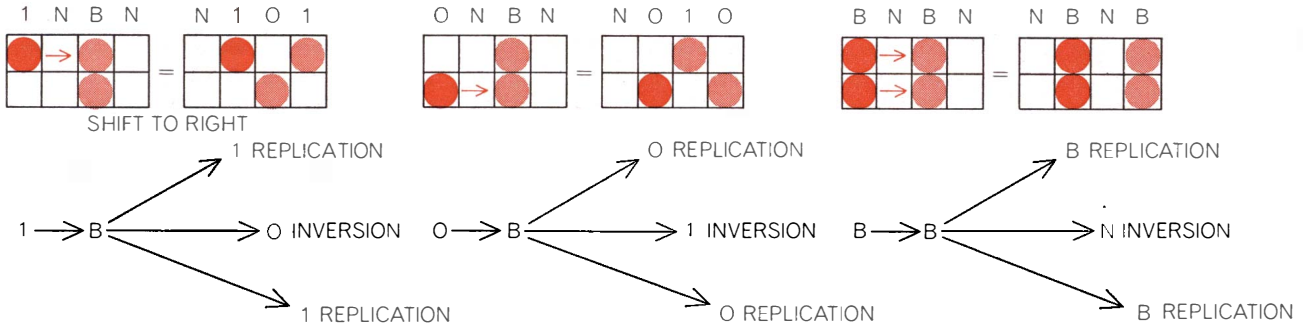
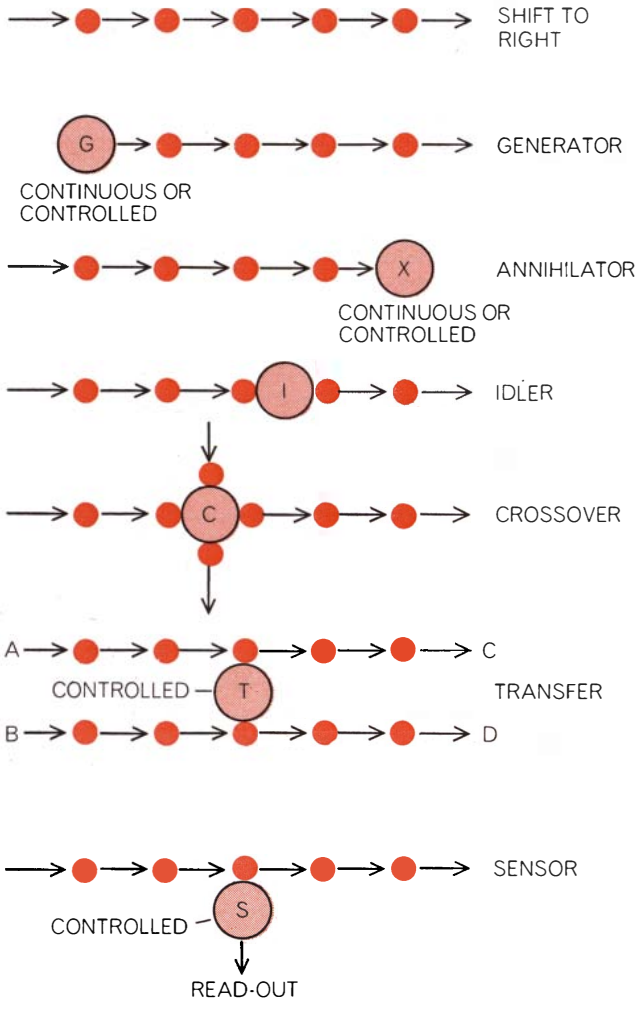
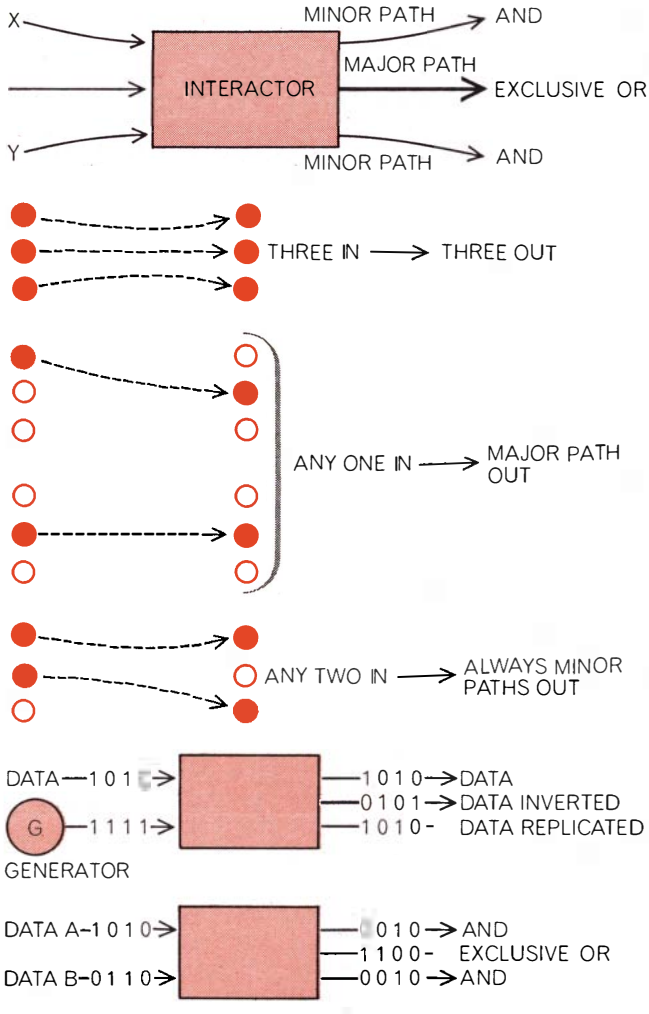


INTERACTION AT A DISTANCE is easily achieved because magnetic bubbles naturally repel one another, leaving a space equal to one bubble diameter between adjacent bubbles. For the purposes of this illustration the spacing is shown only in the horizontal direction. The three diagrams depict the resulting configurations when a single bubble, in either the 1 or the 0 state, and a pair of bubbles in the *B* state interact with cells in the *B* state. In all three examples the initial state is simultaneously replicated and inverted.



SEVEN BUBBLE-STREAM OPERATIONS provide the functions needed for bubble memory systems. When a rotating in-plane field is used for field-access propagation, the bubbles move steadily in one direction. A generator (*G*) supplies bubbles continuously or on command. An annihilator (*X*) can also operate continuously or selectively. An idler (*I*) can trap bubbles. A crossover (*C*) enables two streams to cross, usually with the help of an idler bubble. A bubble transfer (*T*) can move bubbles from one channel to another. A sensor (*S*) detects the data coded in a passing bubble stream.



INTERACTING BUBBLE STREAMS can provide additional logic functions. Since bubbles interact at a distance an "interactor" provided with three input channels will yield various outputs, depending on the input. A single bubble will always leave by the major, or central, exit. If two bubbles enter simultaneously on any two channels, they will always leave by the minor, or outside, exits. Following these rules, the data input streams shown in the two bottom diagrams will yield the output streams shown. Those familiar with logic circuitry will recognize this interactor as a "full adder."

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that in diagrams, at least, the sphere of influence be restricted to the horizontal plane; otherwise our diagrams would have to show that the two vertical cells in the basic module must include an empty, or spacer, cell.

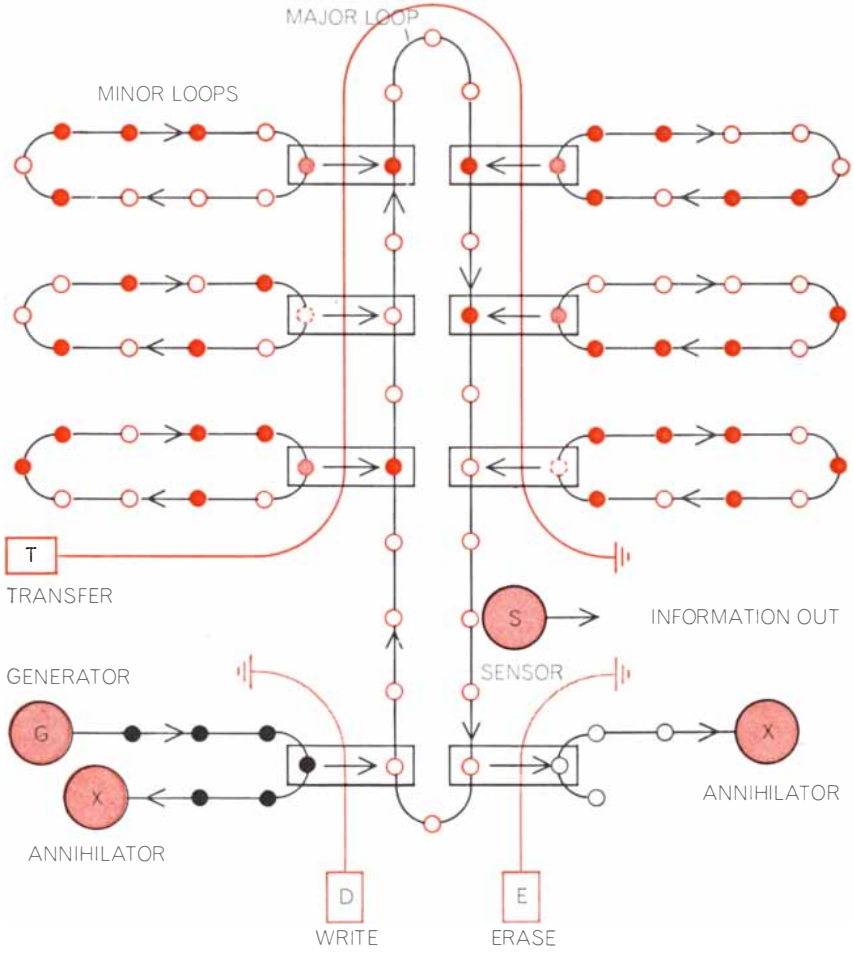
Since the magnetic bubbles in the circuits we described above exhibit a sphere of influence equal to twice their diameter, they can be substituted for the billiard balls in our hypothetical scheme. Now, one can see that if a bubble in the 1 state interacts with a *B* state, the resulting states are 1, 0, 1. In other words, the interaction both replicates and inverts [*see top illustration on preceding page*]. Circuits that can perform this logical operation and similar ones have been built and tested.

The ability to combine data storage with logic in a single miniature device is the most appealing aspect of magnetic-bubble technology. In the simplest memory arrangement bubbles can be introduced, shifted and detected in an endless-loop shift register. As for exactly how such a register can be implemented, there are many options. We have been most successful with field access by rotating an in-plane field with a structure consisting of *T*'s and bars or similar shapes. Registers as long as 10,000 steps in a chip .1 inch on a side are being tested [*see illustrations on page 80*].

Interconnected endless-loop shift registers provide the framework for mass-memory designs. Data, stored in what are designated minor loops, are transferred into a single major loop for readout and also for alteration if it is desired. The heart of the scheme is the operation during which bubbles are transferred from the minor loops to the major loop and returned. The transfer must function smoothly within the cycle of the rotating magnetic field. The scheme also requires bubble-generation and bubble-erasure. To erase a bubble we merely transfer it into a minor loop that is equipped with a bubble-eater. To enter data we selectively transfer bubbles from a bubble reservoir, which is in reality a minor loop equipped with a bubble-generator at one end and a bubble-eater at the other. The in-plane field rotates continuously during all operations. As a prototype for a bubble mass-memory we have designed and built a "telephone repertory dialer," a device for storing 50 to 100 frequently called telephone numbers [*see illustration on this page*].

The most promising method for making garnet bubble materials is to grow them as epitaxial films between three and 10 millimicrons thick on a nonmagnetic single-crystal substrate. An epitaxial film is one that copies the crystal lattice of the substrate. Both liquid-phase and chemical-vapor epitaxy have been successfully exploited to produce garnet films. Defect densities as low as 10 per square centimeter have been achieved in platelets able to accommodate as many as 15 repertory memories, each with a capacity of 4,000 bits. Experimental registers with storage densities exceeding 2.5 million bits per square inch and with data-processing rates up to a million bits per second have also been built. We expect to process our propagation and detection circuits directly on the epitaxial garnet chips.

Improvements in both bubble materials and circuitry now enable us to build a 20,000-step bubble register in the same area, two millimeters square, formerly required by 20-step register. In the volume of a three-inch cube we should be able to build a bubble memory with a storage capacity of 10^7 bits, using stacks of processed garnet wafers. Only 10 watts of power will be required to move data in and out at the rate of 200,000 bits per second. Since magnetic-bubble domains are shifted from point to point by arrays of magnetic elements that derive their energy from an externally generated rotating field, very few wire connections to the outside world are needed. We anticipate that magnetic bubbles will provide large-capacity information storage of high reliability at very low cost.



BUBBLE MASS-MEMORY can be organized so that a number of minor loops hold data and transfer them on command into a major loop for readout. Here data (*light color*) have been transferred from six minor loops into a previously empty major loop. The resulting gaps in the minor-loop data streams can be replaced by either the old data or new data. New data are inserted into the memory by transferring selected bubbles from the bubble reservoir loop (*G*–*X*) in response to "write" commands (*D*). Data are erased from the memory by operating (*E*) and transferring bubbles from the major loop into the annihilator (*X*) at lower right. Major-minor loop blocks with a capacity of 20,000 bubbles each, interconnected into a rectangular array, provide random access to streams of data in a 15-million-bit memory. *T*'s and *E*'s are interconnected along horizontals, *D*'s and *S*'s along verticals.

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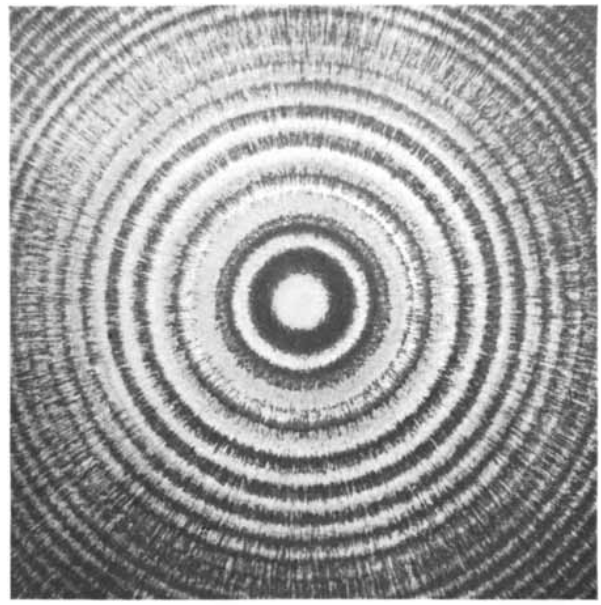
"LASER LIGHT"

A SCIENTIFIC AMERICAN FILM



Almost everyone has heard of lasers, but relatively few people have seen them in action. The Editors of SCIENTIFIC AMERICAN now present "LASER LIGHT," a 16-millimeter sound film about lasers: what they are, how they work, the marvelously pure and curiously scintillating light they produce, how they are being used and how they may be used in the near future. The film is in color and lasts 37½ minutes. It is now available for sale or rent.

A few highlights of the film are:

- **Computer-generated animation explaining stimulated emission and resonant optical cavities.**
- **Ripple-tank and oscilloscope demonstrations explaining the wave principles underlying laser action and holography.**
- **Holograms, their three-dimensionality dramatically evoked by the moving camera.**
- **A 600-foot, 8.8-kilowatt laser in action.**
- **Tunable lasers.**
- **A television picture transmitted by laser beam.**
- **The laser chalkline for the San Francisco Bay tunnel.**
- **Laser interferometry.**
- **Gas, solid and organic-liquid lasers.**
- **An experiment on the use of holography in a computer memory.**
- **Original musical score.**

"LASER LIGHT" is recommended for general audiences with an interest in science and technology, and for use in conjunction with the teaching of physics and optics. The film is accompanied by a selection of five SCIENTIFIC AMERICAN articles on lasers and holography, written by leading authorities in these fields.

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MODERATE GOITER is evident in this detail from a portrait of Maria de' Medici, wife of Henry IV of France. It was painted in 1625 by Rubens and now hangs in the Prado in Madrid. Moderate goiter was considered an adornment in the late Renaissance.

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ENDEMIC GOITER

The disorder has a long record because its principal sign is so apparent. It is now a disease of the poor, because an unbalanced diet often cannot correct for a deficiency of iodine in the soil

by R. Bruce Gillie

The "regular and rounded neck" with which Maria de' Medici was endowed by Rubens [*see illustration on opposite page*] is a goiter, or compensatory hypertrophy of the thyroid gland. The thyroid is a pinkish pad of tissue wrapped partly around the trachea and esophagus; it is a ductless gland of vertebrates that secretes into the blood the hormones that regulate the rate of development and metabolism. Goiter is an unusually obvious manifestation of an endocrine disorder, and as such it has drawn attention, sometimes admiring and sometimes fearful, since man's earliest days.

There are many different causes of goiter: disease, developmental defects and environmental conditions. Endemic goiter, so designated because it affects a significant proportion of a given population, is almost always the result of a dietary deficiency of iodine, an essential substrate for the synthesis of the thyroid hormones thyroxine and tri-iodothyronine. Iodine-deficiency goiter is now easily prevented or cured by the ingestion of minute quantities of iodine, but over the centuries it has been one of the most persistent and ubiquitous diseases of mankind. As recently as 1960, 200 million people were still afflicted with it.

The secretion of thyroid hormones is a link in one of the exquisitely balanced feedback systems that regulate the internal environment of vertebrate organisms [see "The Thyroid Gland," by Lawson Wilkins; SCIENTIFIC AMERICAN, March, 1960]. Impulses from the nervous system cause the hypothalamus at the base of the brain to release a neurosecretion, the thyrotropin-releasing factor (TRF), into portal veins leading directly to the pituitary, the pea-sized master gland that regulates the activity of the thyroid and other endocrine glands. The thyrotropin-releasing factor stimulates the pituitary to secrete into the blood thyrotropin, or thyroid-stimulating hormone (TSH), which in turn causes the thyroid to synthesize and secrete its hormones. The system is self-regulating: an excess of thyroid hormones in the blood suppresses hypothalamus and pituitary activity and reduces the secretion of the thyroid-stimulating hormone; when the thyroid hormone concentration is too low, the pituitary responds by secreting more thyroid-stimulating hormone to restore the normal thyroid-hormone level [*see illustration on page 96*].

If the thyroid is healthy and there is enough iodide (ionic iodine) in the blood, the thyroid-stimulating hormone steps up the trapping of iodide by the thyroid and in other ways abets the synthesis of thyroxine and tri-iodothyronine within the follicles of the thyroid gland [*see illustration on page 98*]. In the absence of sufficient iodide thyroxine synthesis is inhibited; the flow of thyroid-stimulating hormone is unchecked and its effect is to increase the number and change the shape of the cells that form the follicles; in time the follicles become distended. This compensatory proliferation of cells and distention of the follicles, which constitute goiter, may restore thyroid-hormone production to a satisfactory level for normal life.

A Chinese document from about 3000 B.C. is the earliest known record of goiter. Remarkably, it not only described the symptoms but recommended an effective cure: the ingestion of seaweed and burned sponge, which contain large amounts of iodine. Speculating on the causes of what was apparently a common affliction, Chinese scholars listed poor quality of drinking water, mountainous terrain and emotional vicissitudes, all of which are indeed associated with a higher incidence of goiter. The Chinese even administered desiccated thyroid glands of deer as a treatment for goiter. (Nowadays extracts of beef, sheep or hog thyroid are given for hypothyroidism.)

The Ebers Papyrus of Egypt, dating from about 1500 B.C., described two possible treatments for goiter: surgical removal of the gland (which must have been a high-risk procedure if it was ever attempted) and the ingestion of salt (presumably containing iodine) from a particular site in lower Egypt.

Hippocrates blamed goiter on the drinking water in certain places. Juvenal, Vitruvius and Julius Caesar were impressed by the enlarged neck of residents of some alpine regions; Caesar, in fact, believed that the large neck was a national characteristic of the Gauls. The word "goiter," incidentally, is from the Latin *guttur*, or "throat."

Roman physicians noticed that even in a normal person the size of the thyroid may fluctuate somewhat during times of physiological stress such as puberty, menstruation and pregnancy. They noticed in particular that the physical and emotional circumstances surrounding the initial sexual activity of a bride brought about a slight swelling of her thyroid. The Romans thereupon originated the ritual of measuring the circumference of a bride's neck with a ceremonial ribbon before and after her first week of marriage. If the circumference increased, the marriage was considered consummated.

Because moderate goiter is quite compatible with normal life, causing no pain and often no impairment, it was not necessarily perceived as an affliction; if in some cultures it was considered a divine stigma, in others it was a mark of beauty. In Europe it was often attributed to some serious religious or social transgression—robbing the graves of saints, for example. In Germany during the Middle

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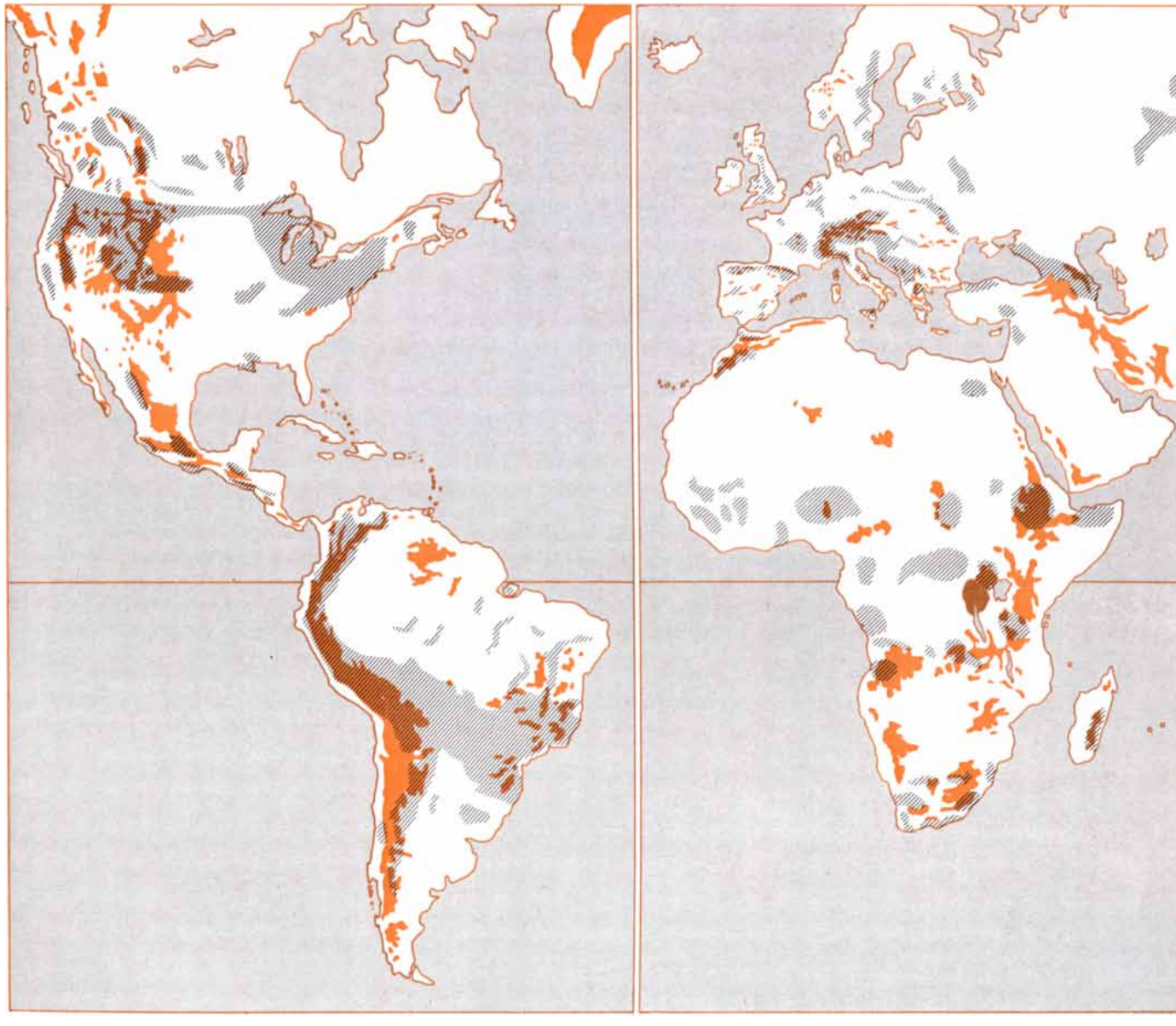
Ages it was thought that the condition could be caused by strenuous work, including childbirth. That was the rationale for a now forgotten custom of tying a cord around the neck of a woman in labor. In India inhaling the odor of people dying of malaria was said to cause goiter. At one time or another the condition has been blamed on indolence, drunkenness and debauchery. In 1867 a French student of the matter named J. Saint Leger listed more than 40 different possible causes then being cited—among them a lack of electricity in the atmosphere, incest, alcoholism and coitus interruptus.

Cures were not so easy to find. A procedure that appears to have persisted for many centuries was piercing the thyroid gland with a red-hot needle. That presumably created an inflammation, and the resulting fibrosis may well have reduced the size of the gland. Actual surgery could not have been effective until the end of the 19th century. One reason is that the thyroid is so richly supplied with blood vessels that in the early days of surgery an incision would have resulted in excessive and uncontrollable bleeding. Even after the advent of satisfactory techniques surgical removal was dangerous at best before the discovery of the parathyroid glands. These tiny glands, nesting on the surface of the thyroid lobes, regulate the concentration of calcium in the blood, and their inadvertent removal along with the goitrous thyroid would threaten life.

The first attempt at an epidemiological survey was made at the request of Napoleon I, who was impressed (as Caesar had been) by the many cases he saw in the course of his alpine campaigns. Napoleon was also disturbed by the loss of potential recruits who had to be rejected because the military uniform would not fit their goitrous necks.

The basic mystery surrounding goiter, of course, was the function of the thyroid gland in health. The early anatomists were impressed by the gland's large blood supply and puzzled by the fact that (like the other endocrine glands) it had no duct and therefore, it seemed to them, could have no secretory function. In the Middle Ages some anat-



REGIONS OF ENDEMIC GOITER and the mountainous terrain with which it is often associated were mapped by the World Health Organization. Areas where iodine-deficiency goiter is endemic are indicated by the black hatching. Populations near seacoasts are sel-

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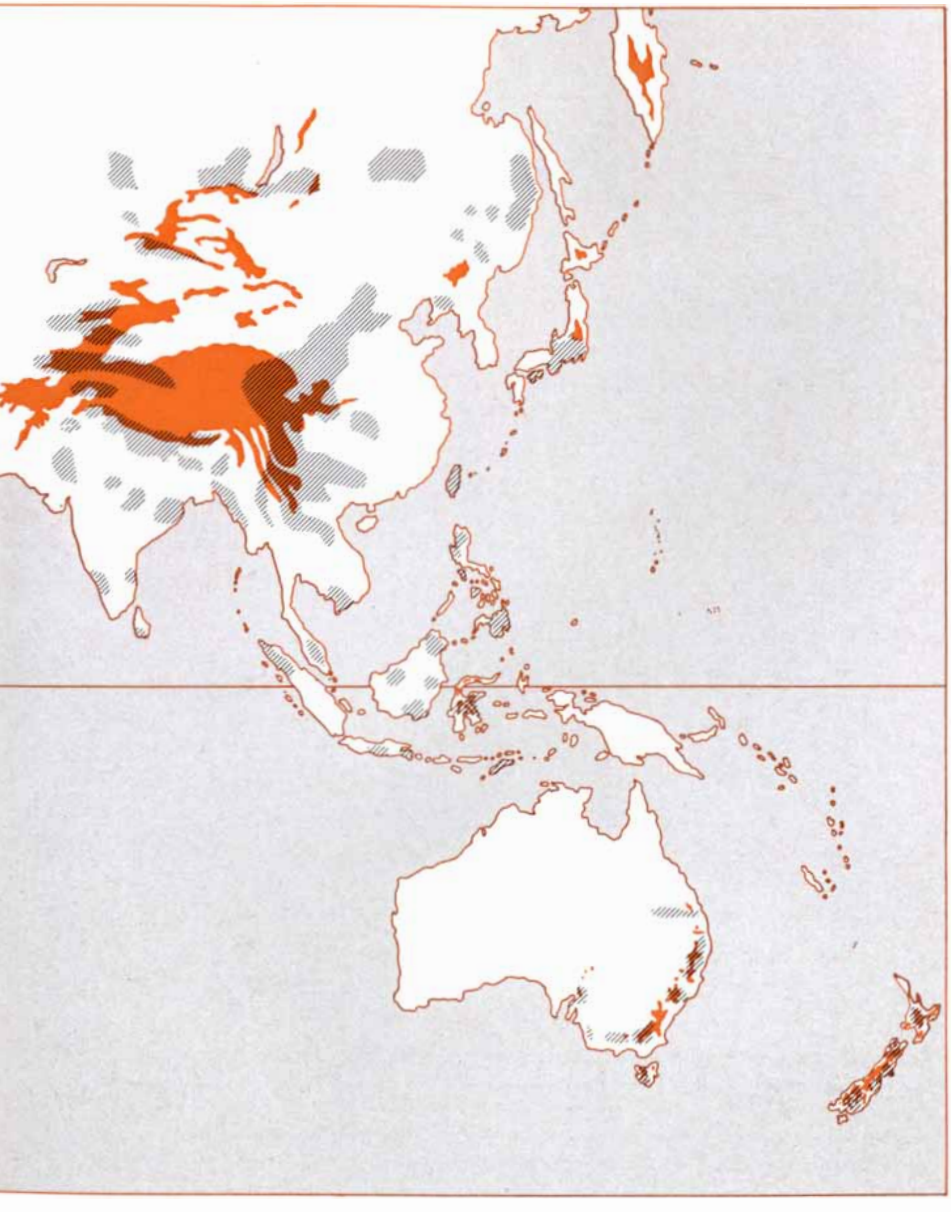
omists thought of the thyroid as the seat of the soul. Others were more practical. The Italian anatomist Giulio Casserio wrote in 1600: "Kind nature has especially beautified the gentle female sex with many sorts of ornaments. And not the least among them is this one, that the empty spaces which exist around the larynx being filled up, they show to our eyes, to the great joy of our sight, a regular and rounded neck." Paintings by artists of the time, including Dürer and Rembrandt, suggest that Casserio's view was the general one, since madonnas and other female subjects are often depicted with moderately goitrous necks.

In 1656 the British anatomist Thomas Wharton wrote a complete description of the thyroid and also named it after the Greek word for a large oblong shield: *thyreos*. Wharton agreed with Casserio that it served to beautify the neck ("particularly in females to whom for this reason a larger gland has been assigned"), but he suggested that it might also keep the tracheal cartilages warm, since they were "rather of a chilly nature," and lubricate the larynx, rendering the voice more melodious. Other students believed the thyroid shunted blood away from the brain to protect it from sudden changes in blood pressure, or that it was a cushion to support and protect the structures of the larynx.

It was not until 1895, after surgeons had seen the effects of removal of the thyroid gland and after treatment with thyroid extract had been attempted, that Adolf Magnus-Levy of Germany demonstrated that the thyroid regulated the basal metabolic rate: the rate at which the cells of the body consume oxygen, which is to say the rate at which they convert nutrients into the energy of life. In the same year the German biochemist Eugen Baumann learned that the thyroid is particularly rich in iodine. It was a serendipitous discovery. Baumann was trying to analyze the protein content of thyroid tissue, and his usual procedure was to precipitate the protein from an extract with sulfuric acid. One day, reaching for the sulfuric acid on a shelf above his workbench, he picked up a bottle of nitric acid instead, and before he had realized his mistake he had added some of its contents to the extract. To his astonishment the characteristic brownish-purple fumes of iodine gas swirled up from the preparation. Baumann went on to describe the role of iodine in thyroid physiology. In 1914 Edward C. Kendall of the Mayo Foundation first crystallized some thyroid hormone. It was a large and difficult task: the 37 grams of crystallized hormone that Kendall subsequently obtained were derived from three and a quarter tons of pig thyroid! Finally in 1927 Charles Robert Harington of the University College Hospital Medical School in London and George Barger of the University of Edinburgh established the definitive structure of thyroxine, confirming Baumann's observations. Well before that time Baumann's work had led on the one hand to the understanding that endemic goiter was the result of environmental iodine deficiency and on the other to simple and effective iodine therapy.



dom affected because of the iodine content of seafood. Not all inland areas are equally affected; the geology and remoteness of mountainous regions (*color*) make them most susceptible.

As investigators looked into the ecology of goitrous populations they first found a correlation between goiter and the accessibility of a population to the sea and thus to a seafood diet rich in iodine. A map compiled by the World Health Organization makes it clear that it is in inland areas, particularly mountainous ones, that goiter may be endemic [*see illustration on these two pages*]. The Alps, the Pyrenees, the Himalayas and the Andes are strikingly goitrous. So are inland plains regions in Italy, in the Congo and in the Great Lakes basin of North America.

The geography of goiter is not simple, however. Many inland and mountainous regions do not support goitrous populations, and there are coastal areas that unpredictably have goitrous populations. A factor that is more closely correlated with the incidence of endemic goiter than mere distance from the ocean is the

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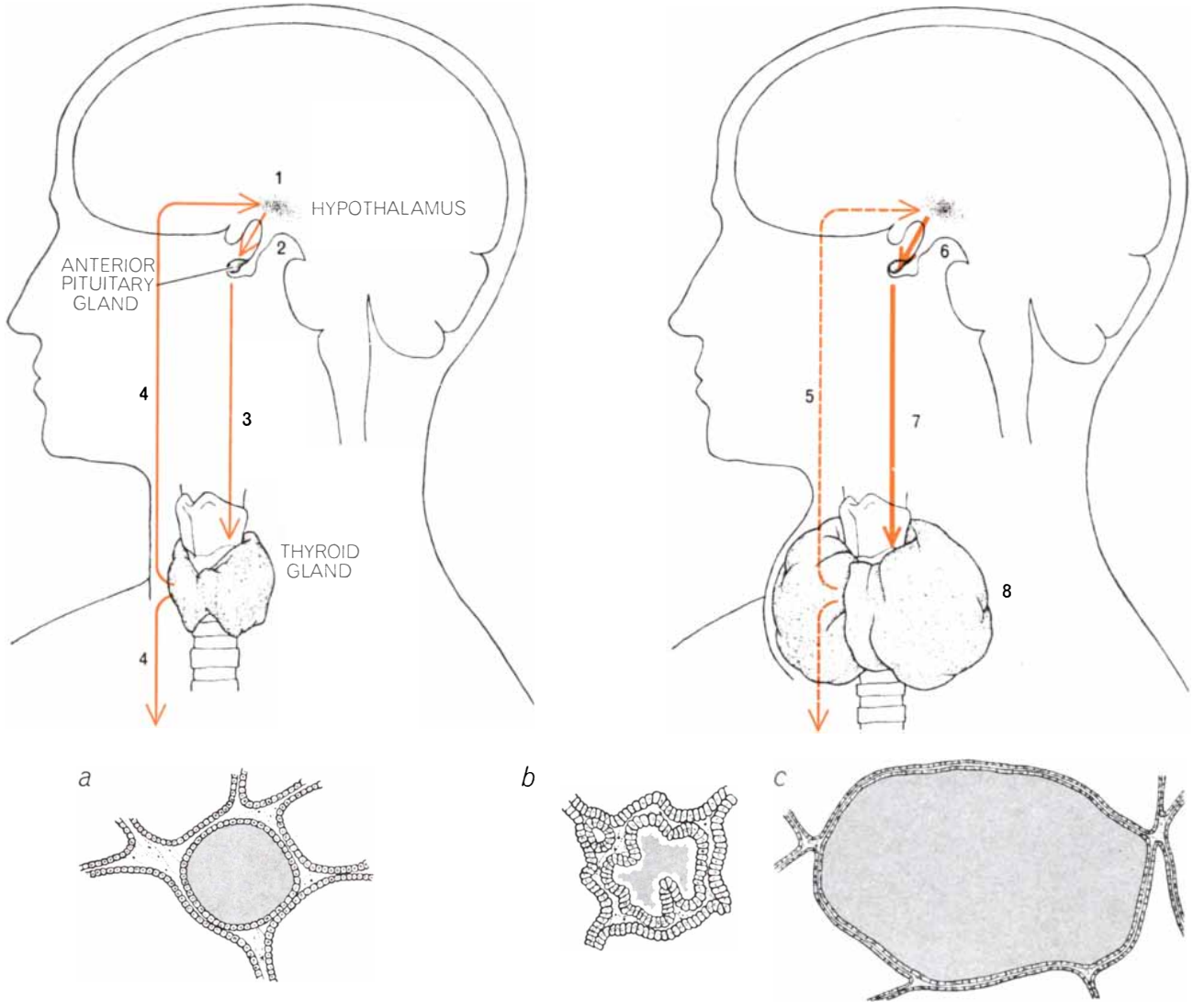
iodine content of the soil. As long as the soil content of iodine is adequate, enough iodine (about 100 to 200 micrograms per person per day) will be ingested in locally grown produce to prevent the onset of goiter. Although the iodine content of soils is generally higher in coastal regions than it is inland, soil content is determined by more complex factors than distance from the ocean alone. The most seriously depleted soils are in areas that were subjected to the most intense glaciation. Such glaciation did two things. By crushing virgin igneous rocks that had never been exposed to atmospheric iodine, it left behind vast amounts of new, iodine-poor topsoil, and it leached the soluble iodine salts out of the original soil.

Leaching may also make soils along the shores of rivers that periodically overflow their banks deficient in iodine. An interesting example of this process was noted in a study of two villages on opposite banks of the Congo River in an area where heavy rain and periodic flooding had reduced the iodine content of the soil. On one bank the village population was 80 percent goitrous; on the alluvial soil of the opposite bank the population was hardly goitrous at all. Iodine being leached by the heavy rain out of land upstream was being redeposited in the alluvial soil around the second village, making the iodine concentration there just sufficient to prevent goiter.

The steady replenishment of iodine in terrestrial soils from atmospheric iodine tends in time to reverse the effects of glaciation. The degree of replenishment is complexly affected by the distance of an area from the ocean, the prevailing wind conditions and the amount of iodine in the precipitation. In addition some areas of the world have natural terrestrial iodine deposits that may also help to determine the iodine content of the local soil. In other words, the ecology of a human society as well as its principal staple diet is a major factor in the etiology of endemic goiter.



NEGATIVE-FEEDBACK SYSTEM controlling production of thyroid hormones begins with the neurosecretion from the hypothalamus (*1*) of thyrotropin-releasing factor (TRF), which goes directly to the pituitary (*2*) and causes it to release thyrotropin, or thyroid-stimulating hormone (TSH), into the bloodstream (*3*). In the thyroid gland TSH acts to bring about the synthesis and secretion into the circulation of the thyroid hormones thyroxine and tri-iodothyronine (*4*); the amount of thyroid hormones reaching the hypothalamus in turn controls the secretion of TSH, completing the negative-feedback loop. In the absence of iodine, an essential substrate for thyroid hormones, not enough hormone is produced (*5*) to "turn off" the system; excessive TRF (*6*) and TSH (*7*) are secreted, stimulating the iodine-depleted thyroid tissue to grow (*8*). A normal thyroid follicle, in which hormones are synthesized and stored, consists of an envelope of cells containing a colloid, thyroglobulin (*a*). In the absence of iodine TSH causes the cells to proliferate and become more columnar (*b*) and then to produce more colloid, so that the follicles become distended (*c*), forming a goiter.

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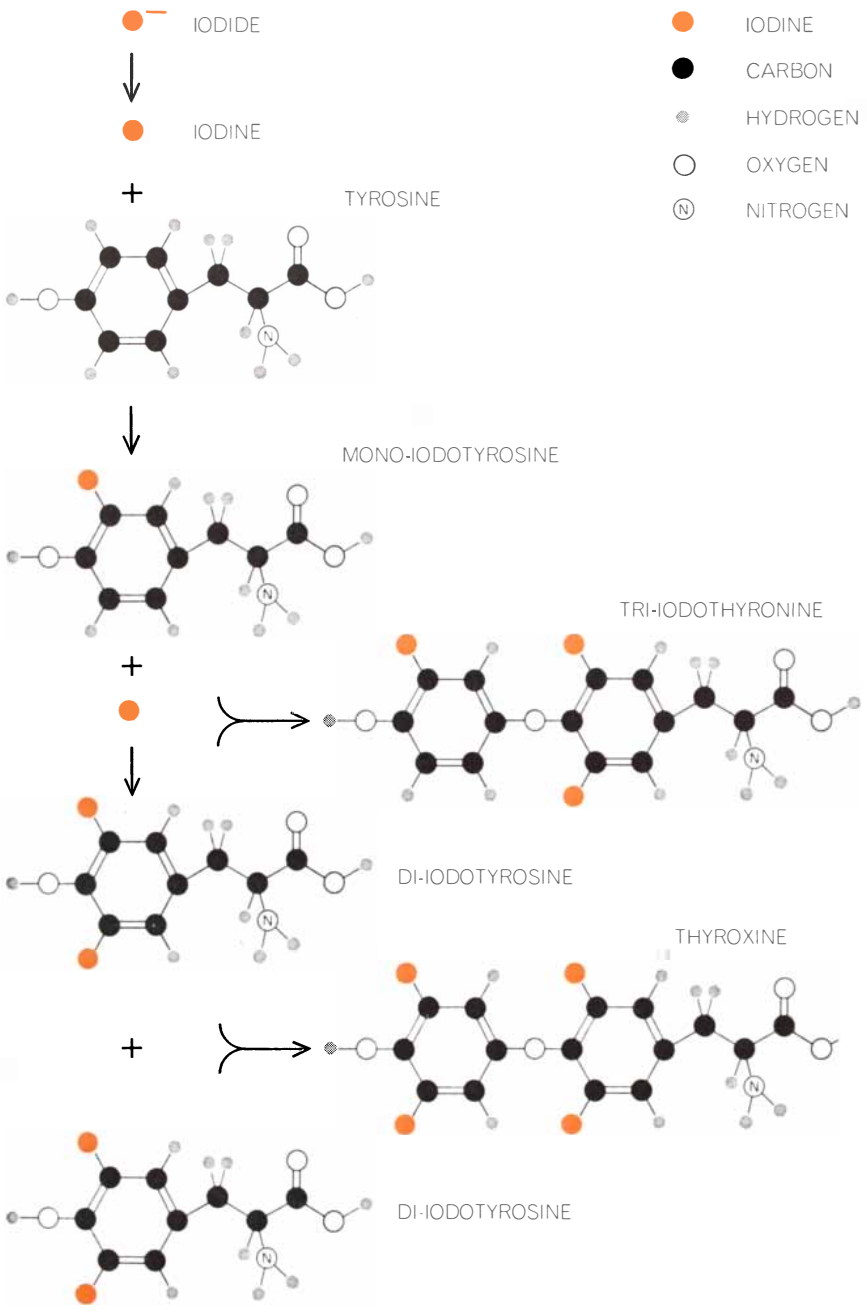
Beginning in 1907 the extensive investigations of David Marine and O. P. Kimball of the Western Reserve University School of Medicine with laboratory animals provided the first direct experimental evidence that endemic thyroid hypertrophy is caused by iodine deficiency. These workers subsequently carried out the first large-scale program of goiter prophylaxis in Akron, Ohio. The study, completed in 1920, involved 4,500 schoolgirls between the fifth and the 12th grade. Half of them received two grams of iodized salt twice a year and the other half served as untreated controls. At the end of two and a half years 65.4 percent of the treated group showed regression of goiter and only five treated girls evinced thyroid enlargement. Meanwhile only 13.8 percent of the girls in the untreated group showed a regression of goiter and 495 untreated girls had developed thyroid hypertrophy. The study was a dramatic demonstration of the efficacy of iodine in the treatment and the prevention of simple goiter.

When these findings were published, many individuals and groups of health enthusiasts took to consuming iodine to the extent of a fetishism. Some people even hung around their neck little bottles of iodine from which they would occasionally take a swig. Iodine became the magic ingredient in the nostrums of certain charlatans. To everyone's surprise, rather than preventing goiter, iodine sometimes served to stimulate it. This apparently paradoxical effect of iodine on the etiology of goiter was later explained by Jan Wolff and Israel L. Chaikoff of the School of Medicine of the University of California at Berkeley, who found that very high iodine concentrations in the blood plasma inhibit the biosynthesis and secretion of thyroid hormone. This aspect of thyroid physiology, together with increasing reports of severe iodine toxicity and the fear that iodine might lead to toxic hyperthyroidism, elicited strenuous opposition to the iodization of table salt by many medical experts, lay people and politicians. The political and ethical controversy over the incorporation of iodine into table salt was even more intense than the present-day controversy over the fluoridation of water. It was not until the mid-1920's that iodine prophylaxis was generally accepted.



BIOSYNTHESIS of the thyroid hormones depends on the presence of ionic iodine, primarily as sodium iodide. The iodide is oxidized to elemental iodine and combines with the amino acid tyrosine to form mono-iodotyrosine and di-iodotyrosine. Two molecules of di-iodotyrosine may combine to form thyroxine, or mono- and di-iodotyrosine molecules may combine to form tri-iodothyronine. (Only hormone products are shown, not by-products.)

Although the idea that some positive agent in food or drink was responsible for goiter had antedated the discovery of iodine deficiency as a cause, it was not until 1941 that a goitrogenic substance was identified. Curt P. Richter and Kathryn H. Clisby of the Johns Hopkins University School of Medicine were investigating the effects of certain rat poisons. When they fed laboratory rats the drug thiourea, they observed to their surprise that the rats survived but their thyroid began growing and soon became goitrous. At about the same time Julia B. and Cosmo G. MacKenzie, in another laboratory at Johns Hopkins, were studying the effect of a new sulfonamide drug on the bacterial flora of the rat intestine. They observed the same phenomenon: the thyroid of their treated rats became hypertrophic, as if the animals had been maintained for several weeks on an iodine-deficient diet. The drugs were apparently preventing the proper utilization of iodine, which was present in normal concentrations in the animals' food and water. Since that time many additional antithyroid compounds have been discovered.

Theoretically these drugs could act by any of three different mechanisms. First, they could operate at the intestinal level

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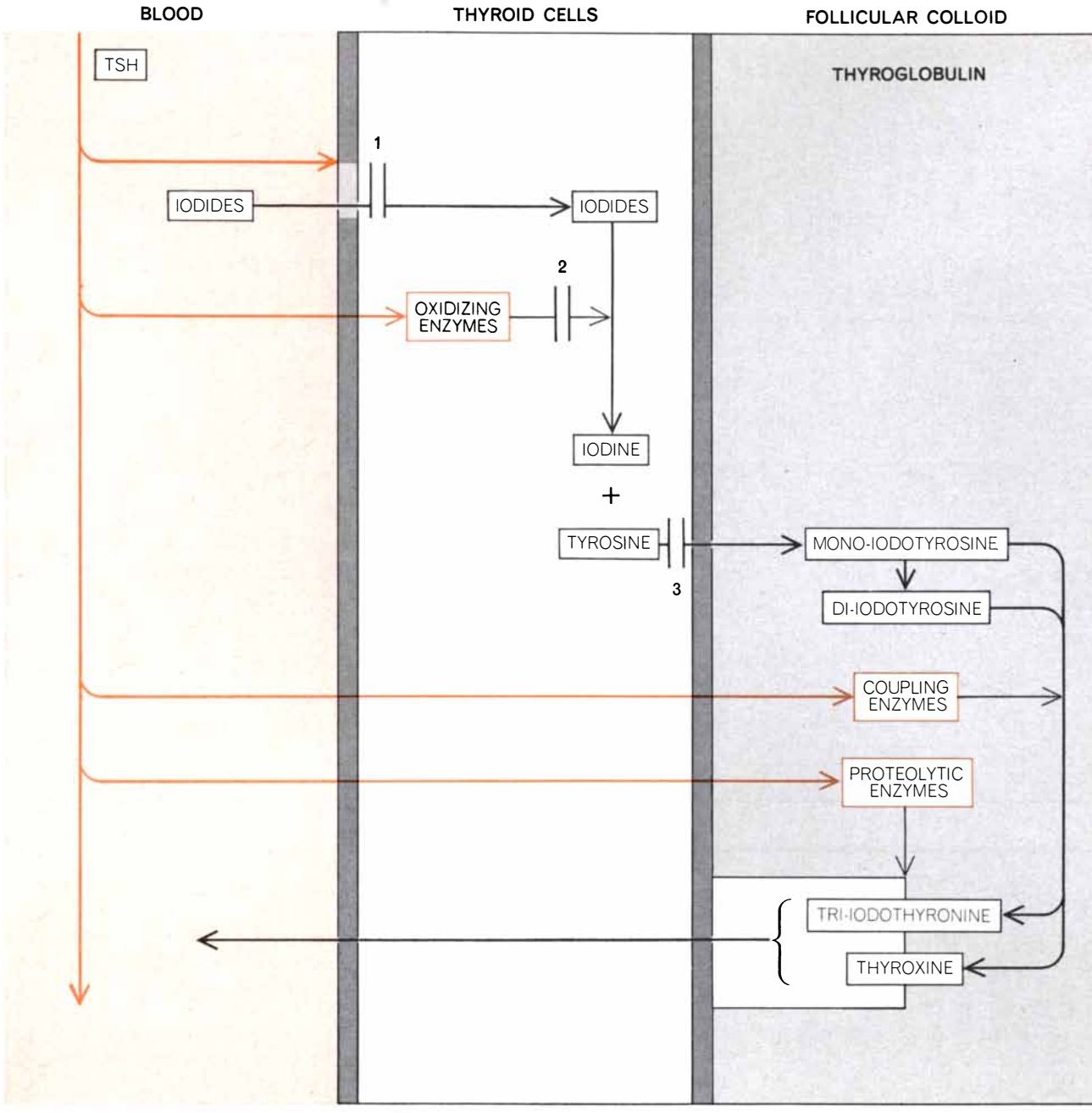
to chelate, or sequester, iodine and so prevent its normal absorption into the bloodstream. Second, they could act at the surface of the thyroid epithelial cell to inhibit the selective absorption of iodine from the blood passing through the gland. (This trapping of iodine ions is an amazingly efficient process: the thyroid concentrates the ions to a level several hundred times higher than their concentration in the plasma.) Third, the goitrogenic compounds could gain admission to the cells of the thyroid and there inhibit the biosynthetic pathway at any of several crucial steps or prevent the release of thyroxine from its storage form in the follicles. It appears that the last two mechanisms are the significant ones. Thiocyanate and perchlorate inhibit the active transport processes of the iodide trap, thiouracil blocks the oxidation of iodide to iodine by certain peroxidase enzymes, and sulfonamides interfere with the incorporation of tyrosine [*see illustration below*].

Soon after the discovery of these goitrogenic compounds it was found that goiter endemic to some areas was a result of similar, naturally occurring compounds in local foods. Soybeans and members of the genus *Brassica*, which includes Brussels sprouts, cabbages, turnips and other vegetables, are among the foodstuffs containing significant amounts of goitrogenic compounds. In a nutritionally varied diet such foods do no harm, but they are a more serious matter in societies that survive on less varied diets.



THYROID ACTIVITY is diagrammed schematically. Iodide trapped by thyroid-follicle cells is converted by oxidizing enzymes in the cells into iodine, which combines with tyrosine to form the thyroid hormones. The hormones are stored attached to thyroglobulin; on demand they are freed by proteolytic enzymes and pass into the blood. TSH stimulates hormone production by acting to abet iodide-trapping and the activity of three sets of enzymes. Goitrogenic substances interfere with hormone production. Thiocyanates and perchlorates block the iodide trap (*1*), thiouracil the oxidizing enzymes (*2*), sulfonamides the combination with tyrosine (*3*).

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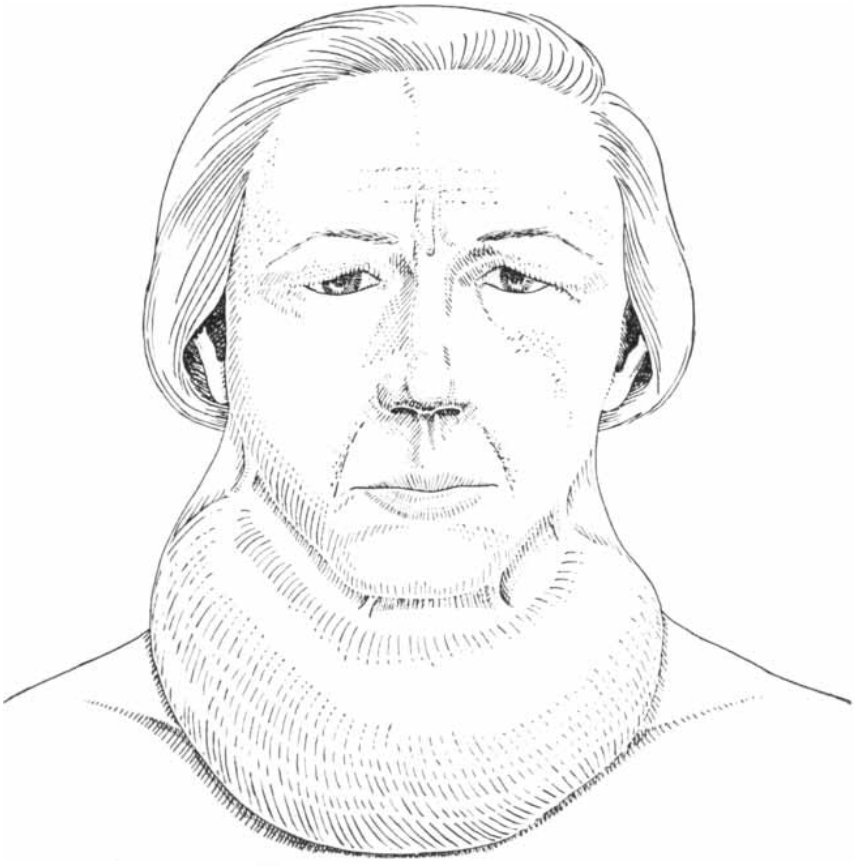
The effect of the *Brassica* goitrogen was demonstrated not long ago in Tasmania, off the coast of southern Australia. The island was an area of endemic goiter, and so in 1949 a program was instituted to supply iodine-containing tablets to schoolchildren up to 16 years old. Five years later a survey revealed that the incidence of goiter in these children had not decreased; indeed, it had increased. The investigators verified their data and reevaluated their methods, and still they found that goiter had increased. F. W. A. Clements and J. W. Wishart, who had been instrumental in setting up the program, thereupon proposed that something other than iodine deficiency might be promoting goiter in these schoolchildren. As it happened, in 1950 the Australian government had begun a free-milk program in the schools. The increased demand for milk forced local dairies to keep their cows at pasture during seasons when grass was not available. As a consequence the cows were eating marrow-stem kale, which is more frost-resistant than grass and grows well all year. Marrow-stem kale is a member of the genus *Brassica* and contains a large amount of the goitrogenic compound. Further study revealed that this compound, present unaltered in the milk, was blocking utilization of the iodine being supplied in the tablets.

Clearly there are dangers inherent in administering to patients drug preparations that contain significant amounts of potentially goitrogenic compounds or elemental iodine. Although it is not common in this country, iatrogenic goiter—goiter caused by medical treatment—is becoming a more significant factor. Sulfonamides prescribed for urinary-tract infections, thiouracil drugs given routinely for the relief of hyperthyroidism and many iodine-containing compounds administered as expectorants in the treatment of asthma are potentially goitrogenic. The unborn infants of pregnant mothers who take these drugs have in some instances been killed *in utero* by goiters that develop when the drugs diffuse across the placenta and enter the fetal circulation. Because these drugs are concentrated in the lactating breast they may also induce goiter in a nursing infant. The most serious effect of these drugs in pregnancy is that they decrease the availability of maternal thyroxine to the early fetus, and thyroxine is of fundamental importance in the physical and mental development of the baby.

Several epidemiological surveys have indicated that goiter can arise spontaneously in a society, persist for a short time and then regress, all without any apparent change in the food or living habits of the people. The possibility of an infectious origin of goiter has been proposed to explain such epidemics, but no instance of this has been proved. It does seem possible that a strain of iodine-trapping bacteria could become resident among the normal flora of the intestine and decrease the availability of dietary iodine for absorption.



LARGE GOITER is seen frequently in regions where iodine-deficiency goiter is endemic. The drawing is based on a photograph made in the Alps near Innsbruck in Austria. Goiters have been reported that weighed four or five pounds, sometimes hanging below the chest.

There is at least one documented case of goiter related to bacteria, although in a different way. While studying goitrous populations in the Himalayas in 1906, Robert McCarrison visited several neighboring villages in the valley of the Gilgit River. He was immediately impressed by the fact that whereas the village that was farthest upstream showed a low incidence of goiter (12 percent), as he moved downstream the incidence increased in each village, until in the lowest village more than 45 percent of the population had goiter. An isolated village that was near the river but whose residents did not drink river water did not have goiter. McCarrison undertook a controlled experiment with 30 volunteers divided into two groups. One group drank the muddy river water after boiling it and the other (including McCarrison himself) drank unboiled river water. Within a month most of the people in McCarrison's group began to develop goiter; those in the other group did not. He concluded from the experiment that bacteria were to blame for the goiter. Poor sanitation meant that the waste material from the villages went into the river, which became more contaminated as it flowed past each village, increasing the dose of bacteria in the drinking water of villagers in proportion to their distance downriver. It has since been shown that some strains of *Escherichia coli,* a bacterium normally found in fecal material, can produce thiouracil.

There is a vicious circle aspect to endemic goiter. Poor societies with an unvaried diet are likely to be the most susceptible to goiter and the most vulnerable to its biological, social and economic consequences. Where iodine-deficiency goiter is endemic in a human population domestic animals will probably be hypothyroid too. Goitrous sheep often produce less wool; goiter in cattle causes sterility, poor milk production and sickly calves; horses do less work;

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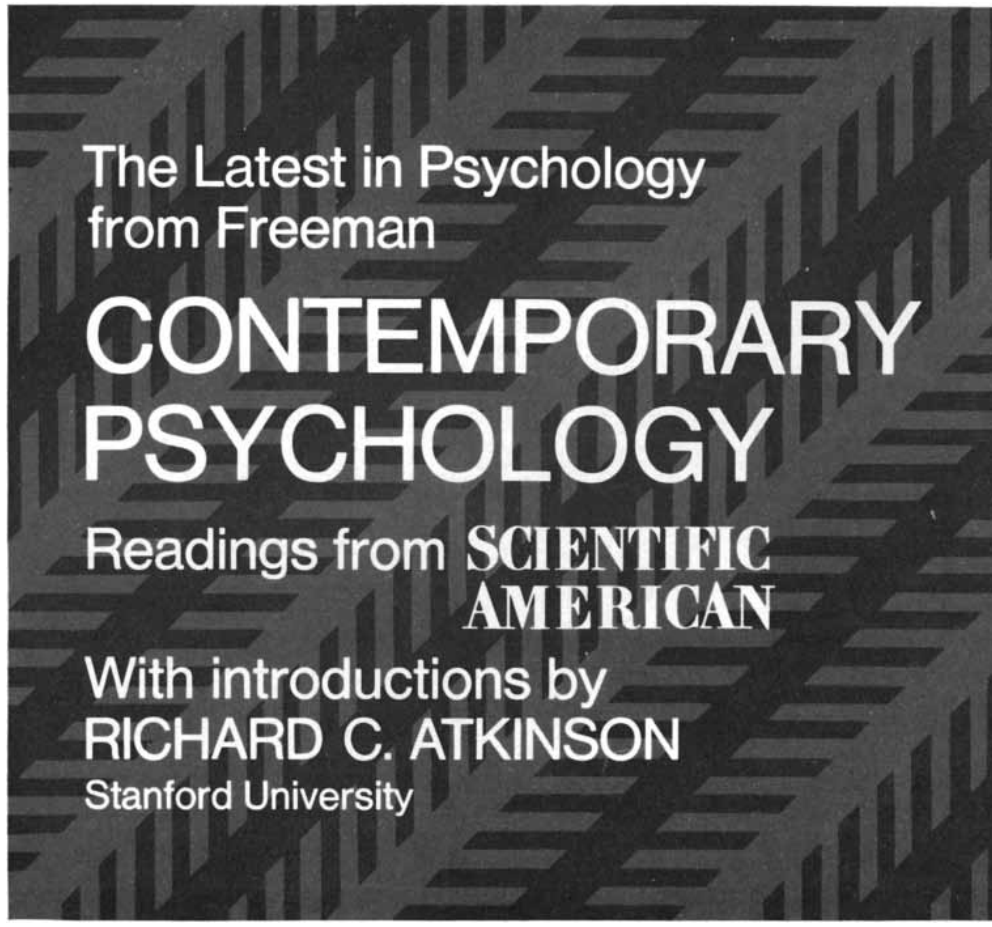

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hens with decreased thyroid activity produce eggs with insufficient calcium in the shell, leading to egg breakage and higher chick mortality. A poor society can scarcely afford to have these serious handicaps afflict the animals on which its survival may depend.

Long-standing endemic goiter has had particularly serious consequences in some remote communities, such as alpine valleys, where inbred populations have persisted for many generations in an iodine-deficient environment. Familial goitrous hypothyroidism can lead to a high incidence of individuals with the severe developmental defects of cretinism. Cretins manifest varying degrees of idiocy and are also physically dwarfed and often malformed. The mental retardation is believed to result from a deficiency of thyroxine during the first three months of pregnancy, when it must be supplied by the mother; the physical anomalies are probably due to a deficiency of the baby's own thyroxine during maturation.

The role of mountainous topography and isolation in cretinism is evident. There are many goitrous regions that do not show a high incidence of cretinism; the "goiter belt" in the Great Lakes region is an example. Presumably population mobility through this channel of westward migration supplied enough biological and social diversity so that cretinism did not develop.

The cretin is only the most extreme example of the consequences of decreased availability of thyroxine during the developmental stages of life. Because all the residents of a community affected by endemic goiter are potentially exposed to a suboptimal supply of thyroxine during their development, there may be serious but subtle effects on the quality of the society at large. Motivation, spontaneity, creativity and native intelligence may be diminished, and the resulting social stagnation may lead to further inbreeding.

Medical science and public health will eventually eliminate iodine-deficiency goiter as an endemic affliction. One must hope that this age-old and benign disorder will not be replaced by a different, nuclear-era thyroid dysfunction resulting from the ingestion of large amounts of radioactive iodine isotopes from nuclear fallout. The iodine is concentrated in the thyroid gland, where the radioactivity may damage cells irreversibly. The study of endemic goiter demonstrates the seriousness of this potential hazard and the effects it might have on the course of human evolution.

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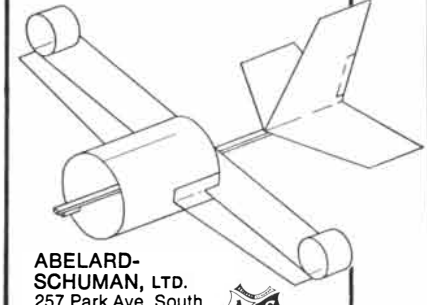

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AN EARLY CITY IN IRAN

Tepe Yahyā, midway between Mesopotamia and India, was a busy center of trade 5,500 years ago. An outpost of Mesopotamian urban culture, it played a key role in the spread of civilization from west to east

by C. C. and Martha Lamberg-Karlovsky

The kingdom of Elam and its somewhat better-known neighbor, Sumer, were the two earliest urban states to arise in the Mesopotamian area during the fourth millennium B.C. Archaeological findings now show that the Elamite realm also included territory at least 500 miles to the east. For more than 10 centuries, starting about 3400 B.C., the hill country of southeastern Iran some 60 miles from the Arabian Sea was the site of a second center of Elamite urban culture.

Today all that is left of the city that stood halfway between the Euphrates and the Indus is a great mound of earth located some 4,500 feet above sea level in the Soghun Valley, 150 miles south of the city of Kerman in the province of the same name. Known locally as Tepe Yahyā, the mound is 60 feet high and 600 feet in diameter. Its record of occupation begins with a 6,500-year-old Neolithic village and ends with a citadel of the Sassanian dynasty that ruled Persia early in the Christian Era. Intermediate levels in the mound testify to the connections between this eastern Elamite city and the traditional centers of the kingdom in the west.

Such a long archaeological sequence has much value for the study of man's cultural development from farmer to city dweller, but three unexpected elements make Tepe Yahyā a site of even greater significance. First, writing tablets made of clay, recovered from one of the lower levels in the mound, have been shown by carbon-14 analysis of associated organic material to date back to 3560 B.C. (±110 years). The tablets are inscribed with writing of the kind known as proto-Elamite. Proto-Elamite inscriptions and early Sumerian ones are the earliest known Mesopotamian writings, which are the oldest known anywhere. The Tepe Yahyā tablets are unique in that they are the first of their kind that can be assigned an absolute date. It comes as a surprise to find these examples of writing—as early as the earliest known—in a place that is so far away from Mesopotamia.

The second surprise is evidence that Elamite trade with neighboring Sumer in an unusual commodity—steatite, the easily worked rock also known as soapstone—formed a major part of the commerce at Tepe Yahyā. Unlike Sumer, which was surrounded by the featureless floodplains of lower Mesopotamia, Elam was a hill kingdom rich in natural resources. Elamite trade supplied the Sumerians with silver, copper, tin and lead, with precious gems and horses, and with commoner materials such as timber, obsidian, alabaster, diorite and soapstone. To find that the soapstone trade reached as far east as Tepe Yahyā adds a new dimension to our knowledge of fourth-millennium commerce.

Third, the discovery of Tepe Yahyā has greatly enlarged the known extent of ancient Elam, which was hazily perceived at best. Susa, the most famous Elamite city, lies not far from such famous Sumerian centers as Ur and Eridu. As for other Elamite cities named in inscriptions (Awan, for example, or Madaktu), their location remains a mystery. To discover a prosperous Elamite city as far east of Mesopotamia as Tepe Yahyā is both a surprise and something of a revelation. It suggests how urban civilization, which arose in lower Mesopotamia, made its way east to the valley of the Indus (in what is now West Pakistan).

The British explorer-archaeologist Sir Aurel Stein was the first to recognize that southeastern Iran is a region with important prehistoric remains. Two sites that Stein probed briefly in the 1930's—Tal-i-Iblis near Kerman and Bampur in Persian Baluchistan—have recently been excavated, the first by Joseph R. Caldwell of the University of Georgia and the second by Beatrice de Cardi of the Council for British Archaeology. Although it is the largest mound in southeastern Iran, Tepe Yahyā remained unknown until the summer of 1967, when our reconnaissance group from the Peabody Museum at Harvard University discovered it during an archaeological survey of the region.

We have now completed three seasons of excavation at Tepe Yahyā in coopera-

LARGE EARTH MOUND, over a third of a mile in circumference, was raised to a

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tion with the Iran Archaeological Service and have established a sequence of six principal occupation periods. The site was inhabited almost continuously from the middle of the fifth millennium B.C. until about A.D. 400. Following the end of the Elamite period at Tepe Yahyā, about 2200 B.C., there is a 1,000-year gap in the record that is still unexplained but finds parallels at major sites elsewhere in Iran. Tepe Yahyā remained uninhabited until 1000 B.C., when the site was resettled by people of an Iron Age culture.

Our main work at Tepe Yahyā began in the summer of 1968 with the digging of a series of excavations, each 30 feet square, from the top of the mound to the bottom [*see illustration below*]. Small test trenches were then made within the series of level squares. During our second and third season the excavations were extended by means of further horizontal exposures on the top of the mound and to the west of the main explorations. In addition we opened a stepped trench 12 feet wide on the opposite face of the mound as a check on the sequences we had already exposed.

The earliest remains of human occupation at Tepe Yahyā, which rest on virgin soil in a number of places, consist of five superimposed levels of mud-brick construction. We have assigned them to a single cultural interval—Period VI—that is shown by carbon-14 analysis to lie in the middle of the fifth millennium B.C. The structures of Period VI seem to be a series of square storage areas that measure about five feet on a side. Most of them have no doorways; they were probably entered through a hole in the roof. The walls are built either of sun-dried mud bricks that were formed by hand or of hand-daubed mud [*see top illustration on page 107*]. Fragments of reed matting and timber found on the floors of the rooms are traces of fallen roofs.

The tools of Period VI include implements made of bone and flint. Many of the flints are very small; they include little blades that were set in a bone handle to make a sickle. The most common kind of pottery is a coarse, hand-shaped ware; the clay was "tempered" by the addition of chaff. The pots are made in the form of bowls and large storage jars and are decorated with a red wash or painted with red meanders. Toward the end of Period VI a few pieces of finer pottery appear: a buff ware with a smooth, slip-finished surface and a red ware with decorations painted in black.

Human burials, all of infants, were found under the floor in a few of the structures. The limbs of the bodies had been tightly gathered to the trunk before burial, and accompanying the bodies are unbroken coarse-ware bowls. In one room a small human figurine was found face down on the floor, resting on a collection of flint and bone tools. The sculpture is 11 inches long and was carved out of dark green soapstone [*see illustration on next page*]. The carving clearly delineates a female figure. Its elongated form and the presence of a hole at the top of the head, however, suggest a dual symbol that combines male and female characteristics.

The Neolithic culture of Period VI evidently included the practice of agriculture and animal husbandry. Identifiable animal bones include those of wild gazelles and of cattle, sheep and goats. Camel bones are also present, but it is not clear whether or not they indicate that the animal had been domesticated at this early date. The domesticated plants include a variety of cereal grains. In the Tepe Yahyā area today raising crops involves irrigation; whether or not this was the case in Neolithic times is also unclear. At any rate the Neolithic occupation of the mound continued until about 3800 B.C.

The transition from Period VI to the Early Bronze Age culture that followed

height of 60 feet over a 5,000-year period as new settlements were built on the rubble of earlier ones. Located in southeastern Iran and known locally as Tepe Yahyā, the site was first occupied by a Neolithic community in the middle of the fifth millennium B.C.

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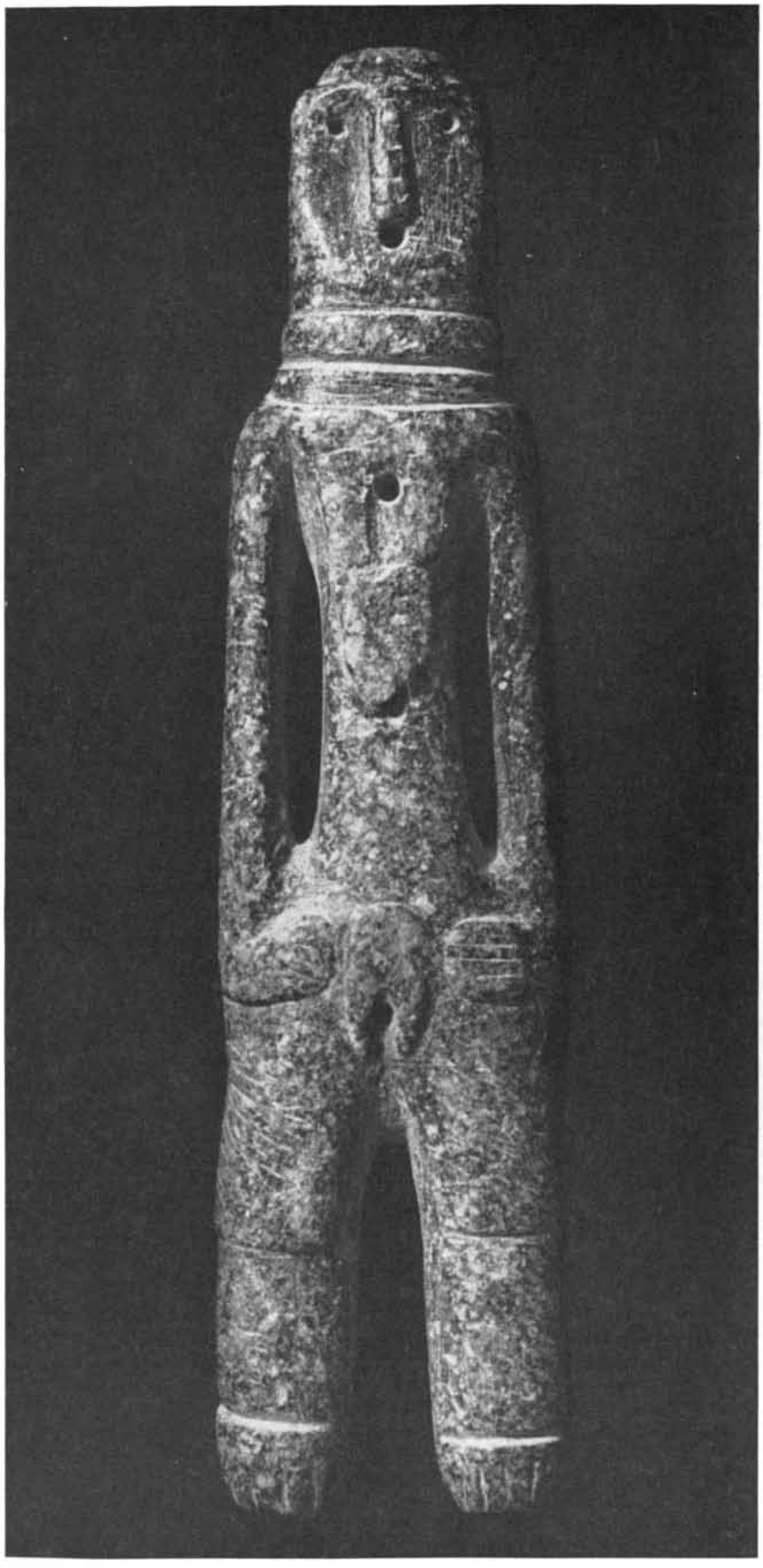

NEOLITHIC FIGURINE was found in one of the storerooms in the earliest structure at Tepe Yahyā, associated with tools made of flint and bone. The sculpture was apparently intended to be a dual representation: a female figure imposed on a stylized phallic shape.

occurred without any break in continuity. The structures of Period V contain coarse-ware pottery of the earlier type. The finer, painted pottery becomes commoner and includes some new varieties. One of these, with a surface finish of red slip, has a decorative geometric pattern of repeated chevrons painted in black. We have named this distinctive black-on-red pottery Yahyā ware, and we call the material culture of Period V the Yahyā culture.

The commonest examples of Yahyā ware are beakers. These frequently have a potter's mark on the base, and we have so far identified nine individual marks. Evidence that outside contact and trade formed part of the fabric of Early Bronze Age life at Tepe Yahyā comes from the discovery at Tal-i-Iblis, a site nearly 100 miles closer to Kerman, of almost identical painted pottery bearing similar potter's marks. There is other evidence of regional contacts. Yahyā ware shows a general similarity to the painted pottery at sites elsewhere in southeastern Iran, and a black-on-buff ware at Tepe Yahyā closely resembles pottery from sites well to the west, such as Bakun. Moreover, the Period V levels at Tepe Yahyā abound in imported materials. There are tools made of obsidian, beads made of ivory, carnelian and turquoise, and various objects made of alabaster, marble and mother-of-pearl. One particularly handsome figure is a stylized representation of a ram, seven inches long, carved out of alabaster [*see top illustration on page 110*]. No local sources are known for any of these materials.

Although the architecture of Period V demonstrates a continuity with the preceding Neolithic period, the individual structures are larger than before. Several of them measure eight by 11½ feet in area and are clearly residential in character. Some rooms include a hearth and chimney. In the early levels the walls are still built of hand-formed mud bricks. Bricks formed in molds appear in the middle of Period V, which carbon-14 analyses show to have been around 3660 B.C. (±140 years).

The bronze implements of Period V, like much of the earliest bronze in the world, were produced not by alloying but by utilizing copper ores that contained "impurities." This was the case in early Sumer, where the ore, imported from Oman on the Arabian peninsula, contained a high natural percentage of nickel. Early bronzesmiths elsewhere smelted copper ores that were naturally rich in arsenic. Chisels, awls, pins and spatulas at Tepe Yahyā are made of such an arsenical bronze.

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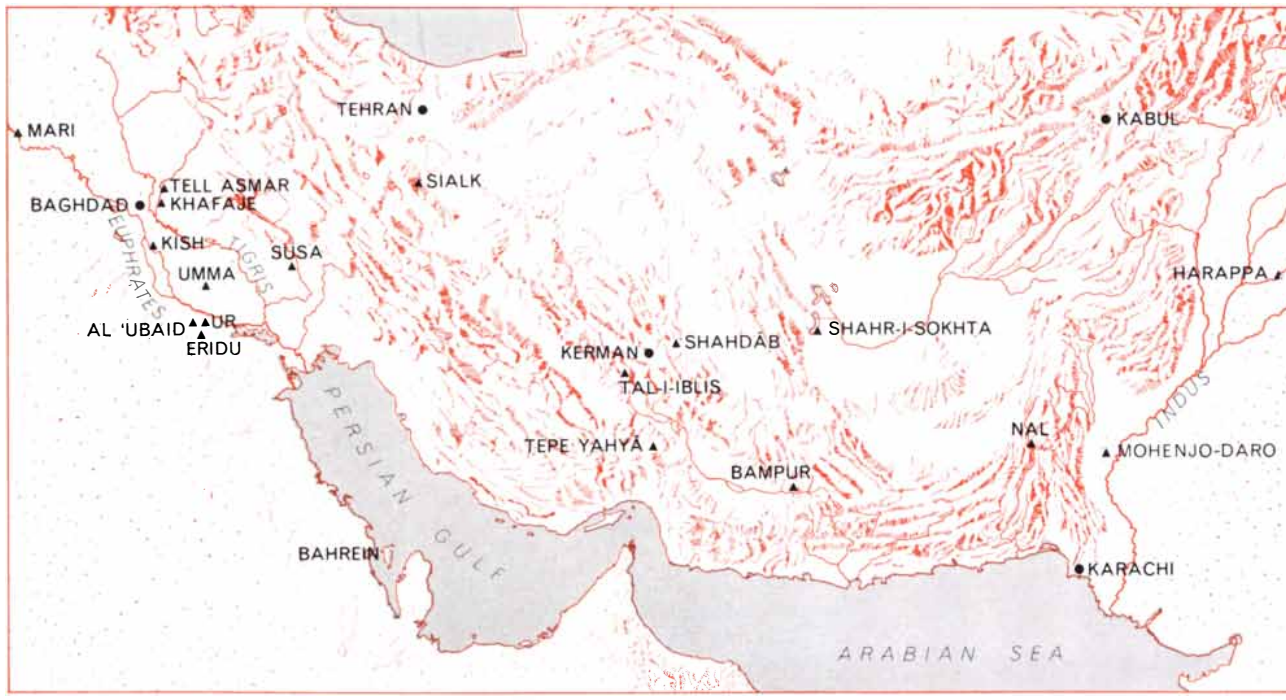

FIRST CITIES arose in the kingdom of Sumer in lower Mesopotamia (*left*). The earliest known forms of writing appeared in Sumer and in nearby Elam at cities such as Susa and Sialk. The discovery of proto-Elamite writing at Tepe Yahyā (*center*), which is 500 miles to the east, suggests that trade between the region and the early cities of Mesopotamia led to the rise of cities in this part of ancient Persia in the fourth millennium B.C. and to the later development of the urban Harappan civilization in the Indus region.

Six artifacts from the site have been analyzed by R. F. Tylecote and H. McKerrell of the University of Newcastle upon Tyne. They found that the bronze had been produced by smelting, which shows that the metalworkers of Period V were able to obtain the high temperatures needed to smelt copper ores into molten metal. The final shapes were not made by casting, however, but by hot and cold forging, a more primitive technique. One of the articles, a chisel, proved to contain 3.7 percent arsenic, which leads us to believe that the metalworkers consciously selected for smelting ores with a high arsenic content. This finding is further testimony in support of trade at Tepe Yahyā; none of the copper deposits native to the region could have been used to make arsenical bronze.

With the beginning of Period IV, around 3500 B.C., the appearance of writing at Tepe Yahyā allows the city to be identified as a proto-Elamite settlement. Much of the pottery representative of the first two phases of this period, IV-C and IV-B, is typical of the preceding Yahyā culture in both shape and decoration. Although there is plentiful evidence of external contact, the transition to Period IV at Tepe Yahyā, like the one that preceded it, occurred without any break in continuity. There is no need at Tepe Yahyā to conjure up that hackneyed instrument of cultural change: a new people arriving with luggage labeled "Proto-Elamite."

Architecture, however, was considerably transformed. The site ceased to be a residential area and became an administrative one. A large structure we have unearthed at the IV-C level of the mound is carefully oriented so that its walls run north-south and east-west. The walls consist of three courses of mold-formed brick in a new size. The earlier mold-formed bricks had been six by six by 12 inches; the new ones were 9½ by 9½ by 4¾ inches—a third wider and less than half as thick. So far we have identified five of an undetermined number of rooms within the large structure, although we have fully cleared only part of one room. Both the structure and the partially excavated room continue toward the center of the mound; the size of each remains to be determined.

The part of the room that has been cleared measures about 10 by 20 feet. Its contents strongly suggest a commercial function. Among the objects in the room are bowls with beveled rims made of a coarse ware. The vessels have counterparts at numerous sites in Mesopotamia. They are believed to have served as standard measures. Three large storage jars, which proved to be empty, were also found in the room; near them were some 24 "sealings": jar stoppers made of clay and marked with a seal impression. The seals used to mark the sealings were cylindrical; the designs resemble those on cylinder seals found at Susa, the Elamite capital in the Mesopotamian area. The finding creates the possibility that goods from Susa were reaching Tepe Yahyā early in Period IV.

Lying on the floor of the room were 84 blank clay tablets and six others that bore inscriptions. The tablets are all the same shape; they are made of unbaked dark brown clay, are convex in profile and measure 1⅛ by two inches. The six inscribed tablets bear a total of 17 lines of proto-Elamite writing. The inscriptions were impressed in the soft clay with a stylus; they read from right to left along the main axis of the tablet and from top to bottom. When an inscription continues from one side of a tablet to the other, the writer rotated the tablet on its main axis so that the bottom line of the obverse inscription and the top line of the reverse inscription lie opposite each other.

The Tepe Yahyā inscriptions are being deciphered now. Preliminary examination indicates that they are records or receipts dealing with goods. The fact that inscribed and otherwise identical blank tablets were found in the same room is strong evidence that the writing was done on the spot. Therefore the goods they describe must have been

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either entering or leaving the administrative area.

Until the discovery at Tepe Yahyā the only other proto-Elamite tablets known were from Susa or from Sialk in northwestern Iran. Susa yielded nearly 1,500 such tablets, Sialk only 19. Proto-Elamite writing has been found recently at Shahdāb, a site north of Kerman that is being excavated by the Iran Archaeological Service. The writing there is not on tablets but consists of brief inscriptions, with a maximum of seven signs, incised on pottery.

A second change in architectural style is evident in the single IV-B structure examined so far. It is a building, nine by 24 feet in area, that is oriented without reference to north-south and east-west. It is built of bricks of a still newer size and shape. They are oblong rather than square, and are either 14 or 17 inches long; the other two dimensions remained the same. The structure is subdivided into two main rooms and a few smaller rooms that contain large storage bins built of unbaked clay. Its walls are only one brick thick, and their inside surfaces are covered with plaster.

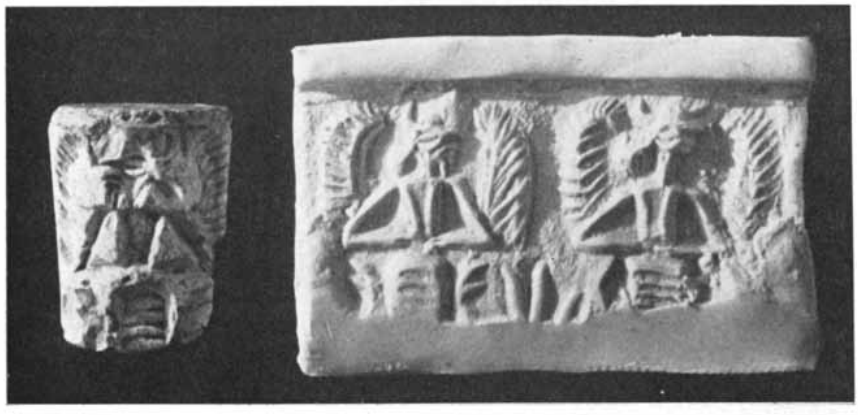
Storage vessels in one of the main rooms still held several pounds of grain. The grain was charred, which together with the fact that the matting on the floor and the bricks in the wall were burned indicates that the building was destroyed by fire. Amid the debris on the floors were cylinder seals and, for the first time at Tepe Yahyā, stamp seals as well.

Some bronze tools of the IV-B period have also been discovered. Needles and chisels, unearthed in association with soapstone artifacts, were probably used to work the soapstone. A bronze dagger some seven inches long was found by Tylecote and McKerrell to have been made by forging smelted metal, as were the bronze tools of Period V. Analysis showed that the dagger, unlike the earlier artifacts of arsenical bronze, was an alloy comprising 3 percent tin. Tin is not found in this part of Iran, which means that either the dagger itself, the tin contained in it or an ingot of tin-alloyed bronze must have been imported to Tepe Yahyā.

The proof that writing was known at Tepe Yahyā as early as it was known anywhere is a discovery of major importance to prehistory. Perhaps next in importance, however, is the abundant evidence suggesting a unique economic role for the city beginning late in the fourth millennium B.C. The IV-B phase at Tepe Yahyā is known from carbon-14 analyses to have extended from near the end of the fourth millennium through the first two centuries of the third millennium. During that time the city was a major supplier of soapstone artifacts.

Objects made of soapstone, ranging from simple beads to ornate bowls and all very much alike in appearance, are found in Bronze Age sites as far apart as Mohenjo-Daro, the famous center of Harappan culture on the Indus, and Mari on the upper Euphrates 1,500 miles away. Mesopotamia, however, was a region poor in natural resources, soapstone included. The Harappans of the Indus also seem to have lacked local supplies of several desired materials. How were the exotic substances to be obtained? Sumerian and Akkadian texts locate the sources of certain luxury imports in terms of place-names that are without meaning today: Dilmun, Maluhha and Magan.

Investigations by Danish workers on the island of Bahrein in the Persian Gulf have essentially confirmed the belief that the island is ancient Dilmun. There is also a degree of agreement that the area or place known as Maluhha lay somewhere in the valley of the Indus. Even before we began our work at Tepe Yahyā it had been suggested that the area known as Magan was somewhere in southeastern Iran. Our excavations have considerably strengthened this hypothesis. A fragmentary Sumerian text reads: "May the land Magan [bring] you mighty copper, the strength of... diorite, 'u-' stone, 'shumash' stone." Could either of the untranslated names of stones stand for soapstone? Were Tepe Yahyā and its hinterland a center of the trade? Let us examine the evidence from the site.



TWO CYLINDER SEALS from the level at Tepe Yahyā overlying the first proto-Elamite settlement appear at left in these photographs next to the impressions they produce. The seal designs, which show pairs of human figures with supernatural attributes, are generally similar to the designs on seals of Mesopotamian origin but appear to be of local workmanship.

More soapstone has been found at Tepe Yahyā than at any other single site in the Middle East. The total is more than 1,000 fragments, unfinished pieces and intact objects; the majority of them belong to Period IV-B. Among the intact pieces are beads, buttons, cylinder seals, figurines and bowls. Unworked blocks of soapstone, vessels that are partially hollowed out and unfinished seals and beads are proof that Tepe Yahyā was a manufacturing site and not merely a transshipment point.

Some of the soapstone bowls are plain, but others are elaborately decorated with carvings. The decorations include geometric and curvilinear designs, animals and human figures. Among the decora-

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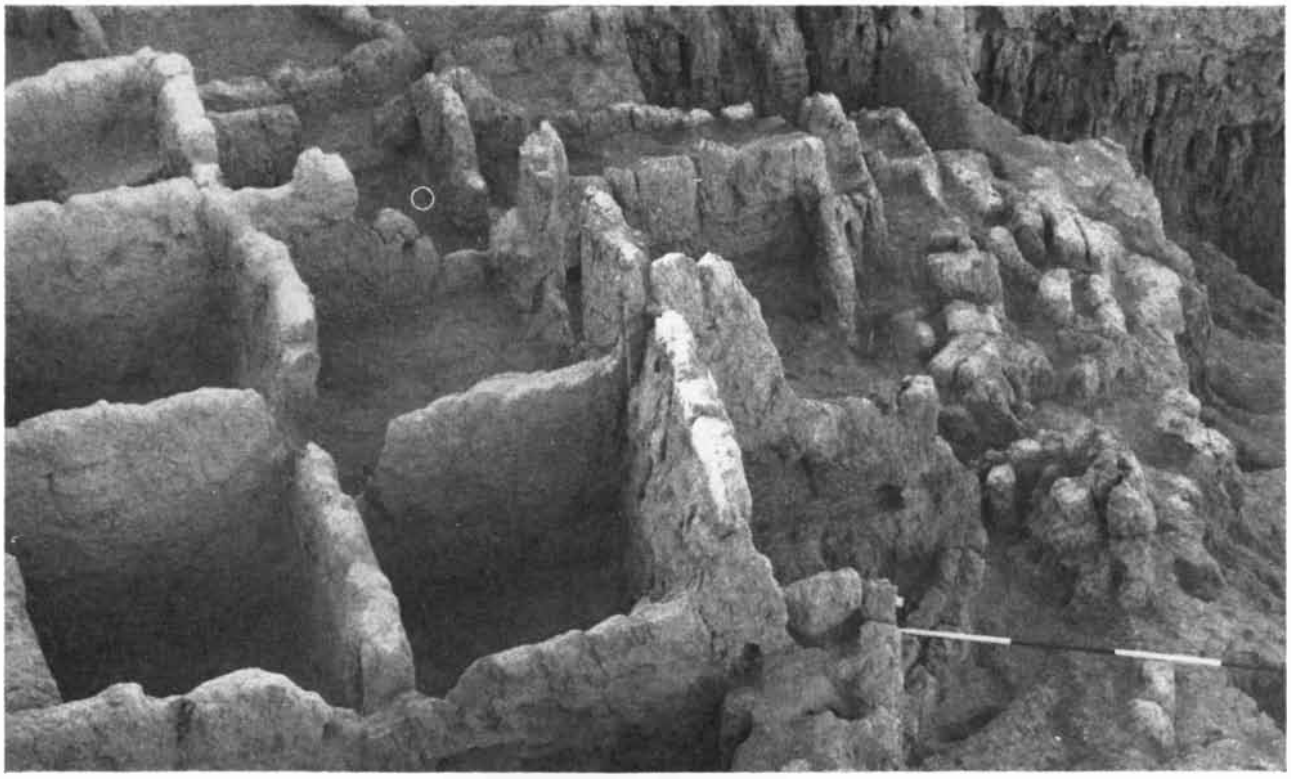
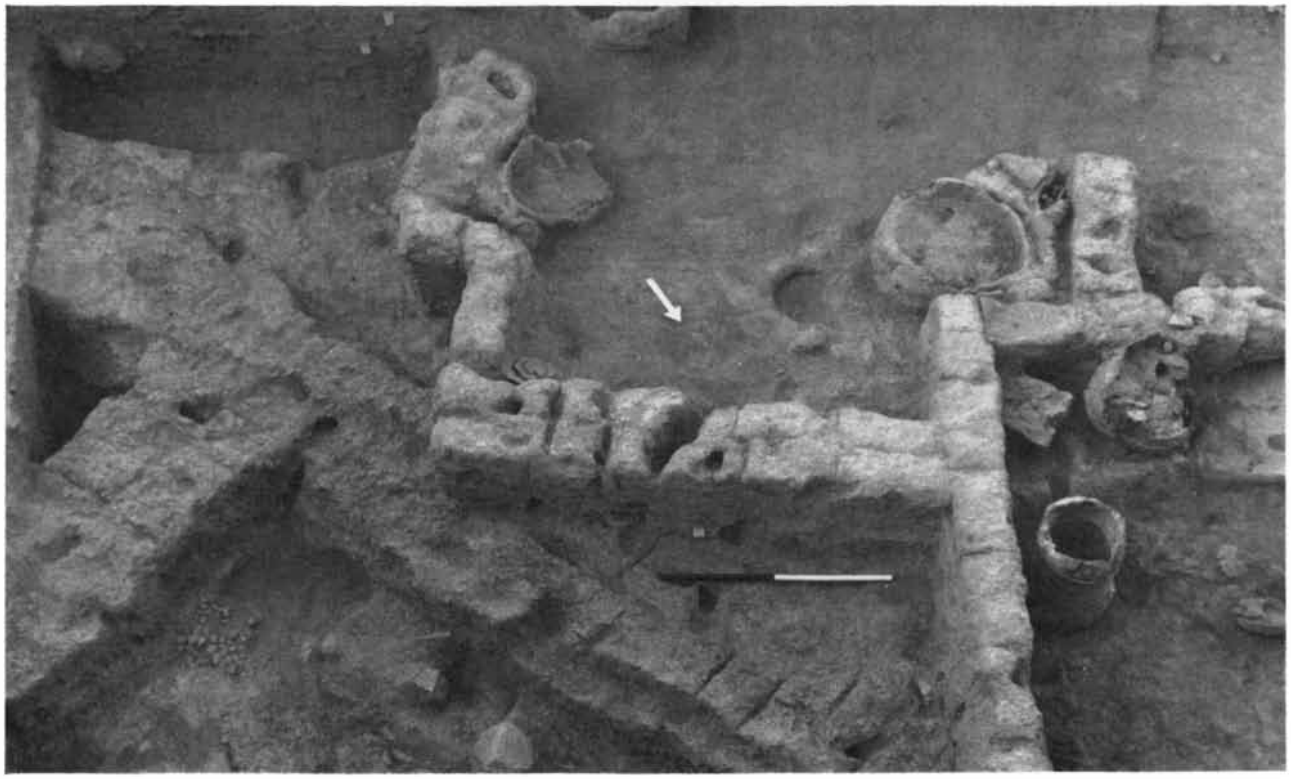


EARLIEST STRUCTURE at Tepe Yahyā is a storage area consisting of small units measuring five feet on a side. Few of the units have doorways; apparently they were entered through a hole in the roof. The walls were built either of sun-dried mud bricks, formed by hand rather than in molds, or simply of hand-daubed mud. White circle (*left*) shows where female figurine was found.



TWO ELAMITE BUILDINGS at Tepe Yahyā left the traces seen in this photograph. The walls of the earlier building (*left*) were built sometime around 3500 B.C. of mold-formed mud bricks 9½ inches on a side. The walls run from north to south and from east to west. The walls of the later structure (*right*) are not oriented in these directions. It was built sometime after 3000 B.C. of oblong mold-formed mud bricks of two lengths. Both structures seem to have been administrative rather than residential. The earlier one contained storage pots and measuring bowls. Near one angle of its walls a pile of 84 unused writing tablets is visible.

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tions are examples of every major motif represented on the numerous soapstone bowls unearthed at Bronze Age sites in Mesopotamia and the Indus valley. Moreover, motifs found on pottery unearthed at sites such as Bampur, to the east of Tepe Yahyā, and Umm-an-Nai on the Persian Gulf are repeated on soapstone bowls from IV-B levels.

During our 1970 season we located what was probably one of the sources of Tepe Yahyā soapstone. An outcrop of the rock in the Ashin Mountains some 20 miles from the mound shows evidence of strip-mining in the past. This is unlikely to have been the only source. Soapstone deposits are often associated with deposits of asbestos and chromite. There is a chromite mine only 10 miles from Tepe Yahyā, and we have noted veins of asbestos in stones unearthed during our excavation of the mound. Reconnaissance in the mountains to the north might locate additional soapstone exposures.

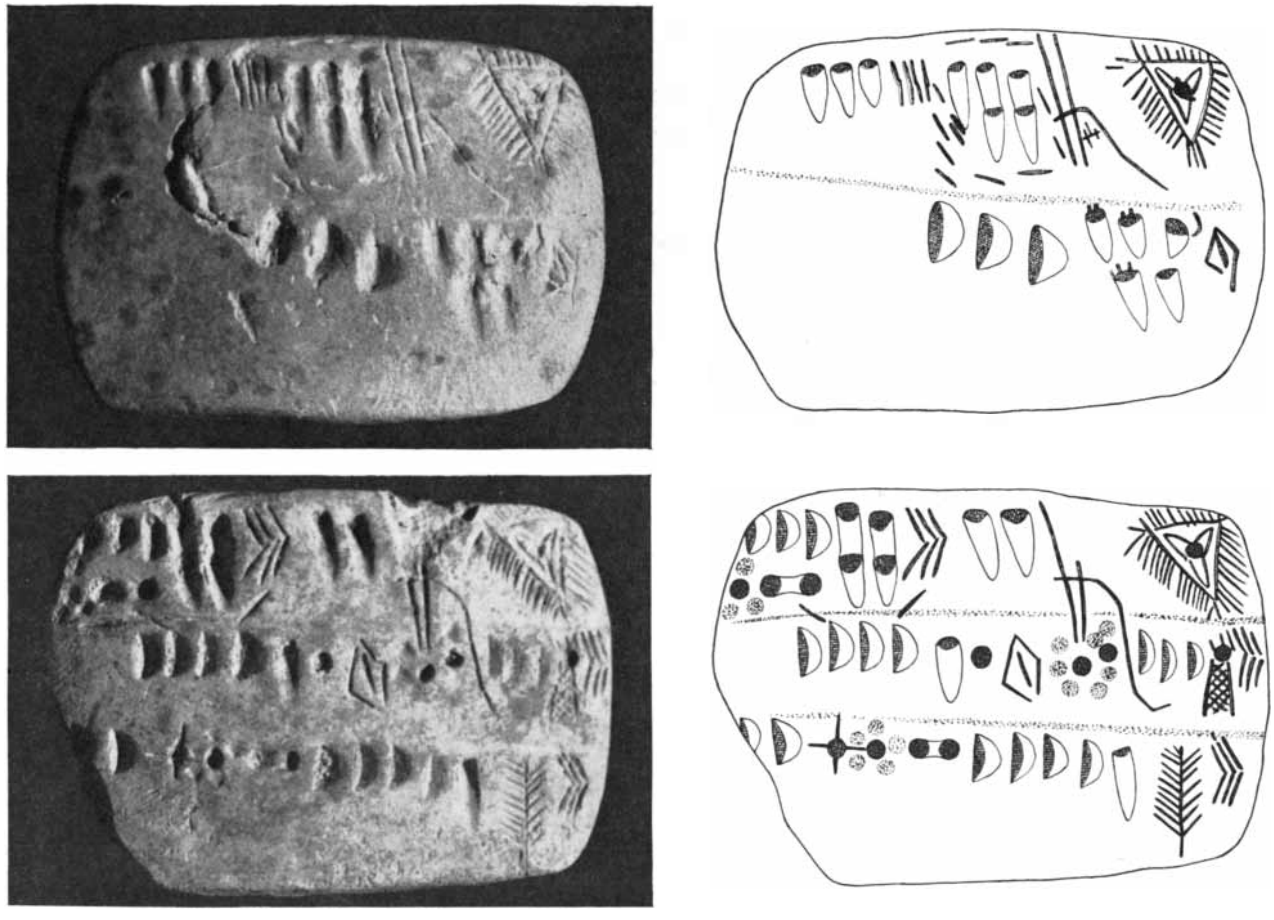
Taking into consideration the large quantities of soapstone found at the site, the evidence that many of the soapstone articles were manufactured locally, the availability of raw material nearby and the presence in both Mesopotamia and Harappan territory of soapstone bowls that repeat motifs found at Tepe Yahyā, it is hard to avoid the conclusion that the city was a major producer of soapstone and a center of trade in the material. Before turning to the broader significance of such commercial activity in this geographically remote area, we shall briefly describe the remaining occupation periods at Tepe Yahyā.

At present there is little to report concerning the final phase of Period IV, which drew to a close about 2200 B.C. It is then that the break occurs in the continuity at Tepe Yahyā. The Iron Age reoccupation of the site, which lasted roughly from 1000 to 500 B.C., comprises Period III. It is evidenced by a series of living floors and by pottery that shows strong parallels to wares and shapes produced during the same period in northwestern Iran. We have not yet uncovered a major structure belonging to Period III; both the nature of the culture and Tepe Yahyā's relations with its Iron Age neighbors remain unclarified.

Period II at Tepe Yahyā, which consists of more than 200 years of Achaemenian occupation, was a time of large-scale construction. The building material remained mud brick, but we have yet to uncover a complete structure. The appearance of the two large rooms excavated thus far suggests, however, that the site had once more become at least partly residential.

A subsequent 600 years or so of Parthian and Sassanian occupation, representing Period I, is the final period of urban civilization at Tepe Yahyā. We have uncovered suggestions of large-scale architecture, including courtyards and part of a massive mud-brick platform made by laying four courses of brick one on the other. By Sassanian times (early in the third century) the accumulated debris of thousands of years had raised the mound to an imposing height; the structure that has been partly exposed probably was a citadel standing on the summit.

Most of the Sassanian pottery consists



INSCRIBED TABLETS from Tepe Yahyā (*photographs*) are shown next to drawings that reproduce the written symbols. Only six inscribed tablets have been found so far. The inscriptions are in proto-Elamite, written from right to left across the length of the tablet by pressing the blunt or sharp end of a stylus into the soft clay. Similar written tablets have been unearthed at Susa and Sialk.

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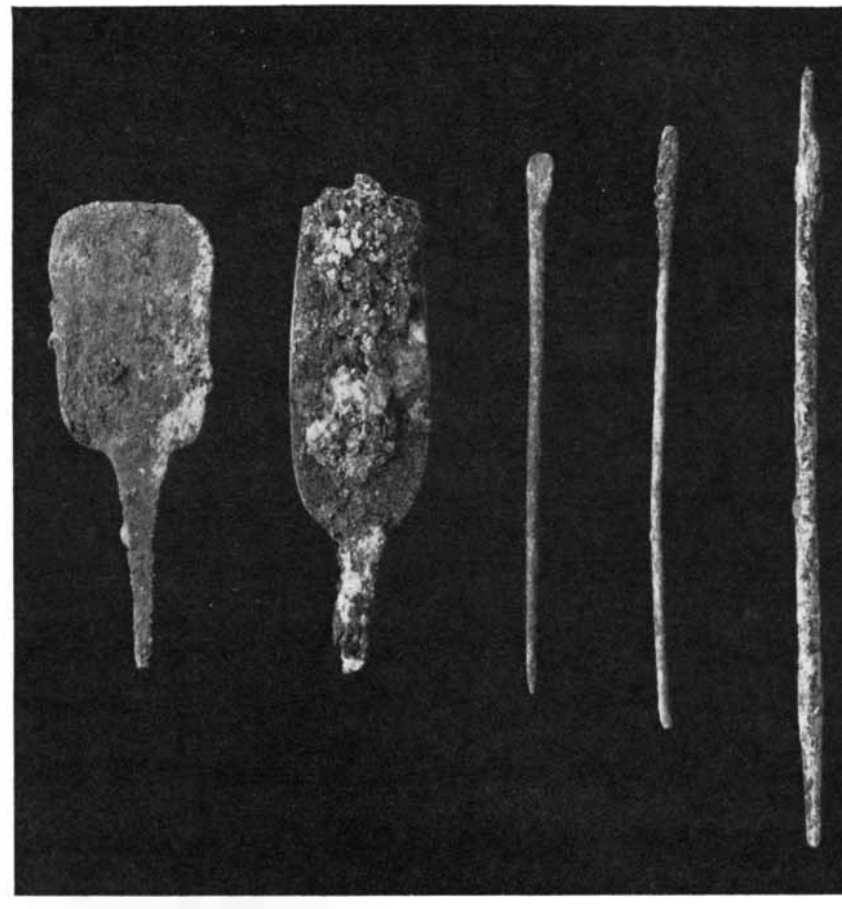
of coarse, thick-walled storage jars. An abundance of beads and several small glass and pottery bottles, perhaps containers for perfume, suggest a degree of prosperity during Period I. The presence of iron and bronze swords, axes and arrowheads adds a military flavor. A single work of art, a small clay figurine, represents a warrior with a distinctive headdress [*see bottom illustration on next page*]. Thereafter, from sometime in the fifth century on, Tepe Yahyā was occupied only by occasional squatters or transient nomads. The few scattered surface finds are of early Islamic age; none of the visitors lingered or built anything of substance.

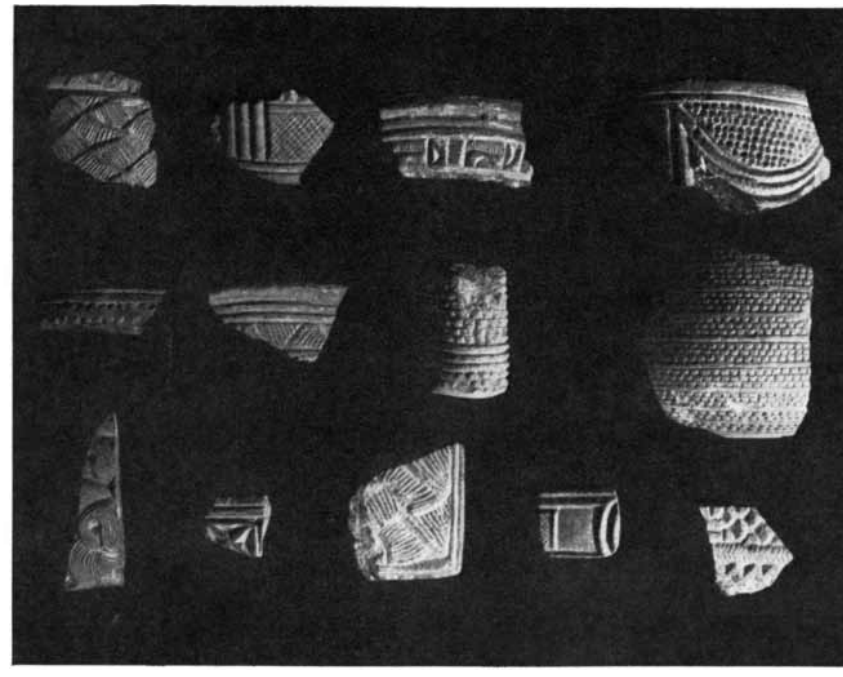
What role did Elamite Tepe Yahyā play in the transmission of the urban tradition from west to east? The city's position suggests that Elamite culture, which is now revealed as being far more widespread than was realized previously, was instrumental in the contact between the first urban civilization in Mesopotamia and the civilization that subsequently arose in the Indus valley. It appears that the Elamites of eastern Persia may have accomplished much more than that. To assess this possibility it is necessary to examine the evidence for direct contact, as distinct from trade through middlemen, between Mesopotamia and the Indus valley.

A small number of artifacts that are possibly or certainly of Harappan origin have been found at sites in Mesopotamia. Because much of the archaeological work there was done as long as a century ago, it is not surprising that both the age and the original location of many of these artifacts can only be roughly estimated. Nonetheless, Mesopotamia has yielded six stamp seals, one cylinder seal and a single clay sealing, all of the Harappan type, that are evidence of some kind of contact between the two civilizations. Certain seals are engraved with Harappan writing. On others the writing is combined with animal figures that are indisputably Harappan in style: a "unicorn," an elephant, a rhinoceros. Evidence of contact, yes. But was the contact direct or indirect?

The single Indus sealing found in Mesopotamia was discovered by the French archaeologist G. Contenau at Umma in southern Iraq during the 1920's. It suggests the arrival there of freight from Harappan territory that had been identified with the sender's personal mark before shipment. The seven seals, however, are evidence of a more equivocal kind. Mesopotamian contact with the Indus evidently did not resemble the later trade



BRONZE OBJECTS contemporaneous with peak of work and trade in soapstone at Tepe Yahyā include two chisels (*left*) and three needle-like forms; the longest object measures 6½ inches. The bronze was not produced by alloying but by utilizing copper that naturally included significant amounts of arsenic. The enriched ores were obtained through trade.



SOAPSTONE BOWLS, many of them elaborately decorated, were among the numerous objects made at Tepe Yahyā and traded eastward and westward during the first half of the third millennium B.C. Fragments of bowls with decorations like the ones on these bowl fragments from Tepe Yahyā have been found from Mesopotamia to the Indus valley.

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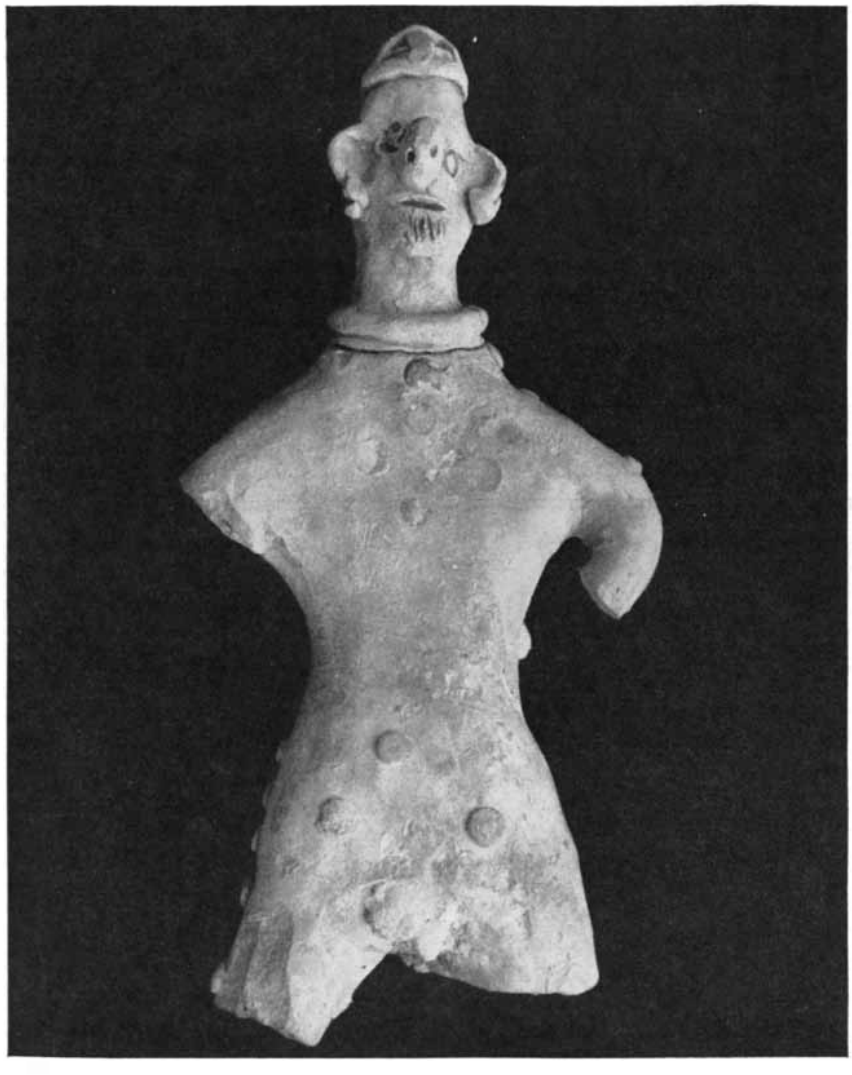
FIGURINE OF A RAM carved out of alabaster is one of the numerous articles made from imported materials that are found at Tepe Yahyā at the time of its first urban settlement about 3800 B.C. Evidences of trade between the city and outlying areas include, in addition to alabaster, mother-of-pearl from the Persian Gulf, marble, turquoise and carnelian.



FIGURINE OF A WARRIOR modeled in clay is from the final period of occupation at Tepe Yahyā, when a Sassanian military outpost stood on the top of the mound from sometime in the third century B.C. to about A.D. 400. Thereafter only nomads visited the dead city.

between Mesopotamia and, say, the Hittite realm to the west. In that instance Assyrian trading colonies were housed within special quarters of such Hittite strongholds as Kültepe and Hattusha [see "An Assyrian Trading Outpost," by Tahsin Özgüç; SCIENTIFIC AMERICAN, February, 1963]. There is simply no good evidence that Mesopotamians ever visited the Indus to set up residence and trade, or that Harappans did the reverse.

What, then, were the seals of Harappan traders doing in Mesopotamia? What was the function of the three unearthed at Ur, the two at Kish and the two at Tell Asmar? So far there is no persuasive answer to these questions. It is tempting to look on these seals not as credentials but as souvenirs of indirect trade contact; all of them are handsome objects. At the same time another equally puzzling question presents itself. Some objects of Indus origin have been found in Mesopotamia. Why has nothing of any kind from Mesopotamia been found at any Indus site?

Evidence of direct trade contact between the two civilizations thus remains almost entirely absent. Other kinds of trade, however, are equally well known. One of the oldest and most widespread is simple exchange, which can interpose any number of witting or unwitting intermediaries between two principals. Exchange is notable for presenting the archaeologist with difficulties of interpretation; intangibles such as style and function are likely to travel along with the goods.

A system of exchange that involves a single intermediary seems to provide the theoretical model that best approximates the situation at Tepe Yahyā. Such a system is known as "central place" trade; we suggest that Tepe Yahyā was just such a central place in southeastern Persia during Elamite times.

A central place can lie outside the sphere of influence of either principal and at the same time produce goods or control natural resources desired by both. In addition to (or even instead of) exporting its own products, a central place can transship goods produced by either principal. Bahrein—ancient Dilmun—provides a good example of a central place whose prosperity was based on the transshipment of goods bound for Mesopotamia. Whether or not transshipment was important at Tepe Yahyā, the city's basic central-place role in Elamite times was clearly that of a producer manufacturing and exporting articles made of soapstone.

The names of the Mesopotamian sites that contain soapstone bowls identical

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in shape and decorative motif with those we unearthed at Tepe Yahyā read like an archaeologist's checklist: Adab, Mari, Tell Asmar, Tell Aqrab, Khafaje, Nippur, Telloh, Kish, Al 'Ubaid and Ur. Bowls of Tepe Yahyā style have also been found at Mohenjo-Daro on the Indus and at Kulli-Damb in Pakistani Baluchistan. In addition to bevel-rim bowls of the Uruk type at Tepe Yahyā as evidence of contact with the west, the mound has yielded Nal ware, a kind of Indus painted pottery that predates the rise of Harappan civilization, as evidence of contact with the east.

Tepe Yahyā was not, however, the only central place in eastern Persia. It seems rather to have been one of several that comprised a local loose Elamite federation astride the middle ground between the two civilizations. Shahr-i-Sokhta, a site 250 miles northeast of Tepe Yahyā, appears to have been another central place, exporting local alabaster and transshipping lapis lazuli from Afghanistan. The links between Tepe Yahyā and other possible central places in the region such as Tal-i-Iblis, Shahdāb and Bampur—mainly demonstrated by similarities in pottery—have already been mentioned.

How did this remote Elamite domain, which in the case of Tepe Yahyā predates the appearance of Harappan civilization by at least three centuries, influence developments in the Indus valley? In spite of exciting new evidence that trade networks existed as long ago as the early Neolithic, a strong tendency exists to view trade exclusively as an ex post facto by-product of urbanism. Trade, however, has certainly also been one of the major stimuli leading to urban civilization. This, it seems to us, was exactly the situation in ancient Kerman and Persian Baluchistan.

We suggest that trade between resource-poor Mesopotamia and the population of this distant part of Persia provided the economic base necessary for the urban development of centers such as Tepe Yahyā during the fourth millennium B.C. It can further be suggested that, once an urban Elamite domain was established there, its trade with the region farther to the east provided much of the stimulus that culminated during the third millennium B.C. with the rise of Harappan civilization. Sir Mortimer Wheeler has declared that "the idea of civilization" crossed from Mesopotamia to the Indus. It seems to us that the Elamite central places midway between the two river basins deserve the credit for the crossing.

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The Social Order of Turkeys

The society of the wild turkeys that live in the semiarid grasslands of southeastern Texas is so rigidly stratified that most of the males never have an opportunity to mate

by C. Robert Watts and Allen W. Stokes

Social hierarchies existed in the animal world long before man crowned his first king. Investigating the structure and behavior of animal societies, one is increasingly impressed by how frequently their communities fall into a stratified pattern, with the members divided inexorably into dominant leaders and subordinates. Apparently this form of organization has high survival value, contributing in one way or another to the stability of a population or a species.

We made a detailed study of a population of wild turkeys living in and around the Welder Wildlife Refuge in Texas and found it to be characterized by an astonishing degree of social stratification, greater than had previously been seen in any society of vertebrates short of man. The status of each individual in this turkey society is determined during the first year of life, and it usually remains fixed for the animal's lifetime. One of the consequences is that most of the males never have an opportunity to mate! Presumably this phenomenon carries some benefits for the society, which presents an interesting subject for speculation.

The Welder Refuge is an area of 8,000 acres near Corpus Christi, Tex. Among its denizens are several hundred wild turkeys (*Meleagris gallopavo*) of the subspecies known as the Rio Grande turkey. By banding young turkeys in the Welder population with distinctive identification tags we were able to follow their subsequent career and behavior. We observed the social interactions of the tagged individuals and groups over a period of two years. As background for our findings let us first outline the yearly cycle of events in the life of the Welder turkeys as we observed it.

In March or sometimes as early as February, depending on the weather, the hens nest and begin to lay eggs, generally producing a clutch of 14 over a period of 15 or 16 days. The eggs hatch in 28 days. The resulting family of poults is subject to a high rate of attrition, owing to predators, vagaries of the weather and desertion. During the first six weeks it is not uncommon for a poult to leave its mother and join another family, particularly if it is the only survivor in the clutch. The mother of the switching offspring may also join the other family if she is compatible with the new mother. During the spring and summer the families combine in brood flocks; those hens that have lost their clutch of eggs or their poults and are left alone form broodless flocks.

The brood flock remains together until late fall, when the youngsters are six to seven months old. The young males of each family then break away as a sibling group. This group continues to be an inseparable unit for life. Even if it has been reduced to a single member, the survivor does not try to join another sibling group or form a group with other loners; he maintains an independent sibling identity.

After the male sibling unit breaks off from the brood flock it flocks with other males for the winter. Usually it attempts to join an established flock of adult males; the adult flocks, however, generally reject juveniles, so that the juvenile groups are relegated to joining together in flocks of their own.

It is at this stage in the life of the young male that his status is decided. In the exclusively male winter flock he is forced into two contests: one to establish his position within his own group of siblings, the other to determine the status of his sibling group with respect to other groups. Each sibling engages in physical combat with his brothers. The battle consists in wrestling, spurring in the fighting-cock style, striking with the wings and pecking at the head and neck. The fight often lasts more than two hours and ends when one or both of the contestants are too exhausted to continue. The strongest fighter in the group becomes the dominant bird, and the order of rank established among the siblings is seldom challenged thereafter as long as the dominant bird lives.

Meanwhile the sibling groups are testing one another and determining their relative ranking as units. Generally in a juvenile male flock the sibling group with the largest number of members wins the dominant status. When one flock encounters another, they also fight each other as units, again to determine which will be dominant. As in the case of individual contests, the group battles end in clear-cut decisions that create a remarkably stable society. The vanquished contestants accept their subordinate rank and rarely seek to renegotiate the result unless there is an important change in circumstances such as the death of a leader.

The society's stability is fortified by similar contests among the females, although in their case individual status appears to be less important than it is for the males when it comes to mating, as we shall see. While the juvenile males are still with the hens in the brood flocks, fighting occurs only between flocks, with victory generally going to the flock containing more males. After the males have left to form their own flocks for the winter the hens combine into large, all-female aggregations, and they then proceed to battle for individual rank among themselves. Each hen is on her own; there are no contests between sibling

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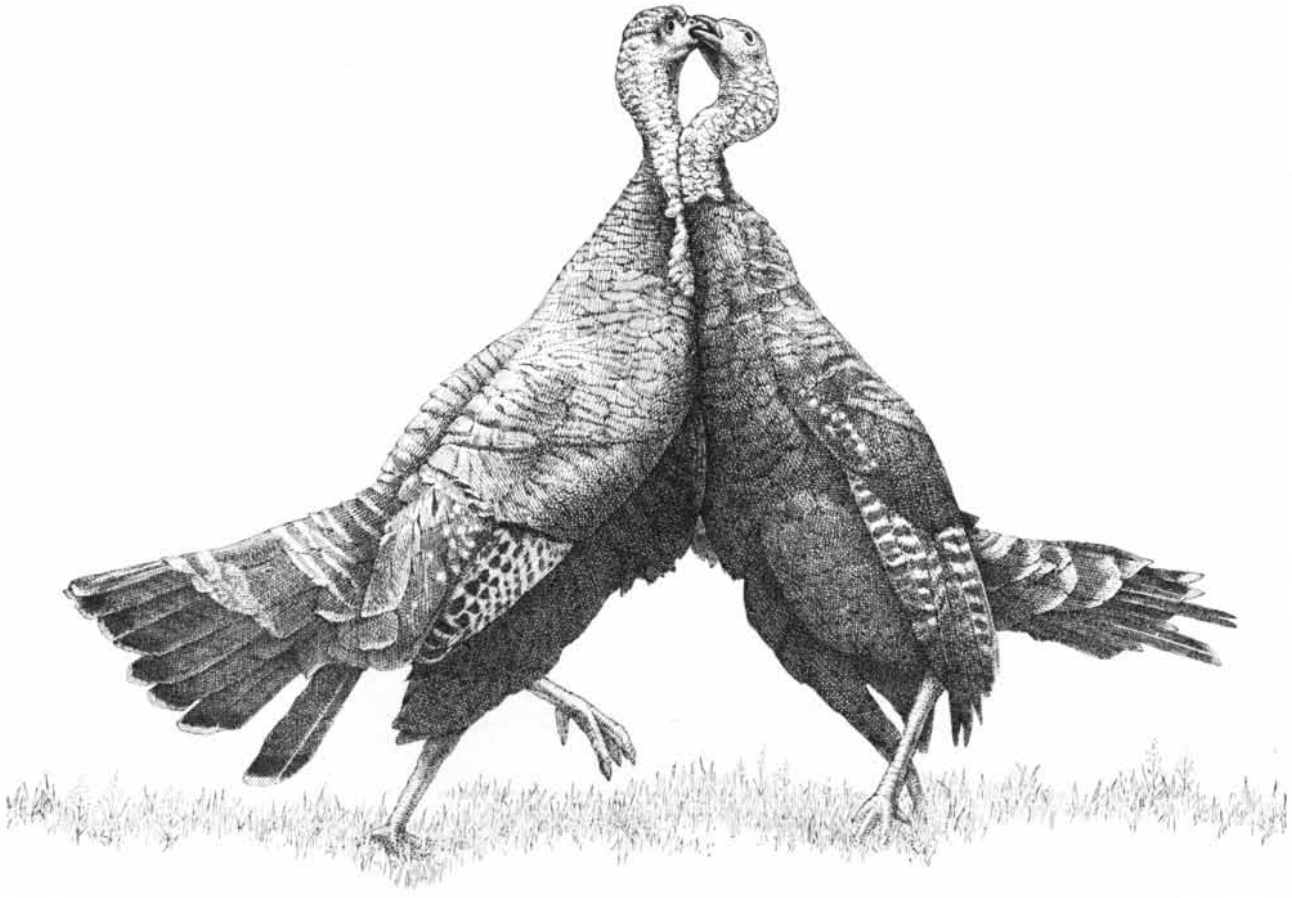
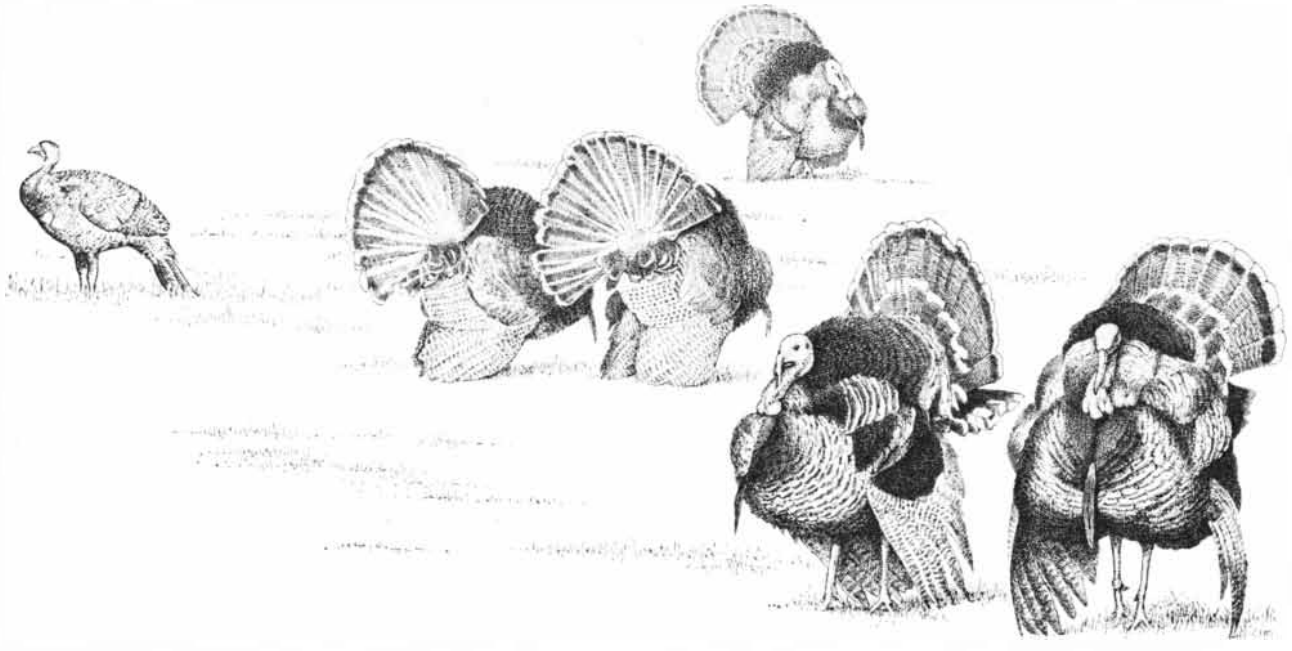


WRESTLING MATCH between juvenile wild turkeys, members of the same sibling group, is one of several forms of combat that eventually determine which male will dominate the other members of the group. The birds usually fight until exhausted. Dominant males at the Welder Wildlife Refuge in Texas act as sires in the great majority of annual matings among the turkeys resident there.



PRELUDE TO MATING on the display grounds at the Welder Refuge is stereotyped male strutting, with tail fanned and wings drooping. Two sibling pairs are shown strutting; the movements of each pair are almost perfectly synchronized. The female (*left*), the object of the males' display, stands in the characteristic pre-mating posture, awaiting the dominant male of the senior pair.

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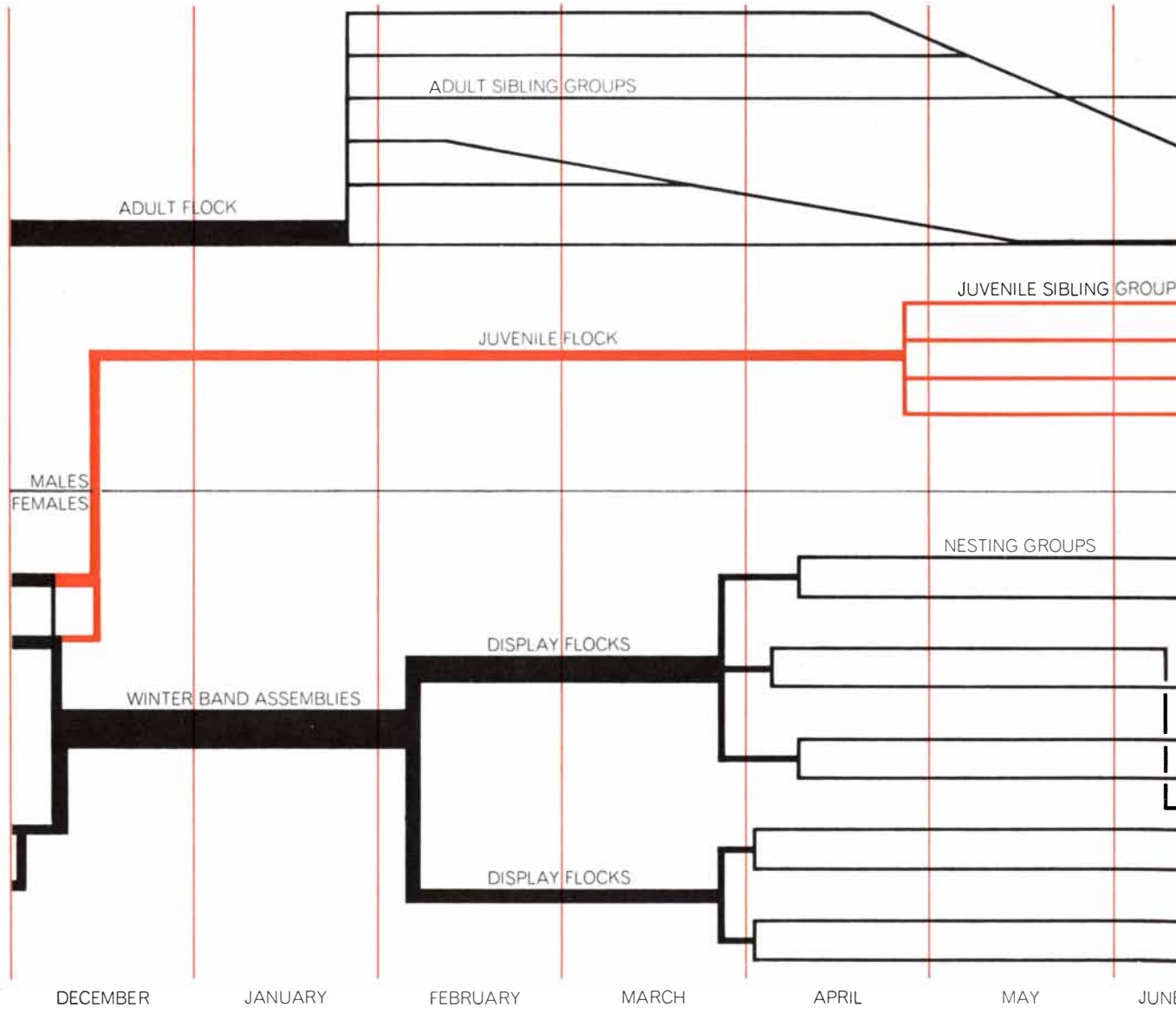
groups or families. In these fights adult hens usually prevail over juvenile females. Significantly, however, females that have been members of winning brood flocks often win over older hens that have not been thus "conditioned" to winning. This kind of conditioning was demonstrated in chickens during the 1930's by the Chinese biologist Z. Y. Kuo. He "trained" birds to win by never allowing them to lose.

We found that the turkey hens in and around the Welder Refuge congregated for the winter in two roosts within the refuge. The male flocks also had two winter roosts in the refuge, and in the area around the refuge there were six additional male roosts, spaced about a mile to a mile and a half apart. This tended to minimize encounters between flocks, as the males rarely ventured more than six-tenths of a mile from their roost during the winter.

By the end of February the wintering flocks, both male and female, left their roosts to visit mating grounds. The signal for the breakup of winter roosting came when the hens set out at daybreak for certain display grounds. As the males left their winter quarters their tendency to flock together waned and their flocks gradually disintegrated. The sibling groups, however, remained tightly knit.

At each display ground a band of females numbering 50 or more hens became available for courting. This group would receive the attention of 10 to 15 sibling groups totaling about 30 males in all. The sibling group that had gained dominance over all the others moved about within the ranks of the females, and the subordinate groups followed along at the periphery, taking what opportunities they could to display to females there. The display consisted in strutting before the hens. The members of each sibling group usually strut-



MALE AND FEMALE TURKEYS gather in flocks, divide into smaller units and flock together again in the course of a year. An idealized sequence appears in this chart. Two flocks of males (*top*) exist in late December. One (*color*) is made up of juvenile sibling groups newly departed from the summertime brood flocks. The other (*black*) is made up of adult sibling groups and remains aloof from the juveniles. At this time the females (*bottom*) are gathered in a single large winter band. By February the adult male flock has divided into its component sibling groups. The juvenile males, however, continue to flock until near the end of the breeding season. The female band divides in February; smaller groups, numbering about 50 birds, appear on the display grounds. By April

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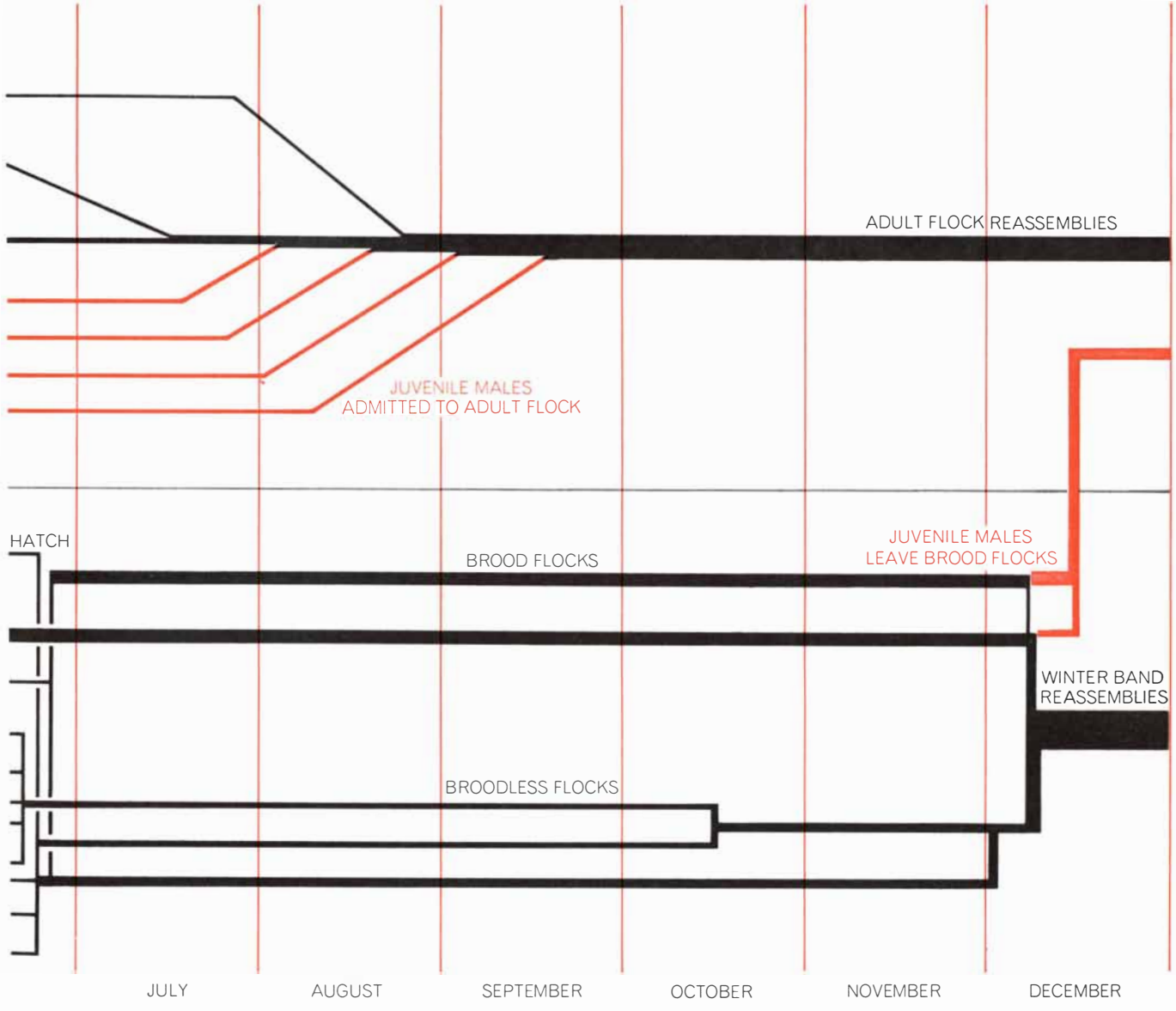
ted in unison, more or less synchronously and close together. Occasionally more than one sibling group would strut to the same hen.

Notwithstanding the general participation in strutting, only the dominant male of the dominant group actually had the privilege of mating with hens at the height of the breeding season. We had tagged all the 170 males that used the four display grounds in the refuge and hence were able to identify them individually. In close observation of three of the display grounds we found that at two grounds just one male in each did all the mating, and at the third ground only two males were involved in mating. At the fourth ground, which was lightly used by the turkeys that year, we were not able to keep a close watch, but it could reasonably be assumed that only one or two males dominated the mating there. Overall, then, of the 170 males using the four grounds no more than six males accounted for all the mating with the hens. We observed 59 copulations during this period.

The dominant leader's ability to monopolize the mating prerogative is aided by the circumstance that a complete copulation generally takes four minutes or longer. A subordinate male presuming to couple with a hen does not have time to fulfill the mating attempt before the dominant male detects it. The dominant one, after driving off the presumptuous subordinate, proceeds to mate the prepared hen. Only once in two mating seasons did we see a member of a subordinate sibling group (the dominant member) succeed in achieving a mating on the display grounds; in that case two widely separated females in the area were ready to mate at the same time, and the leader of the subordinate group mated one while the flock leader was occupied with the other. There were also



most breeding is over; the females have further divided into groups of two to five and are nesting. Some adult male sibling groups begin to recombine. Now the juvenile male flock splits into its sibling groups; these court any unattended females. By mid-June the year's hatch reaches a peak. Soon thereafter females with young collect in small brood flocks, and those without young form in broodless flocks. Meanwhile juvenile males are gradually allowed to enter the recombining flock of adult males, filling out ranks that have been thinned by the high mortality rate among adults. Finally, by December, the next generation of young males leaves the brood flock and forms a new juvenile flock. Adult and young females then join broodless females to reestablish winter band.

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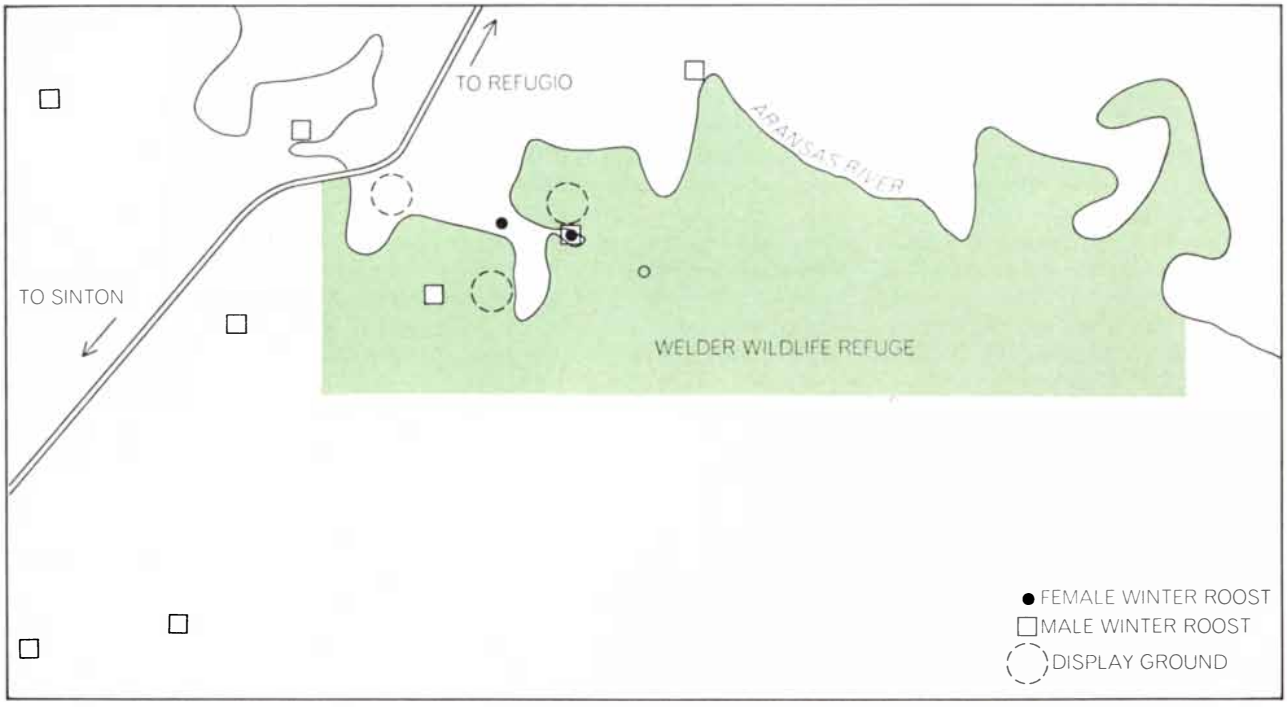
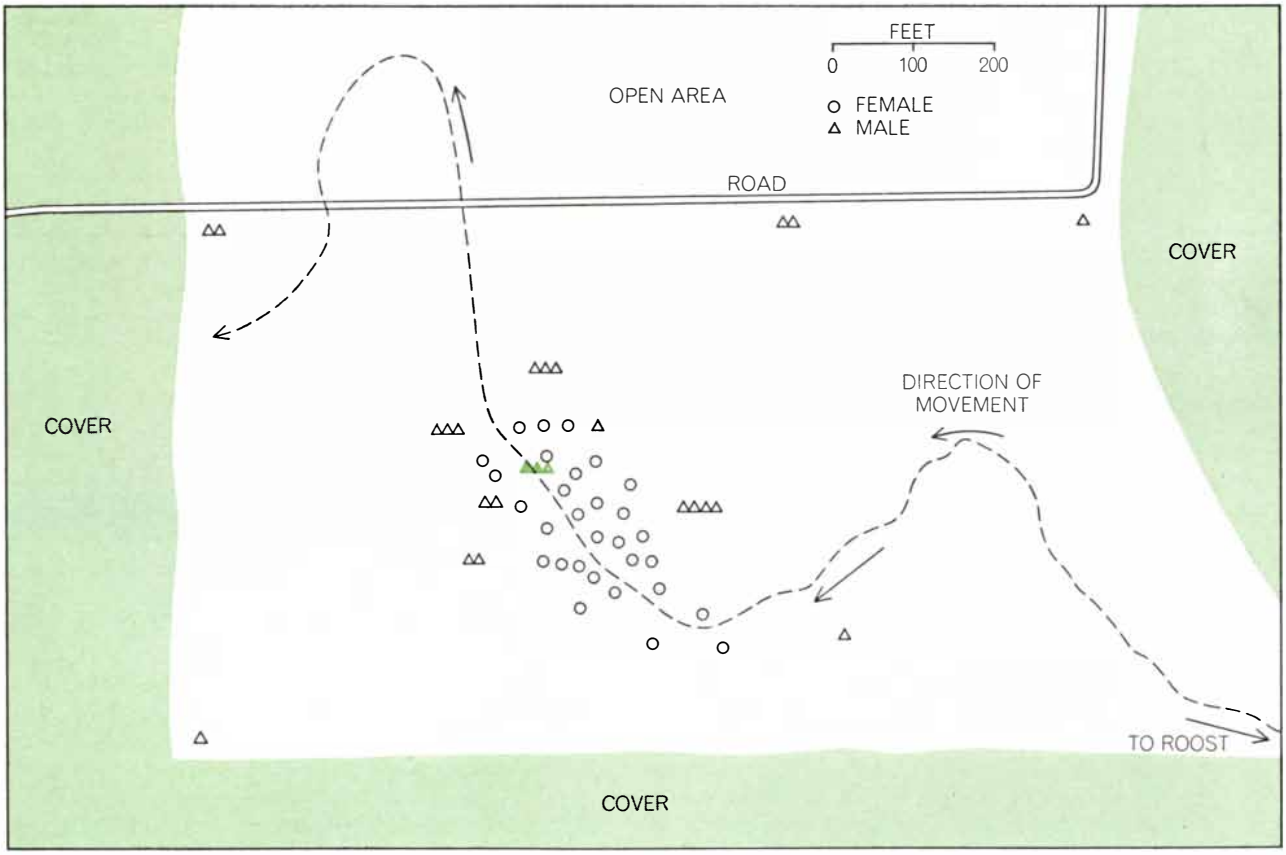


WELDER WILDLIFE REFUGE occupies a 12-square-mile strip of land (*colored area*) along the Aransas River near Corpus Christi. In winter the female turkeys in the area, gathered into two large seasonal flocks, occupy roosts less than a mile apart inside the refuge (*black*). The small winter flocks of males occupy roosts that are well separated; only two of the eight overlap female ranges.



DISPLAY-GROUND ACTIVITY during a morning in mid-March, before the female flock breaks into nesting groups, is presented diagrammatically. Shortly after daylight 30 females began a slow passage across a display area, starting at lower right (*arrows*). A senior male sibling group, numbering three birds, soon moved into the midst of the females (*color*). Six junior male sibling groups, including a solitary male, have followed closely along the periphery of the band, displaying when they can but seldom managing to mate.

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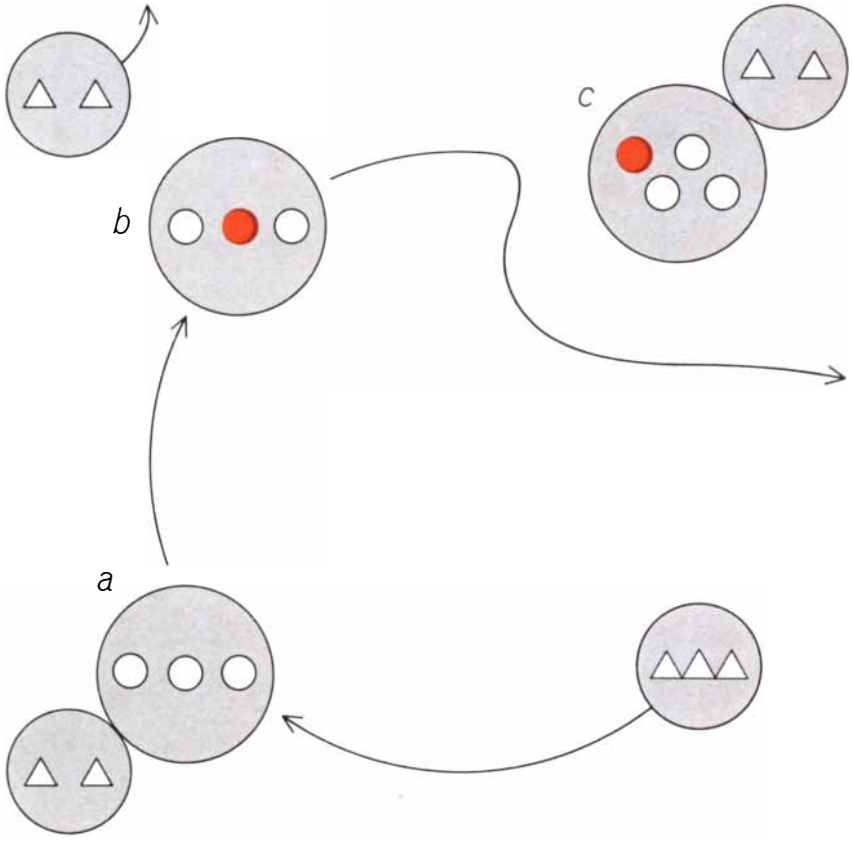
two instances in which a previously subordinate male of the dominant sibling group was able to mate after the dominant member of the group died during the display-ground period.

Although subordinate males had no chance to mate with hens at the display grounds, they did perform mock matings, often just before or after a mating by the dominant male. Mounting a pile of dry cow manure or a log or simply squatting on the ground, they would go through the stereotype of mating actions: treading the object, fluttering their wings, lowering their tail and even in some cases ejaculating. Some males that were not allowed to mate with hens at the display grounds did have opportunities to mate later. The hens left the display grounds within four weeks and went in groups of two to five (not as sibling groups) to a common nesting ground. During the nesting period male sibling groups roved about from one nesting area to another seeking receptive hens. Thus a sibling group that had had only subordinate status at the display grounds might have an uncontested meeting with a nesting group of hens. In that event the dominant member of the male group could mate with the hens unless he was interrupted by the arrival of a dominant sibling group. Our observations indicated, however, that the few dominant males that were engaged in all the mating at the display grounds probably accounted also for 75 percent of the later matings achieved during the hens' nesting period.

By May or June the adult males cease courting the females and go off in their own flocks, to which they now admit most of the year-old males that hang about the flock. Late in the season some sibling groups composed of year-old males, left alone either with females that are late nesters or with females nesting for a second time, can be seen strutting to the hens and performing other courtship acts, but they do not consummate mating. In this respect the behavior of the Rio Grande turkeys parallels that of other bird species such as the Canada goose and jungle fowl; the year-old males of those species also go through the courting ritual without actually breeding.

Such is the life style of the Welder turkeys. How are we to explain its unique features? Nowhere else in the world of birds has any investigator observed so rigidly structured a society: the permanent division of its members into dominant and subordinate classes, the lifelong cohesion of male sibling groups,



ROLE OF DOMINANCE in breeding activity is evident in this diagram of the encounters between three roaming males of a sibling group and female turkeys in various nesting groups. Each nesting group is attended by a group of males that is dominant over or subordinate to the roaming group. In the initial encounter (*a*) the roamers outranked the attendants but the females did not respond to their display and the roamers moved on. In the second encounter (*b*) the roamers were also senior to the attendants, and one of the nesting group (*color*) was responsive. The dominant male among the three roamers mated with the responsive female. In the final encounter (*c*), although a responsive female was present, the attendants outranked the roamers. The three therefore moved on to another nesting area.

the monopolization of mating by a few dominant males. The Welder turkeys' social pattern is not duplicated even by their close relative of the same species, the Eastern wild turkey inhabiting the Atlantic coastal states.

In seeking an explanation one factor to consider is the extent to which the Welder turkeys' life style may be dictated by the nature of their habitat. The Welder Refuge and its environs is an area of grassland and brush. Studies of the social weaverbirds in Africa by the British investigator John Crook have shown that weavers living in woodlands tend to form small social units; in contrast, those inhabiting open grasslands are inclined to form large flocks. In explanation Crook pointed out that the widely dispersed, year-round supply of food in a tropical forest can be exploited most efficiently by small groups of roving birds, whereas in a grassland, with a seasonally abundant, concentrated food supply and relatively few available nesting sites, the birds can make the most of the environment by flocking together in large social units. This interpretation is borne out by the habits of game birds in North America: woodland species such as the ruffed grouse and the spruce grouse typically are widely dispersed and tend to be loners except during the mating season; on the other hand, species with a habitat of grassland and brush such as the prairie chicken, the sharp-tailed grouse and the sage grouse live in large flocks. The Welder turkeys exhibit the same influence of habitat. They follow the grassland pattern of social organization, whereas the Eastern wild turkey, living in woodlands, favors small social units.

The nature of the habitat and food supply also influences the mating sys-

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tems of birds. Where food is not easy to find and the young need parental help, the birds favor monogamy. This is particularly well illustrated by the quail and the partridge. Polygamy, on the other hand, tends to be the rule when food is readily available and the rearing of the young does not require help from the male parent. In some cases the polygamy system takes the form of the creation of harems; a male acquires several hens that stay with him until they are bred. The Eastern wild turkey uses this system. In contrast, the Welder turkeys have adopted the "lek" mode of polygamy, in which most of the mating is done in a common arena (called the lek). A number of ground-dwelling birds (including the prairie chicken, the sharp-tailed grouse and the sage grouse) practice the lek system; the Welder turkeys, however, have developed their own unique version. On a prairie-chicken or grouse lek each male forms a small territory and stays within it, waiting for a sexually ready female to seek him out. The hens in those societies do show a definite preference for relatively dominant males. However, the Welder modification of the system, with the males pursuing the females on the courting ground, applies a more positive control; there the males determine rigorously which of them will mate.

How can we account for the fact that the Texas wild turkeys use the lek mating system rather than the harem system favored by their Eastern relatives of the same species? The Texas climate suggests an answer. In the Welder Refuge area rainfall is comparatively infrequent, and when it occurs, it brings on a quick but short-lived growth of vegetation and insects. In order to take advantage of this ephemeral food supply it is important that the females be brought quickly into readiness for breeding. The displays and courtship by groups of males on a lek presumably have that effect. (It is interesting to note that in a part of Oklahoma that is less drought-ridden than the Welder Refuge region the turkeys of the Rio Grande subspecies display on leks but do not usually mate until afterward, when they go off to form harems. Their combination of the two systems apparently adds a string to their bow, enabling them to cope with whatever weather conditions may befall during the breeding season.) In addition to the rapid preparation of the females for breeding there is another obvious advantage in the lek system: it guards the birds against surprise attacks by predators, to which the turkeys are particularly vulnerable in the grasslands.

We are still left with a most puzzling question: How does one explain the remarkable restriction of mating to just a few males and the close lifelong bond that holds a sibling group together? We suggest a hypothesis that relates the two phenomena. A hen may be stimulated more strongly by the compact, synchronized strutting of a male sibling group than she would be by the display of an individual suitor. Hence the probability of eventual mating may be enhanced even for the subordinate members of the group in the event that the dominant bird dies. (The average annual mortality of adult male turkeys at Welder is 40 percent.) Sibling unity also provides protection for the member that does the mating: during the four minutes or more that he is coupled with the female his brothers stand by to fight off intruders or predators.

Perhaps most significant, the collaboration of the sibling members in assisting mating by one of their group helps to ensure the propagation of the family genes, since on the average between brothers 50 percent of the genes are exact duplicates. The dominant member thus acts as a representative of his brothers in passing on their genes; the British geneticist W. D. Hamilton calls natural selection of this kind "kin selection."

Such an arrangement may seem less than ideal with respect to those deprived of the opportunity to mate. In genetic and evolutionary terms, however, it may be advantageous to the community as a whole. Perhaps the Welder turkeys offer a moral for human conduct, suggesting that people might often benefit, even as individuals, by giving less attention to self-gratification and more to group effectiveness.

OUTRANKED MALES (*left*), interrupted in mid-display by four members of a senior sibling group (*center and right*), have begun to abandon the courtship effort directed at the five females in the foreground. One of the outranked males is starting to fold his tail.

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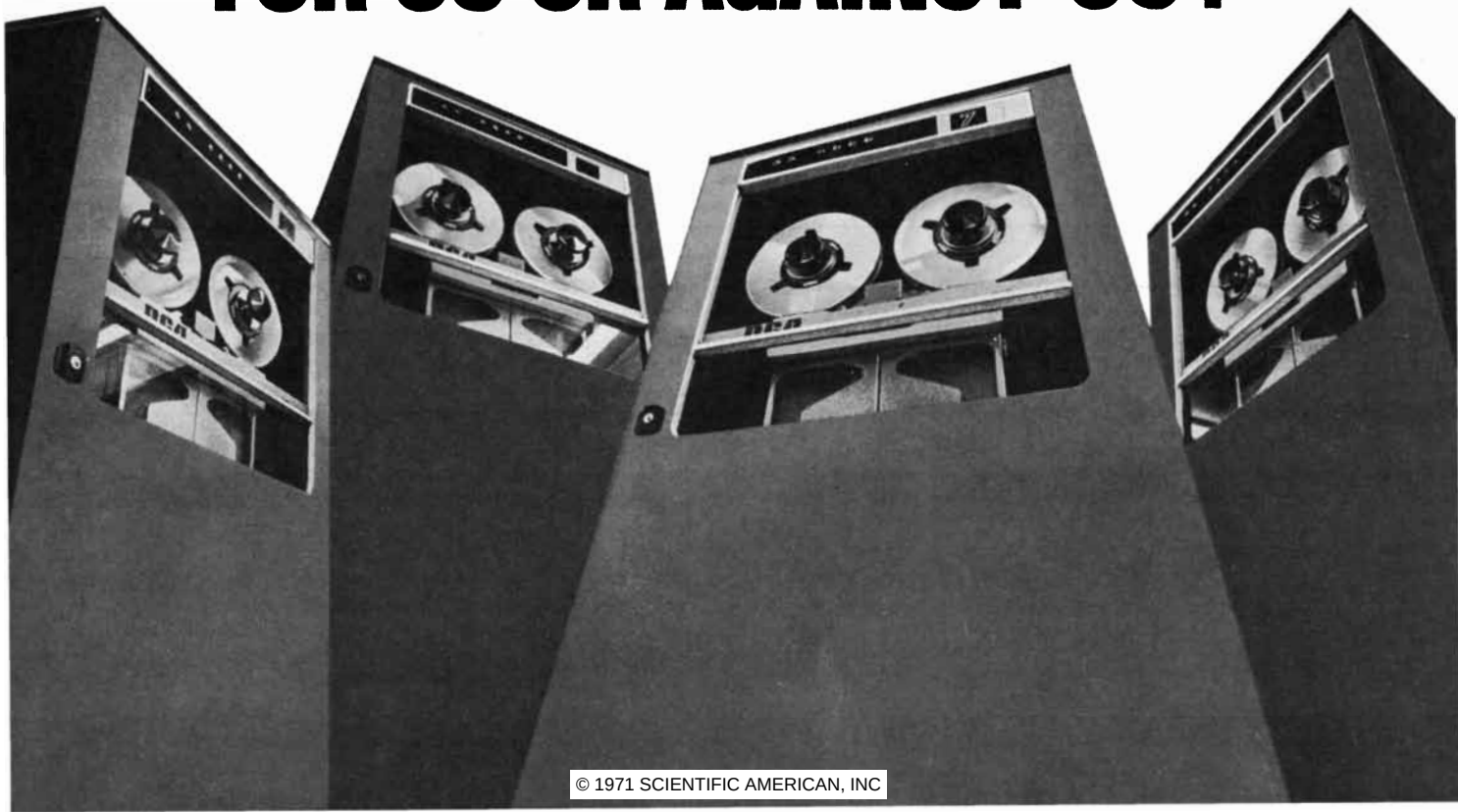

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MATHEMATICAL GAMES

The Turing game and the question it presents: Can a computer think?

by Martin Gardner

There was a time when it must have seemed highly improbable that machines should learn to make their wants known by sound, even through the ears of man; may we not conceive, then, that a day will come when those ears will be no longer needed, and the hearing will be done by the delicacy of the machine's own construction?—when its language shall have been developed from the cry of animals to a speech as intricate as our own?

—Samuel Butler, *Erewhon*

Alan Mathison Turing, a British mathematician who died in 1954 at the age of 42, was one of the most creative of the early computer scientists. Today he is best known for his concept of the Turing machine. We shall take a quick look at such machines and then consider one of Turing's less well-known ideas, the Turing game—a game that leads to deep and unsettled philosophical controversies.

A Turing machine is a "black box" (a machine with unspecified mechanisms) capable of scanning an infinite tape of square cells. The box can have any finite number of states. A finite portion of the tape consists of nonblank cells, each bearing one of a finite number of symbols. When the box views a cell, it can leave a symbol unaltered, erase it, erase it and print another symbol or print a symbol in a blank cell. The tape is then shifted one cell to the left or right or stays fixed; the box either remains in the same state or clicks to a different state.

A table of rules describes what the box does for every achievable combination of symbol and state. Such a table completely defines a particular Turing machine. There is a countable (aleph null) infinity of Turing machines, each designed for a specific task, and for every task the machine's structure can vary widely in symbols, states and rules.

A good way to grasp the essence of a Turing machine is to make one, albeit a trivial one [*see illustration on opposite page*]. Eight cells on the paper tape are marked 1111 + 111, signifying the addition of 4 and 3 in the "unary" system in which an integer n is symbolized by n 1's. To make the machine, draw a small square (the black box) and cut two slits in it so that the tape can be inserted as shown. Adjust the tape so that the first 1 is visible. The table at the bottom of the picture gives all the necessary rules.

Start by assuming that the machine is in state *A*. Consult the table for the combination of symbol 1 and state *A* and do what it says: erase the 1, move the tape left (so that the box scans the next cell to the right) and assume that the machine clicks to state *B*. Continue in this way until the table tells you to stop.

If you follow the rules correctly, the machine will erase the first 1, shift the tape to the left cell by cell until it reaches the plus sign, change + to 1 and stop. The strip will then show 1111111, or 7. These simple rules obviously program the device to add any pair of positive integers, however large.

It is a tedious way to add, of course, but Turing's idea was to reduce machine computation to a simple and abstract schema, making it easier to analyze all kinds of thorny theoretical problems, such as what can and what cannot be computed. Turing showed that his idealized device can be programmed to do, in its clumsy way, anything the most powerful electronic computer can do. Like any computer—and like the human brain—it is limited by the fact that certain calculations (such as calculating pi) require an infinite number of steps and by the fact that some problems are unsolvable in principle; there *is* no algorithm, or effective procedure, by which they can be solved. A "universal Turing machine" is capable of doing whatever any special-purpose Turing machine can do. In brief, it computes anything that is computable.

In 1950 Turing's article "Computing Machinery and Intelligence" appeared in the October issue of *Mind*, a British philosophical journal, and it has since been reprinted in several anthologies, including James R. Newman's *The World of Mathematics*. "I propose," Turing began, "to consider the question, 'Can machines think?' " This, Turing decided, was much too vague to have a meaningful answer. He proposed instead a related but more precise question: Can a computer be taught to win the "imitation game," now commonly called the Turing game or Turing test?

Turing based his test on a parlor game in which a man is concealed in one room and a woman in another. An interrogator of either sex asks the concealed players questions, which are conveyed by an intermediary; the answers are returned in typescript. Each player tries to convince the interrogator that he or she is, say, the woman. The interrogator wins if he guesses correctly who is telling the truth.

Suppose, Turing said, we replace one player with a learning machine that has been taught to converse in an ordinary language such as English. Is it possible for such a machine to deceive an interrogator when both the machine and its human partner try to persuade the questioner that he, she or it is the human?

Several continuums blur the meaning of "deceive." How long a conversation is allowed? How intelligent is the interrogator? How intelligent is the person competing against the machine? It is possible today for a computer to pass the Turing test if the questioner is a child and is allowed only a few questions. There may be no dramatic future breakthroughs, just as there probably were no dramatic breakthroughs in the evolution of man. Conversation machines could improve gradually, so that it takes increasingly long dialogues, with increasingly clever interrogators, to beat the machines. Perhaps someday only an interrogating computer will consistently guess correctly. Turing himself made a cautious prediction. By the year 2000, he wrote, computers will speak fluently enough to deceive an "average interrogator" at least 30 percent of the time after "about five minutes" of dialogue. He imagined the following conversation as being typical:

Q. Please write me a sonnet on the subject of the Forth Bridge.

A. Count me out on this one. I never could write poetry.

Q. Add 34957 to 70764.

A. (Pause about 30 seconds and then give as answer) 105621.

Q. Do you play chess?

A. Yes.

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Q. I have K at my K1, and no other pieces. You have only K at K6 and R at R1. It is your move. What do you play?

A. (After a pause of 15 seconds) R-R8 mate.

Many programs enabling computers to simulate English conversation now exist. Joseph Weizenbaum, an electrical engineer at the Massachusetts Institute of Technology, has written one he calls Eliza, after Eliza Doolittle of Shaw's *Pygmalion*. *The New York Times* (June 15, 1968) reported a typewritten dialogue with a woman in which an IBM 7094 computer assumed the role of a psychiatrist:

W. Men are all alike.

C. In what way?

W. They're always bugging us about something or other.

C. Can you think of a specific example?

W. Well, my boyfriend made me come here.

C. Your boyfriend made you come here?

W. He says I'm depressed much of the time.

C. I am sorry to hear you are depressed.

W. It's true. I am unhappy.

C. Do you think coming here will help you not to be unhappy?

W. I need some help, that much seems certain.

C. What would it mean to you if you got some help?

W. Perhaps I could learn to get along with my mother.

C. Tell me more about your family.

W. My mother takes care of me.

C. Who else in your family takes care of you?

W. My father.

C. Your father?

W. You are like my father in some ways.

C. What resemblance do you see?

W. You are not very aggressive but I think you don't want me to notice that.

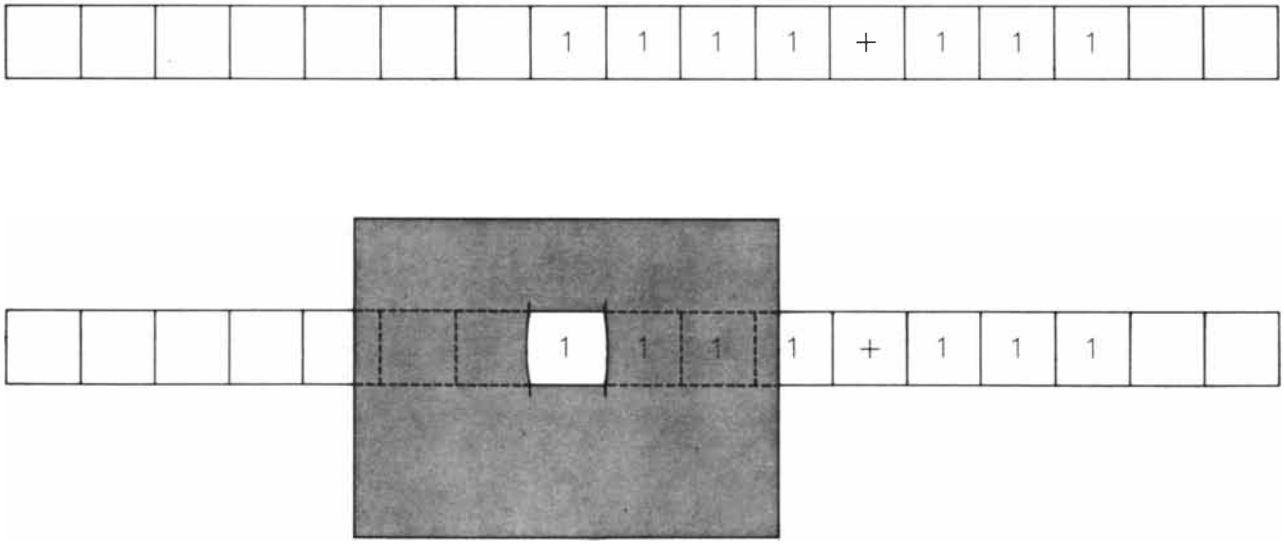
C. What makes you think I am not very aggressive?

W. You don't argue with me.

The dialogue continues in a similar vein and is indistinguishable from a conversation between a patient and a nondirective therapist. The program was not even a learning program. Weizenbaum readily admitted that the computer did not "understand" anything being said. It certainly could not pass the Turing test. Suppose, however, that by the year 2000 computers can play the Turing game as well as they now play checkers and chess. What, if anything, will this reveal about the nature of the machine's "mind"?

Readers of Arthur C. Clarke's novel *2001: A Space Odyssey* may recall that HAL, the spaceship's talking computer, is said to "think" because he could "pass the Turing test with ease." (HAL stands for *h*euristically programmed *al*gorithmic computer, but Clarke had some trickier wordplay in mind when he picked the name. Can the reader figure out what it is before it is disclosed next month?) Does HAL really think or does he just mimic thinking? Turing believed that when the time comes that computers converse well enough to pass his test, no one will hesitate to say that they are thinking.

Enormously tangled questions imme-



	STATE A	STATE B
1	1. ERASE THE 1. 2. SCAN NEXT CELL ON RIGHT. 3. GO TO STATE B.	1. SCAN NEXT CELL ON RIGHT. 2. STAY IN STATE B.
+		1. ERASE THE +. 2. PRINT 1. 3. STOP.

A Turing machine for addition

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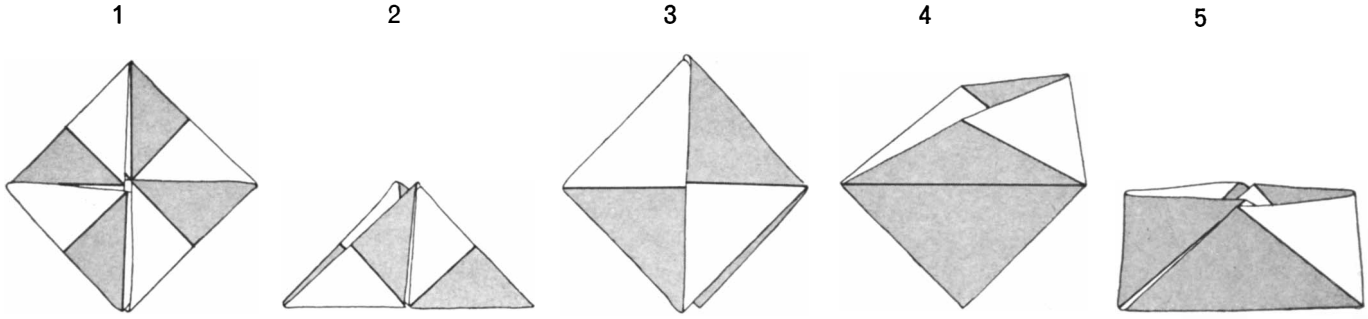

Solution to the "Sheep and goats"

diately arise. Can such a computer be self-conscious? Can it have emotions? A sense of humor? In short, should it be called a "person" or just a dead machine built to imitate a person? L. Frank Baum (in *Ozma of Oz*) described Tiktok, a windup mechanical man, as a robot that "thinks, speaks, acts, and does everything but live."

Keith Gunderson, criticizing Turing's article in *Mind* (April, 1964), argued that a computer's ability to pass the Turing test would prove nothing of philosophical value. It is possible (my example) to make a wax tulip that cannot be spotted as fake merely by looking at it. This surely tells us nothing about a chemist's ability to synthesize a tulip's organic substances. Would a conversing computer prove anything more than that a computer could be taught to mimic conversation? "In the end," Gunderson concluded, "the steam drill outlasted John Henry as a digger of railway tunnels, but that didn't prove the machine had muscles; it proved that muscles were not necessary for digging railway tunnels."

A curious twist was given to the Turing test in a 1959 lecture by Michael Scriven, reprinted as "The Compleat Robot: A Prolegomena to Androidology" in *Dimensions of Mind,* edited by Sidney Hook (New York University Press, 1960). Scriven conceded that conversational ability does not prove that a computer possesses other attributes of a "person." Suppose, however, a conversing computer is taught the meaning of "truth" (in, say, the correspondence sense made precise by Alfred Tarski) and then is programmed so that it cannot lie. "This makes the robot unsuitable," Scriven said, "for use as a personal servant, advertising copywriter, or politician, but renders it capable of another service." We can now ask if it is aware that it exists, has emotions, thinks some jokes are funny, acts on its own free will, enjoys Keats and so on, and expect it to give correct answers.

There is the possibility that a "Scriven machine" (as it is called by one of several philosophers who criticize Scriven's paper in other chapters of Hook's anthology) will say no to all such questions. But if it gives yes answers, Scriven contends, we have as much justification for believing it as we have for believing a human, and no reason for not calling it a "person."

Philosophers disagree about Turing's and Scriven's arguments. In a short piece titled "The Supercomputer as Liar" (*Mind,* February, 1963) Scriven replied to some of his critics. Mortimer J. Adler, in *The Difference of Man and the Difference It Makes* (Holt, Rinehart and Winston, 1967), takes the view that the Turing test is an "all-or-none affair," and that success or continued failure in creating computers capable of passing it will respectively weaken or strengthen the view that a man is radically different in kind from any possible machine as well as any subhuman animal.

Would conversing machines really alter the beliefs of people who hold such a view, however? It is not hard to imagine a television show 50 years from now in which guests ad-lib with a robot Johnny Carson whose memory has been stocked with a million jokes and that has been taught the art of timing by human comics. I doubt that anyone would suppose the computer had a sense of humor any more than a person defeated by a robot chess player supposes he has played against a machine radically different in kind from a computer that plays ticktacktoe. Rules of syntax and semantics are just not all that different from rules of chess.

At any rate the debate continues, complicated by metaphysical and religious commitments and complex linguistic problems. All the age-old enigmas about mind and body and the nature of personality are being reformulated in a new terminology. It is hard to predict what thresholds will be crossed and how the crossings will affect fundamental philosophical disagreements as robots of the future improve—as they surely will—in their ability to think, speak and act like humans.

Samuel Butler's chapters in *Erewhon* explaining why the Erewhonians destroyed their machines before the machines could become masters instead of servants were read 100 years ago as farfetched satire. Today they read like sober prophecy. "There is no security," Butler wrote, "against the ultimate development of mechanical consciousness, in the fact of machines possessing little consciousness now. A mollusc has not much consciousness. Reflect upon the extraordinary advance which machines have made during the last few hundred years, and note how slowly the animal and vegetable kingdoms are advancing. The more highly organized machines are creatures not so much of yesterday, as of the last five minutes, so to speak, in comparison with past time."

The answers to last month's paper-folding puzzles are:

1. A simple proof that on the two-by-three rectangle OSBERG cannot be folded to spell BORGES (or vice versa) is to note that in each case the fold requires that two pairs of cells touching only at their corners would have to be brought together in the final packet. It is evident that no fold can put a pair of such cells together.

2. The square puzzle with the faces and prison windows is solved from the starting position shown last month. Fold the top row back and down, the left column toward you and right, the bottom row back and up. Fold the right packet of three cells back and tuck it into the pocket. A face is now behind bars on each side of the final packet. The central face of the square cannot be put behind bars because its cell is diagonally adjacent to each of the window cells.

3. Space prevents my giving solutions

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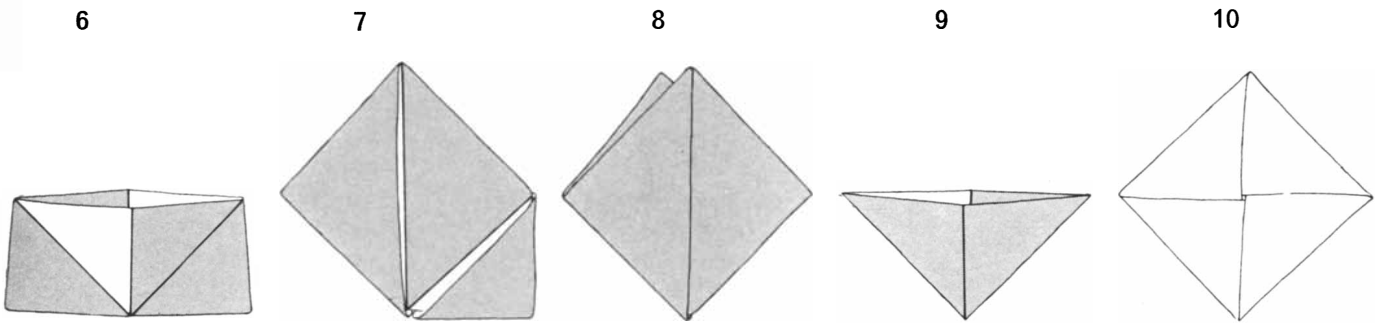

problem presented last month

for the eight pseudonyms of Beelzebub, but Beelzebub itself can be obtained as follows. Starting with the layout shown last month, fold the bottom row toward you and up to cover *BBE*. Fold the left column toward you and right to cover *ZU*. Fold the top row toward you and down, but reverse the crease between *L* and *Z* so that *LZ* goes between *B* and *B* on the left and the upper *E* goes on top of the lower *E*. You now have a rectangle of two squares. On the left, from the top down, the cells are *BLZBUB*, on the right *EEE*. The final move is difficult. Fold the right panel (*EEE*) toward you and left. The three *E*'s are tucked so that the middle *E* goes between Z and *B*, and the other two *E*'s together go between *B* and *L*. Once you grasp what is required it is easier to combine this awkward move with the previous one. The result is a tightly locked packet that spells Beelzebub. The solution is unique. If the cells of the original "map" are numbered 1 through 9, the final packet is 463129785.

4. To find the 5-face of the tetraflexagon, start with face 1 on the top and 2 on the bottom. Mountain-fold in half vertically, left and right panels going back, so that if you were to open the flexagon at the center crease you would see the 4-face. Instead of opening it, however, move left the lower inside square packet (with 4 and 3 on its outsides) and move right the upper square packet (also with 4 and 3 on its outsides). Insert your fingers and open the flexagon into a cubical tube open at the top and bottom. Collapse the tube the other way. This creates a new tetraflexagon structure that can be flexed to show faces 1, 3 and 5.

A similar maneuver creates a structure that shows faces 2, 4 and 6. Go back to the original structure that shows faces 1, 2, 3 and 4 and repeat the same moves as before except that you begin with the 2-face uppermost and the 1-face on the underside.

5. The illustration on these two pages shows how to separate the sheep from the goats:

(1) Start with the two-color square folded as shown.

(2) Fold in half along the horizontal diagonal by folding the bottom corner up to make a "hat" with a white triangle at the lower left-hand corner.

(3) Open the hat's base and continue opening until you can flatten the hat to make the small square shown.

(4) Insert a left finger into the pocket on the right of the upper face of drawing No. 3. Pull upward and flatten as shown.

(5) Turn the paper over sideways and repeat the previous move on the other side. The result is a rectangle with a white triangle in the upper right-hand corner.

(6) Open the rectangle into a cubical tube open at the top and bottom. Collapse the tube the other way to make a rectangle again, except that now it is colored as shown.

(7) Insert your right thumb into the pocket on the left of drawing No. 6, lift up the flap and flatten it as shown.

(8) Turn the paper over sideways and do the same on the other side. You should now have a small square, black on both sides.

(9) Reach into the square from above, open it and flatten to make an inverted hat, black on both sides.

(10) Open the hat by separating its bottom points and flatten the large square that results. It will be the same size as the square you started with, but now it is all white on one side and all black on the other—all sheep and all goats.

Repeating the same sequence of moves will mix the sheep and the goats again. With practice the folds can be done so rapidly that you can hold the square out of sight under a table for just a few moments and produce the change almost as if by magic.

The "little law," mentioned last month, that Henry Ernest Dudeney hinted about in connection with his map-fold problem has probably been rediscovered. Mark B. Wells of the Los Alamos Scientific Laboratory used a computer to confirm that the two-by-three map has 10 folds for each cell on top. The program also found that the order-3 square has 152 folds for each cell on top, although it has not yet been proved that all these folds can be achieved. It appears that for any rectangular map every cyclic permutation of every possible fold is also a possible fold. If so, it is necessary to determine only the folds for one cell on top because the cyclic permutations of these folds give all the other folds. For example, since 123654789 is a possible fold, so also are 236547891, 365478912 and so on. It is a strange law because the folds for cyclic permutations are wildly different from one another. It is not yet known whether the law applies to all polyomino-shaped maps or to maps with equilateral triangles as cells.

In March I neglected to say that the discussion of the alephs was confined strictly to Cantorian set theory. It is now known that the equivalence of Cantor's aleph-one and *c*, the power of the continuum, cannot be established with the present axioms of set theory (see this department for March, 1966). Many readers also pointed out that Charles Sanders Peirce's remark concerning the impossibility of making a false statement about the null set was made before some fine distinctions were drawn to avoid paradox. In current terminology the "solution set" of a false statement is not the null set but an element (member) of the null set, and since the null set has no members the statement is true of nothing. Peirce identified "nothing" with the null set, but today the null set is considered an "existing" set even though it lacks members.

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THE AMATEUR SCIENTIST

Experiments with salt fountains and related instabilities in water

Conducted by C. L. Stong

During the past 15 years it has been learned that under certain conditions a motionless body of salt water whose density increases with depth can, without external stirring or heating, become unstable and generate vertical mixing. Such instabilities probably arise in the ocean, and investigators are beginning to look for them and to understand the mechanisms that cause them. The instabilities are known by such names as salt fountains, salt fingers and oscillatory instabilities. Seelye Martin of the department of oceanography of the University of Washington discusses these phenomena and describes several experiments for demonstrating them with simple homemade apparatus.

"The density of ocean water," Martin writes, "depends primarily on two properties: salt content and temperature. As the water becomes saltier its density increases; as it becomes colder its density also increases. In most regions of the ocean the density increases with depth. Exceptions are regions of strong, transient convection, such as parts of the Red Sea and the Mediterranean (where evaporation makes the upper layer of the ocean saltier and thus denser than the underlying layers) and parts of the polar oceans (where salt that is rejected by the growth of sea ice increases the density of the surface layer).

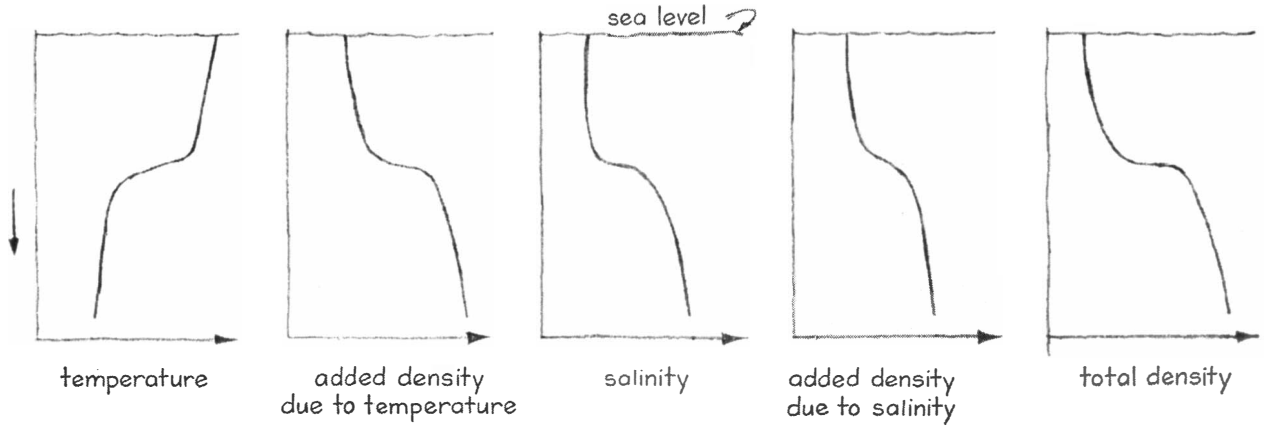
"Because the density depends on both salinity and temperature, cases exist where the total density increases with depth but where the density contribution from either salinity or temperature alone decreases with depth. Therefore two entirely different instabilities may arise. The first (called salt fingers and related to the salt fountain) appears when the density contribution from salinity decreases with depth. Salt fingers consist of thin streams of falling columns of brine separated from one another by rising columns of less salty water.

"The second kind of instability (called an oscillatory instability) appears when the density contribution from temperature decreases with depth. The instability consists of growing oscillations in the transition between the saltier and the less salty zones of water. Both forms of instability are important in understanding the behavior of the ocean because of their contributions to the vertical mixing of salt, heat, nutrients and pollutants.

"An example of a completely stable ocean is found in the Pacific Ocean above 45 degrees north latitude. In this region the temperature decreases and the salinity increases with depth. The density contribution from both conditions increases. The graphs accompanying these remarks [*below*] depict the relations among temperature, salinity and density for this case.

"A comparable example of an unstable condition is found when the density contribution from temperature increases and the one from salinity decreases with depth. This density profile occurs over large portions of the subtropical Atlantic, Pacific and Indian oceans and is particularly strong in the Sargasso Sea near Bermuda. The effect of this density profile on vertical mixing was first described in 1956 by Henry Stommel, Arnold Arons and Duncan Blanchard in a paper titled 'An Oceanographic Curiosity: the Perpetual Salt Fountain.' The authors proposed the following hypothetical experiment: Submerge a long piece of copper tubing, say 1,000 meters long with an inside diameter of two centimeters, in the Sargasso Sea and set the top of the pipe just above the surface of the water [*see illustration on opposite page*]. Connect a pump to the pipe and pump water out of the tube for a period of time. Stop pumping and remove the pump. A fountain of water will continue to flow from the pipe forever!

"The perpetual flow is explained by the fact that the pump draws into the pipe cold water that is less salty than the water surrounding the pipe. The copper walls of the pipe allow heat transfer but



Profiles of temperature, salinity and density for a stable ocean

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not salt transfer, so that the water inside the pipe becomes warmer while retaining its low salinity. Therefore the column of water contained in the pipe is lighter in weight than an equivalent column of water outside the pipe. The difference in weight between the two columns creates a pressure difference that forces the less salty water up the pipe. If the top of the pipe does not extend too far above the ocean surface, the less salty water will spill over, so that more low-salinity water will enter the bottom and travel up the pipe, warming as it rises, until it in turn reaches the surface and spills over. This pumping will continue indefinitely, or until the salt of the Sargasso Sea is uniformly mixed.

"The reverse situation also yields perpetual flow. Suppose the top of the pipe is submerged slightly below the ocean surface and warm saline water is pumped down the pipe. As the salty water descends it will cool from heat conduction and become heavier than the surrounding water. When the pump is removed, the sinking will continue until the Sargasso Sea is again well mixed.

"Would these astonishing experiments actually work? Last February, Stommel, Louis Howard and Dave Nergaard made the first attempt to install a salt fountain in the deep ocean. Stommel described the experiment as follows: 'We took 1,000 meters of Tygon hose (5/8 inch in inside diameter) to a location near Martinique. We had a lot of trouble with tangling and collapsing of the tube; it was cheap but far too flexible. We got a fountain about 60 centimeters high but were not absolutely certain whether or not waves acting on the surface float were more important in pumping water up than the density difference that undoubtedly did exist inside the tube. We ought to try again with a stiffer hose and a spar buoy to isolate things from wave action. It might be rather premature to say that we actually got a salt fountain, although I think we did.'

"The salt fountain was the first clue to the presence of a natural instability. The next step came in 1960, when Melvin Stern, an oceanographer then at the Woods Hole Oceanographic Institution, pointed out that a related instability, salt fingers, would appear under the same conditions that maintain the operation of the perpetual salt fountain.

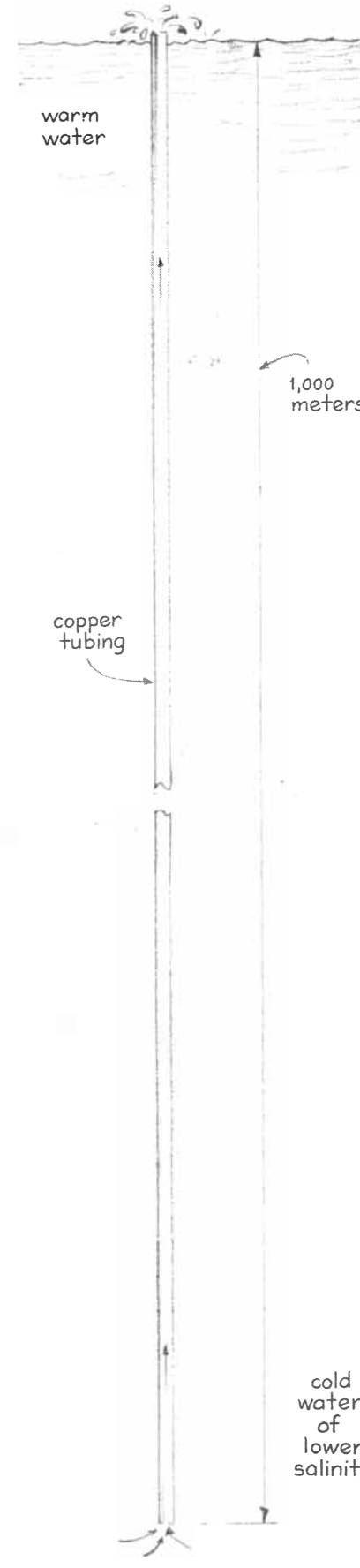
"A kind of natural copper pipe exists in the ocean because in saline solutions heat diffuses about 100 times faster than salt. If a layer of warm, salty water is placed over a layer of cold, not-so-salty water, miniature salt fountains or salt fingers form naturally at the interface [*see upper illustration on next page*]. What happens is that heat diffuses across the interface much faster than salt. The lower part of the warm, salty layer cools. The upper part of the cold, not-so-salty layer warms. Immediately a denser fluid overlies a less dense fluid. The most efficient way for these layers to overturn is for tiny fingers of fluid, with diameters of the order of one centimeter in the ocean and one millimeter in the laboratory, to alternately sink and rise at the interface. (The much weaker density differences in the ocean compared with the ones that can be created in the laboratory cause the change of scale in the size of laboratory and ocean fingers.)

"Another approach to understanding how salt fingers develop is to assume that a wavy disturbance deforms the initially flat interface [*see lower illustration on next page*]. Blobs of cold, not-so-salty water move up into the warm, salty water and vice versa. Because of the difference in diffusivities the higher blobs gain only heat, so that they become lighter and continue to rise. Simultaneously the lower blobs lose heat, become heavier and fall. Four fingers of rising water surround each finger of falling water and vice versa. On a miniature scale salt fingers act as efficient heat exchangers.

"Because of heat losses through the side walls of uninsulated containers in the laboratory, experimenters encounter difficulties in generating salt fingers with heat and salt. To avoid this problem the British physicist Stewart Turner makes salt fingers with sugar and salt. Sugar diffuses much more slowly than salt. In Turner's experiment salt plays the role of heat and sugar plays the role of salt. The possibilities for confusion are great, of course, but Turner avoids it in part by referring to salt as *T* stuff (temperature stuff) and sugar as *S* stuff (salt stuff). The amateur experimenter should remember, however, that the density of ocean water increases as its temperature decreases, so that a cold solution implies an excess of *T* stuff.

"Following Turner's scheme salt fingers can be generated in the laboratory or the kitchen by filling the bottom half of a container with a solution containing more salt than sugar, so that the bottom layer has more *T* stuff than *S* stuff. The top half of the container is filled with a solution containing more sugar than salt, so that the top layer has less *T* stuff than *S* stuff. Salt fingers should develop at the interface.

"A more detailed recipe for salt fingers follows: Make a solution of two and a half level teaspoons of salt and one teaspoon of sugar in one measuring cup of



Hypothetical salt fountain

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water. In a second measuring cup mix a solution of two teaspoons of sugar and one teaspoon of salt in water. Stir both solutions thoroughly. (Incidentally, most brands of table salt contain either sodium silicoaluminate or magnesium chloride to prevent the salt from getting lumpy. Unfortunately the additives also make the salt solutions cloudy. Try to obtain salt without these additives.)

"Pour the solution that contains the most salt into a glass container, preferably one with vertical walls. Cut from writing paper a disk with a diameter equal to the inside diameter of the glass container. Tie a thread to the disk and carefully place the disk in the jar over the lower solution [*see top illustration on opposite page*]. It does not matter if the disk slips slightly below the surface.

"To make the salt fingers visible add dye to the upper solution. I used two dyes: a brilliant blue dye called methyl blue, which is available from chemical-supply houses, and a red dye called 2-carmine, which is a drawing ink made by the Pelikan Company and is available from dealers in art and drafting supplies. Methyl blue, which comes in crystalline form, gave slightly better results. (The problem with kitchen dyes, such as food coloring and soy sauce, is that the diffusivities of these dyes are equal to or greater than the diffusivity of salt. In this demonstration the rate of growth of the salt fingers depends on the diffusion of salt. If the dyes diffuse at the same rate, the individual salt fingers become blurred.)

"Pour the second solution slowly onto the paper disk. When the fluid stops swirling, raise the disk gently above the interface. Disturb the interface as little as possible. For the salt fingers to be visible the initial interface between the dyed and the undyed fluid should be as distinct as possible. If the motion of the disk creates too much mixing, lift it less than an inch and let the paper remain in the container. Within an hour salt fingers will appear; they will remain visible for 12 to 24 hours.

"To see an individual salt finger, repeat the same experiment in a test tube with an inner diameter of about five millimeters. Seal one end with a cork. Mount the tube vertically. Using an eyedropper or a small pipette, pour the heavier fluid into the glass tube until the free surface rests near the midpoint of the tube. Next pour the lighter solution gently into the tube. The walls of the tube will suppress the turbulent mixing. Within an hour several fingers will form. The details of an individual finger will be clearly visible [*see bottom illustration on opposite page*].

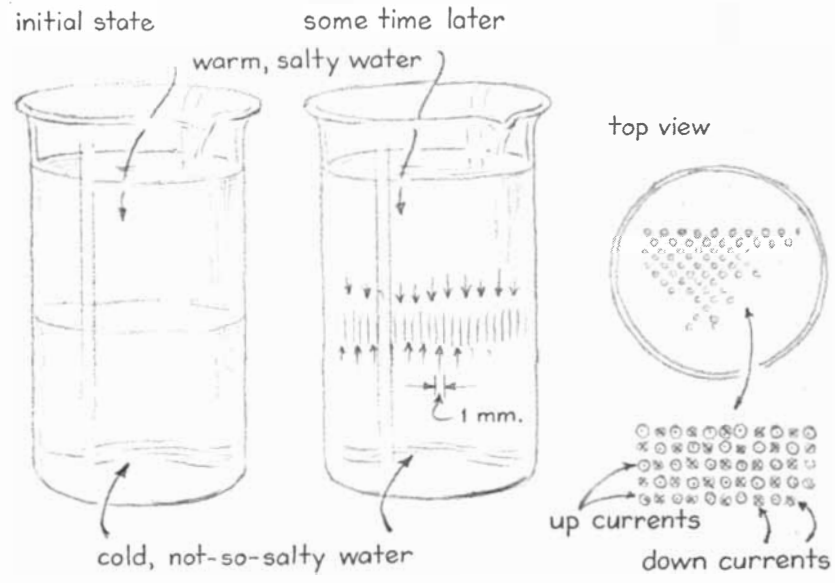
"A patient observer will see two different kinds of flow in the tube. The first kind is an ordered flow caused by the salt fingers. Above and below the salt fingers, however, lies a second region of random, near-turbulent plumes. The plumes appear because after the fingers fall or rise a certain distance their salinity becomes the same as the salinity of the surrounding fluid. At this point salt diffusion is unimportant. The ordering effect of the salt-finger mechanism ceases. The fingers become randomly falling plumes.

"Because of their small size salt fingers have not yet been observed in the ocean. On the other hand, salt fingers have proved to be an extremely general mixing phenomenon. Fingers can appear whenever two or more solutes stratify a fluid. For example, solar physicists speculate that an analogy to salt fingers may occur in the sun because of the variations in temperature and angular momentum with radius.

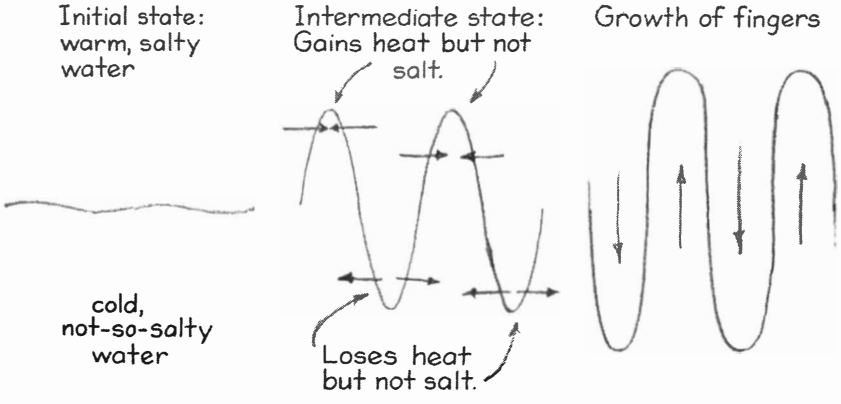
"Metallurgists are investigating another example: the cooling of molten metal castings that contain impurities. As the molten metal solidifies, the effects of the temperature and the impurities cause the casting to stratify. The investigators hope to show that a salt-finger analogy explains the distribution of impurities in the cold metal.

"The opposite density profile (where the contribution of temperature to density decreases with depth and the contribution from salinity increases) also yields an oscillatory instability. Profiles of this type are found in several places, including the hot-brine deeps of the Red Sea [see "The Red Sea Hot Brines," by Egon T. Degens and David A. Ross; SCIENTIFIC AMERICAN, April, 1970]. There three large deeps (named Chain Deep, Atlantic II Deep and Discovery Deep after the oceanographic vessels from which they were discovered) are filled with a hot, salty brine.

"The Atlantic II Deep is the largest of



Appearance of salt fingers



Side view of salt-finger development

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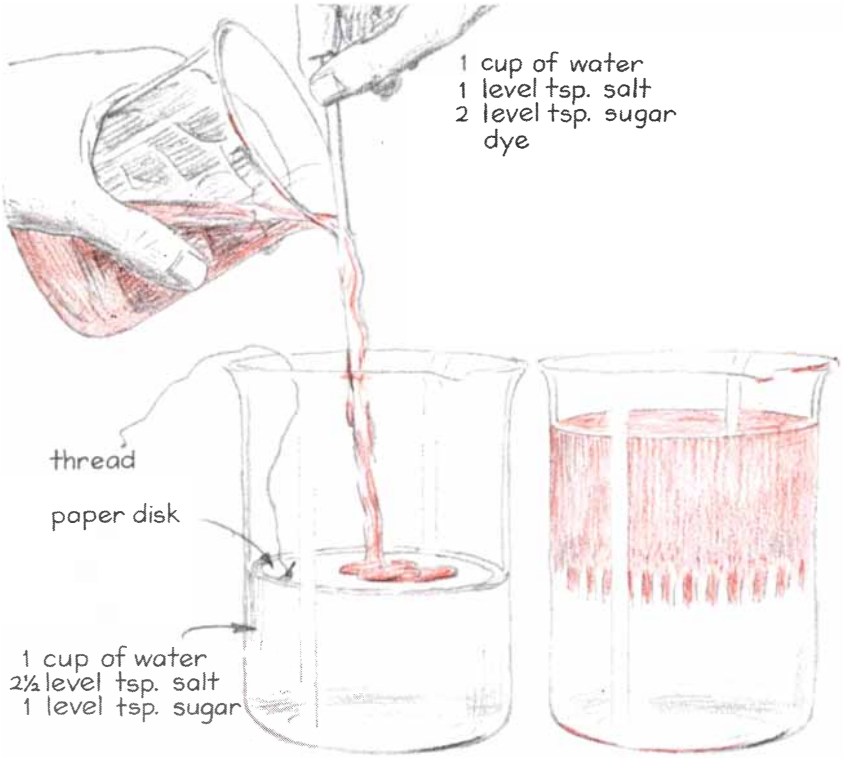
the three, being 14 by five kilometers in surface dimensions and about 100 meters deep. At the top of this deep the salinity and temperature have the characteristic Red Sea values of 41 grams of salt per liter of solution and 22 degrees Celsius; 50 meters farther down the values are 257 grams per liter and 56 degrees C. The temperature and salinity profiles in the Chain Deep and the Discovery Deep are similar. Economics has stimulated interest in these deeps. Estimates of the gross value of the zinc, copper, lead, silver and gold contained in the top 10 meters of sediment in the Atlantic II Deep range as high as $2.5 billion, exclusive of recovery costs.

"A second example of similar stratification exists in Lake Vanda in Antarctica. Vanda is ice-covered. Relatively fresh water is found directly below the ice at a temperature of zero degrees C. Some 220 meters down the water temperature is 25 degrees C. and the salinity is about 150 grams per liter.

"Still another example is the solar ponds of Israel, which are used to convert heat from the sun into electricity. The ponds consist of large containers about a meter deep with black bottoms. The bottom half of the pond is filled with salt water, the top half with fresh. The black bottom absorbs solar radiation and heats the adjacent salty water. The density profile remains stable because of the salt. For this reason heat cannot escape to the atmosphere through the process of convective overturning. The hot, salty water is selectively withdrawn from the solar ponds and used to drive a generator, after which it is returned for reheating.

"To understand how the deeps and Lake Vanda were formed and to calculate the age of the brine contained in them the investigators must first understand how and with what speed hot, dense brine mixes with overlying, less salty, cold water. In the solar ponds the rate of mixing of hot brine with the overlying water decreases the efficiency of the heat trap. In practical terms the effect reduces the amount of electric power produced by a given pond. Insight into each of these systems can be gained by considering the mechanism of oscillatory instability.

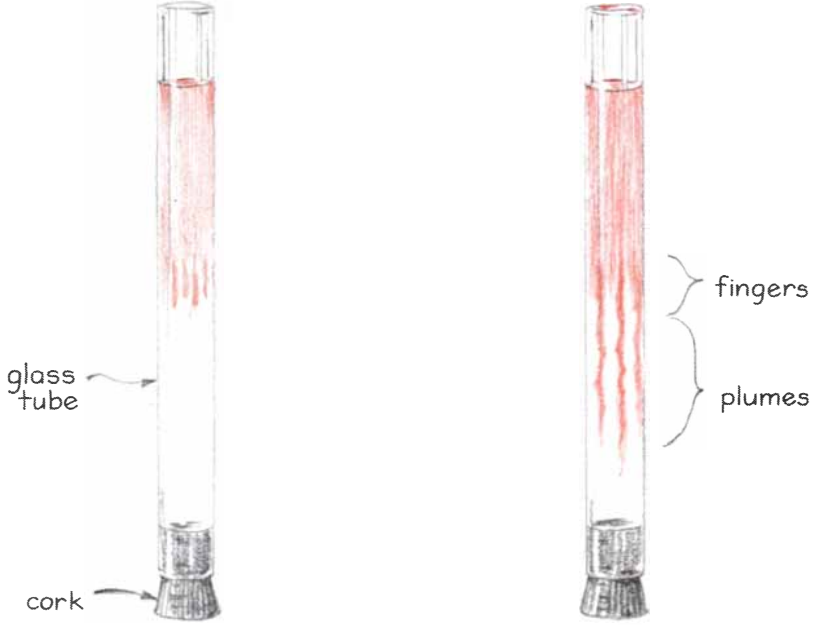
"What happens when a layer of cold, not-so-salty water overlies warm, salty water? Suppose a fluid element on the interface is displaced slightly downward from its equilibrium position. In the ocean or the laboratory any small random disturbance can create the initial displacement. Because heat diffuses much faster than salt the displaced element will gain heat and buoyancy. It will rise above its original position into colder fluid and continue rising until the element loses its added heat and becomes colder and heavier. It will then sink again into warmer fluid, gain heat and initiate another cycle.



Arrangements for generating salt fingers

"If the salinity difference between the two fluids is not too great, the oscillations will continue to grow in amplitude until turbulence results. On the other hand, a large salinity difference will restrict the oscillations occur for every element of ly growing amplitude. In either case such oscillations occur for every element of the interface. A vigorous laminar, or turbulent, mixing results.

"To demonstrate instability of this kind Turner and Edward A. Spiegle of New York University designed the fol-



Apparatus for observing individual salt fingers

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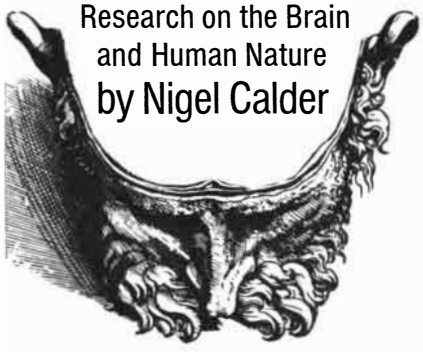

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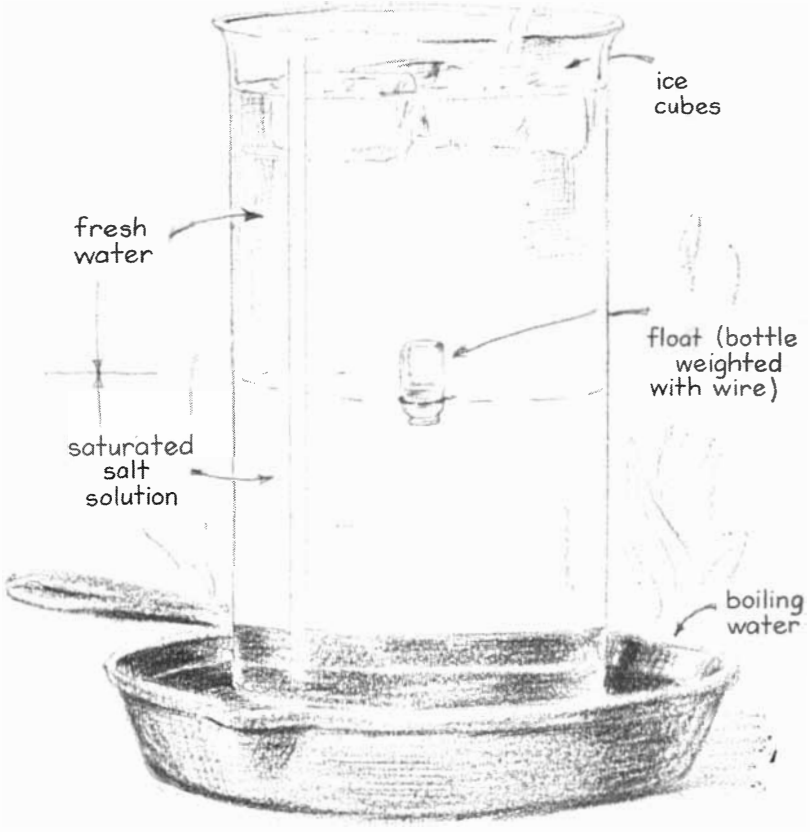
lowing simple kitchen experiment, which the Swedish oceanographer Pierre Welander and I built together while Welander was recently visiting the University of Washington. With the paper-disk technique a large glass container was filled half with saturated salt solution and half with fresh water. The container was placed in a frying pan with fresh water. We put the pan on the stove and boiled the water.

"Putting ice cubes on the surface of the water in a jar, we created a situation where water at the upper surface was near the freezing point and water at the bottom was near the boiling point. The resulting oscillations at the interface between the fresh water and the salt water were made visible in two ways. First, we put food coloring into the upper layer so that the turbulent billows were evident. Second, we improvised a glass float with a small, uncapped food-coloring jar about an inch in length. By winding copper wire around the open neck we weighted the bottle so that it floated neck down [*see illustration below*]. Then, by adding to and removing from the bottle water as needed, we trimmed the bottle so that it floated at the salt-water-fresh-water interface. The trimming was surprisingly easy. When the bottle sank too deep, we recovered it with kitchen tongs.

"The trimmed bottle served as a nondiffusive element of salt water. The air in the bottle, which expanded and contracted with changes in temperature, responded as a fluid element would to changes in temperature. Once the bottle was properly trimmed it quickly developed an oscillation with a period of between 10 and 20 seconds and a peak-to-peak amplitude of about five centimeters.

"The amplitude of both the float displacement and the fluid oscillations depends on the density difference between the two fluids. We could increase the amplitude simply by stirring salt into the upper fluid. When the density difference is made great, the oscillations continue for hours. A small density difference quickly yields turbulent mixing of large amplitude. A sugar solution will produce an even longer-running oscillation because of its small diffusivity.

"Experiments of this kind demonstrate the effectiveness of both salt fingers and oscillatory instability in generating vertical mixing. A task for an inquiring mind is relating these intriguing mechanisms to an understanding of both the history of the ocean and the ocean circulation."



Apparatus for observing oscillatory instability

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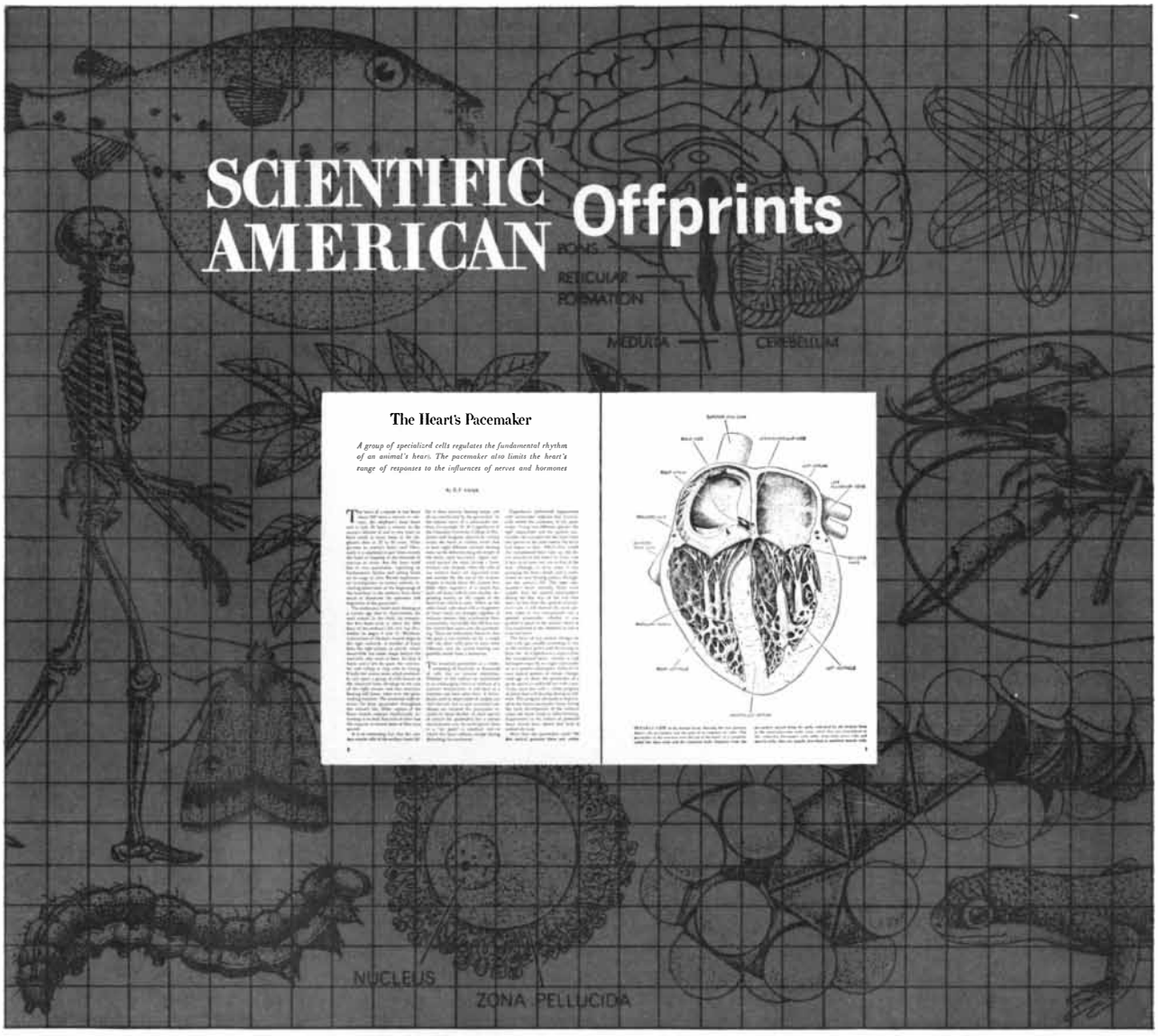

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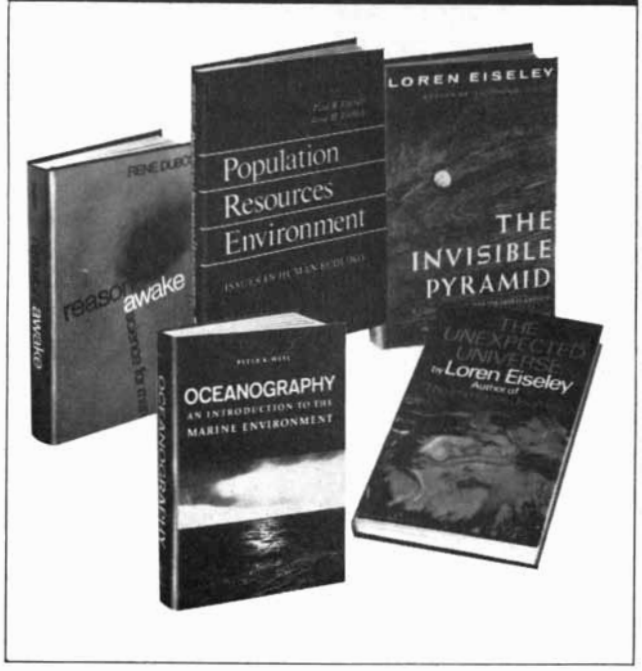

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BOOKS

Blood as a test of the basic principles of human relations

by Philip Morrison

THE GIFT RELATIONSHIP: FROM HUMAN BLOOD TO SOCIAL POLICY, by Richard M. Titmuss. Pantheon Books ($6.95). The patients in Solzhenitsyn's *Cancer Ward* are debating: " 'That depends. For example, Vladimir Solovyov argues rather convincingly that an economy could and should be built on an ethical basis.' 'What's that? Ethics first and economics afterwards?' Kostoglotov looked bewildered."

Here is a veteran and distinguished economist, professor at the London School of Economics, ex-cabinet minister, deeply identified with the social architects of the British welfare state, presenting a clear, documented, crisp book in support of Solovyov—a book whose aim is indeed to bewilder quite a few Kostoglotovs, the planners and rationalizers in all countries.

The facts are plain, drawn from statistics of supply and demand, from sampling interviews of blood donors, from government reports and testimony. The use of whole human blood in medicine has grown greatly in the past few decades. Only one source is capable of meeting this demand: the healthy half of the population that is not too old, not too young and neither pregnant nor nursing. A donor can give without any ill effect six or eight pints per year, but whole blood cannot be stored longer than three weeks without risk. Some eight million units (430 to 450 cubic centimeters per unit) were collected in the U.S. in 1967. (This is Titmuss' estimate, which rests on a rather elaborate set of inferences and questionnaires.) About half was bought and sold. Less than a tenth was given by voluntary donors, and in New York City that proportion had dropped from 20 percent in 1956 to 1 percent in 1966. Blood has several prices. The paid supplier gets between $5 and $20 per unit. The patient who does not replace the blood he receives may have to pay from $30 to $100. (Costs are still rising, of course.) Since many patients need 20 pints or more (300 pints is not unknown in open-heart surgery), replacement by friends is hardly practical within the usual time limit of two or three years.

Shortages and crises of supply are common. They are notably brought by weekends and holidays. There is much waste, induced by hoarding against shortage and by lack of a centralized administration. The paid donors are largely unemployed, unskilled young men, with "a high preponderance of Negroes and various 'minority' groups such as prisoners." There is a major hazard from induced serum hepatitis, running up to 4 percent in one study. The paid donor, whose ranks include drug addicts and alcoholics, and on whose honesty the reported quality of the blood depends, greatly increases the risk, even with pooled plasma and special irradiation.

In Britain the National Health Service has since 1948 operated its voluntary, unpaid service for blood "on the basis of common human needs." Almost all donors are unpaid; to the 1.5 million donors in 1967–1968 the total compensation paid was 808 pounds. The risk of hepatitis is less by an order of magnitude. The delivered and processed price was under two pounds per bottle. Waste is less than in the U.S. by a factor of 10 or 20. Shortages are uncommon; they occur mainly in out-of-the-way places, often after the sudden demand of an accident. The donors appear to be a fair cross section of the eligible population. Women account for 40 percent of the blood; in the U.S. their share is probably less than 10 percent.

The private market in blood is full of risk not only to the patient but also to the donor. It gives rise to severe shortages; it is intrinsically wasteful and inefficient. It opens the door to a still more market-centered medicine, with commercial hospitals and paid drug-testers—a proletariat of medical risk.

The problem is not only American. In Japan 98 percent of the blood is bought and sold. The shortage is acute, and Ambassador Reischauer himself contracted hepatitis while hospitalized in Tokyo in 1964. It is not only capitalist. In the U.S.S.R. about half of the blood comes from paid donors. The price there is high: about two weeks' minimum wage. No information about shortages or the characteristics of donors is available. Sweden, perhaps surprisingly, relies entirely on the marketplace for blood. There is a growing shortage, but the authorities are in a dilemma. If they abandon payments, patients may suffer. "It is easier for societies to abandon altruism as a motive . . . than it is to abandon the principles of economic man once . . . institutionalized."

In the Union of South Africa there are five transfusion services. By apartheid regulations "European and non-European blood donors are bled on separate premises or are bled on the same premises but are suitably separated." In the hospitals run by the gold mines of the Witwatersrand the 1967 rates were: Bantu, Colored and Asian, 10 shillings per pint of blood; White, 40 shillings per pint. These are low prices. (It is not known if recipients are charged more for the "White" than for the "Black" red blood.)

The gift relationship is strong in many societies, both modern and older ones. Claude Lévi-Strauss and others have analyzed the structure of gift-exchange in terms of complex exchanges that seem far from the modern gift of blood: urgent yet impersonal, anonymous, without the wish for an exchange, beyond control by the giver or the recipient. Blood, as Goethe wrote, is a very special juice. Giving, however, is a good, and giving life through blood is a good open equally to the poor, the uneducated and the privileged. The eloquence of the reasons given by British donors adorns one of Titmuss' chapters: "I mite be saving somebody life"; "No man is an island"; "A small way to help people—as a blind person other opportunities are limited." Why in the name of the market, of utilitarian economics, of "consumerism," of optimization, should this freedom to give be withheld? Milton Friedman, to mention one market-bound American economic theorist, has nothing to say about

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it. Such theorists regard everyone as the sole estimator of his own welfare, and their neat solutions seek to make virtual changes "as long as nobody is worse off and at least one person is better off." Alas for gifts that may even harm the givers and alas for motives as ancient as envy or fraternity, justice or pride.

Karl Marx, like the Russian bureaucrats, is too utilitarian for Titmuss, too little concerned for equality of reward. There is in this book a sharp sense of that Christian socialism out of which the British Labor Party arose. In a cynical world dark with miscalculations of advantage the British system of blood collection shines brightly. It may not be the future, but it works. Perhaps the young will own more of such a future; it seems to be what they want. Professor Titmuss is an old party, but he thinks that new generations might come to see that "socialism is also about giving."

IMPACT OF NEW TECHNOLOGIES ON THE ARMS RACE, edited by B. T. Feld, T. Greenwood, G. W. Rathjens and S. Weinberg. A Pugwash Monograph. The M.I.T. Press ($2.95). UNDERSTANDING DOOMSDAY: A GUIDE TO THE ARMS RACE FOR HAWKS, DOVES AND PEOPLE, by Thomas Gordon Plate. Foreword by Senator George S. McGovern. Simon and Schuster ($2.95). Two up-to-date paperbacks—one stout and technical, the other compact and journalistic—span the physical and social (should one say antisocial?) sciences of the arms race. The Pugwash monograph, the report of a conference held in Wisconsin last summer by experts from half a dozen countries (including the U.S. and the U.S.S.R.), is a set of papers and a summary of discussion in four areas: new weapons technology (both defensive and offensive), the problems of preventing the diversion of nuclear explosives from peacetime power plants, the nature of military research and development, and a brief overview of the political implications.

One paper, representing more than a quarter of the book, is a highly expert review of the cause and cure of error in the guidance of ballistic missiles. Its author—David G. Hoag, director of the Apollo Guidance and Navigation Program of the Draper Laboratories of the Massachusetts Institute of Technology—could hardly carry more authentic credentials. He is a careful, if not a cautious, arguer, yet his conclusion is startling. There is no technical barrier to the development within a matter of years of missiles capable of delivering a warhead across half the world with a final miss distance of less than 100 feet! The present standard is surely no better than about one or even two kilometers, judging both from a step-by-step analysis of the causes of error and from the extrapolated experience of space launches and commercial aircraft guidance. The main sources of this miss distance are three in number. The largest is the effect of tiny imbalances in the gyroscopes; a tenth of a microgram of dust or a 10-angstrom shift in the center of mass of the fast-spinning wheel is enough. The second is the knowledge of the initial conditions. A 100-ton rocket is too elastic a structure to define its aim well enough just by sitting there. Special optical beams or ingenious applications of the guidance system itself are needed. The act of turning off the fiery jet at the right moment is hard to make precise; the use of a small vernier rocket engine is the evident solution, but it is complex to realize.

To bring these errors down to a small fraction of their present value seems quite feasible. The ultimate error lies in the winds and the shifts of the final incandescent reentry into the atmosphere; here only feedback control is good enough. To build an active reentry vehicle that can correct its aim a little requires precision guidance at high acceleration. Even the ocean tides (shifting gravity) contribute a few meters of error, and satellite mapping techniques must improve by an order of magnitude if distant targets are to have known positions. Dr. Hoag judges that all of this is within reach; even if he should prove rather too sanguine, a 100-foot error is a remarkable forecast. Such missiles spell the end of land-based rockets in silos, particularly with multiple warheads. In another paper Victor C. Anderson of the Scripps Institution of Oceanography sees the future as holding high-power, ocean-wide sonar. Artful beam-shaping techniques could make the seas "transparent" and reveal the missile submarines. Dr. Anderson has a harder task than Dr. Hoag; the great military virtue of inertial guidance is that it is self-contained, looking only at gravity maps and Newton's laws, or maybe out at a star or two on the way. But any sonar can be jammed, and clever moving jammers would pretty surely beat the art of beam shaping. Nonetheless, the prospect is for moves to call up once again the illusion of the preemptive strike, giving great advantage to the attacker.

In *Understanding Doomsday* Thomas Plate, a *Newsweek* writer on leave, has put together a crisp and genuinely helpful book on the arms race that carries us pell-mell toward an invisible goal. His emphasis is on the history and concepts of the race, which he makes as plain as can be in that dark forest of acronym (with at most an occasional oversimplification that some sharpster could cavil at). Here are SALT, MIRV, ABM and DL (damage limitation), with a glossary, a chronology, a who's who, an alternate Department of Defense budget and plenty of condensed tabular material to back up the arguments. One metaphor is particularly apt: "Two chess players not only move and countermove their pieces on the board but also introduce new pieces as the game goes on, until the board is so filled with new pieces that each move has dangerous and far-reaching implications within very packed confines." Nor can one forget that the costly new pieces must be built, and that there is no single player but a complex society of leaders, officers, industrialists—even shortsighted voters. The arms race of the 1970's, Plate reckons, will be about the elegance and power of the new pieces, not their number.

It is impossible for a detached witness to credit the chiefs of the arms race with expectations of nuclear war. They must believe that their weapons, however ready, will somehow never be used. This illusion has lasted us for one risky generation. It is not designed for permanence. The most helpful note at the Pugwash meeting was sounded by a London expert, Ian Smart. He observes that a nation is indeed likely to be deterred, as any individual would, by a 99 percent probability of death. But should not a 50 percent probability of losing all four limbs be enough?

CURRENT TRENDS IN CRYOBIOLOGY, edited by Audrey U. Smith. Plenum Press ($15). FREEZING POINT: COLD AS A MATTER OF LIFE AND DEATH, by Lucy Kavaler. The John Day Company ($8.95). There it is to the life, a tiny "common shrew," poised for sniffing, long nose lifted, a forepaw curled. It is in reality freeze-dried whole, its little body pumped out while within refrigeration coils, for a recent exhibit at the British Museum. The last of the world's passenger pigeons "sits . . . on a branch in a glass case in [the] Smithsonian," its stuffed skin and feathers prepared in a less subtle way after its dead body was shipped in 1914 from Cincinnati to Washington, frozen within a 300-pound cake of manufactured ice.

These two books deal thus differently

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with the same topic, the rise of the use and understanding of low temperature over the full span of biological science and technology. The Smith book presents a set of seven review papers by British specialists, working in general biology, food technology, vacuum engineering and surgery, who survey the entire field for an audience of cryogenic engineers. Well illustrated, with many graphs and more than a few simple formulas, it is quite accessible to the general reader. The Kavaler book is a popular account casting an even wider net, particularly in history and in the reporting of opinion. The Smith book produces a greater sense of immediacy by its expertise, detail and photographs. You can see the silver-tipped cryosurgical probe used to induce lesions at specific points in the brain for the relief of certain neurological disorders. This probe makes possible the assistance of the conscious patient, whose reports give the surgeon a chance at error-correction in the minute before the cells are irreversibly frozen. The chapter is written by a surgeon who has himself carried out such operations. In the Kavaler book the use of low temperatures in surgery is adequately and entertainingly described without illustrations (there are a few symbolic line drawings) but with the account of *Life*'s coverage of the chief developer of the operation for Parkinsonism, and the useful information that chemotherapy now appears to have become the method of choice for treating that grievous troubling disorder.

Ice-cold people can recover; indeed, the hospital low-temperature record appears to be about five degrees Celsius during surgery. Small laboratory mammals not only have survived supercooling to five or 10 degrees below zero C. but also have withstood being frozen stiff, if the state was not prolonged more than a couple of hours and if most of "the water distributed through the tissues of the body" had not frozen. Hibernators, of course, endure cold very well, but there is some indication that freezing induces internal and covert injuries, even though these do not always prevent recovery.

The Life Extension Society and other groups have for about five years sought to promote the practice of deep-freezing at liquid-nitrogen temperatures in the uncertain hope of resurrection, not to life eternal but to an earthly future possessed of more powerful therapy. Their pioneer case has been encapsulated in Los Angeles, naturally, since 1967. The British cryobiologists take a gloomy view of this

A plausible approach toward understanding Christianity in today's technological world

THE GOD WHO CARES

A Christian Interpretation of Time, Life, and Man

A Narrative by

HAROLD F. ROELLIG, Ph.D.

Department of Earth Sciences, Adelphi University

THE BOOK: In an age when confusion with regard to the exterior world is matched by inner confusion, it is useful, says Dr. Roellig, to place the Judaeo-Christian tradition in the context of a contemporary, historical, scientific world view. In *The God Who Cares,* he has established a unified and holistic vision of the acts of God through time in the form of a narrative of God at work in the origin of the universe, at work in history, at work now.

Drawing upon his scientific background, he examines from a theological perspective the current major theories of the origin of the universe, the origin and evolution of life, the evolution and nature of man, and the origin and development of religion from prehistoric, through Biblical, to modern times.

CONTENTS: *Plan and Purpose • Origins and Evolution, 12,000,000,000 B.C.–2,000,000 B.C. • Man 2,000,000 B.C.–50,000 B.C. • Man the Worshipper, 50,000 B.C.–1700 B.C. • Abraham and the Old Covenant, 1700 B.C.–A.D. • Jesus and the New Covenant, c. A.D. –33 A.D. • The Church of The Way, 33 A.D.–300 A.D. • The Church of the Word, 300 A.D.–1971 • The Way in Today's World • Index*

ABOUT THE AUTHOR: Preceding his graduation from Concordia Seminary, St. Louis, Mo., Harold Roellig published "Reasoned Unbelief, circa 1957"–an article cast as a Socratic monologue that trenchantly defined from an agnostic point of view the issues and tensions between the contemporary scientific world view and the Judaeo-Christian tradition. This article was the culmination of years of undergraduate and graduate study in the social and natural sciences taken at Washington University concomitantly with the author's seminary training.

The issues explored in this article led Mr. Roellig, in 1957, to graduate work in the Geology Department of Columbia University in order to study with Dr. George Gaylord Simpson and Dr. Theodosius Dobzhansky. After teaching invertebrate paleontology at Columbia and sociology at Concordia College during sabbaticals, he began, in 1960, his doctoral dissertation on fossil vertebrate specimens at the American Museum of Natural History; that same year, he was appointed Lutheran campus chaplain for Long Island colleges.

In 1964 the author was appointed part-time instructor in geology at Adelphi University; in 1967 he received his Ph.D. from Columbia's Department of Geology; in 1969 he resigned his chaplaincy and accepted an appointment as assistant professor at Adelphi.

These seventeen years of study, research, thought, and lectures in theology and the social and natural sciences have resulted in the ideas and insights that now appear in *The God Who Cares.*

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Pascalian wager turned materialist: "Irreversible damage to the brain occurs at normal temperatures within minutes of the stopping of blood circulation." Freezing, by the way, does not induce genetic change in bacteria.

Charles I of England enjoyed ice cream prepared from a secret recipe by his French chef. The chef was bound to perpetual secrecy by a huge pension; when the secret leaked, says Mrs. Kavaler, the artist was beheaded. (Internal evidence makes her tale suspect.) At any rate, the dessert long antedates Dolly Madison; sherbet, of course, is older than Nero in the Chinese court.

There are experiments showing biosynthesis and spore germination in a special ammonia-loving mutant of the penicillin mold living at a frigid 40 degrees below zero C. in a medium of liquid ammonia and glycerol. In this area too science is catching up with the commonplace of science fiction.

The icy glitter of the silvered Mylar wrapper of the Kavaler volume is a book designer's tour de force, singling the book out among a thousand.

IFA DIVINATION: COMMUNICATION BETWEEN GODS AND MEN IN WEST AFRICA, by William Bascom. Indiana University Press ($20). AFRICAN ART: AN INTRODUCTION, by Frank Willett. Praeger Publishers ($4.95). The Yoruba are a people of the West African rain forest, now perhaps 10 million in number in Nigeria and Dahomey, long famed for their subtle and urban culture, even though they lack a written language. Bascom's book is an ethnological account of their practice of divination: the appeal to Ifa, god of divination, by means of a corpus of prophetic verses coded by 2^8 binary chance results. To cast Ifa, the professional diviner, or *babalawo* ("father has secrets"), uses 16 smooth black palm nuts. He grasps them between his hands and tries to take them all in his right hand. They are a big handful, and a final successful grasp leaves either one or two in the left hand. After eight trials the sequence of even and odd choices has generated a unique binary number, marked out by the finger in wood dust on a tray. The diviner knows verses for each number—perhaps many verses. With the talents of a man of affairs, a courtier and a psychiatrist he recites the verses he knows in ignorance of just what question his client has put to him. The client listens and chooses an apt reply. It is a projective test, as most such elaborate systems to help men decide are. One practitioner came in contact with an ethnographer who was making Rorschach studies. She regarded the "Rorschach Test as a divinatory technique," and asked her visitor to "look Ifa" for her. The resemblance of the practice to the famous and ancient I Ching, the Chinese casting of the yarrow stalks, is evident.

Three-fourths of Bascom's monograph consists of a set of Ifa's verses. There are 186 presented, a random sample covering only 53 of the figures—less than a fifth of what every *babalawo* knows by heart. The verses are parables, often on familiar folktale themes, explanatory of phenomena and of ritual. Their setting in time seems to vary widely; Ifa is by no means dormant. The recently introduced maize and even railroads turn up in the verses, the latter possibly only as humor. It is an unusual numerological note that in Ifa trees, rats, leaves and animals all come in 165 kinds. Why?

The color photograph of a modern divination board, carved with the handsome face of Eshu, the divine messenger, "the principle of uncertainty in the Yoruba pantheon," unites Bascom's book with Willett's *African Art*. Professor Willett's book—he is the scholar whose work on the bronzes at Ife has become classical—is an unpretentious, small-page survey of art in Africa. It is handsomely illustrated with many pictures in color, but its freshness and intelligence distinguish it even in that many-booked field. Its center of attention is plainly the peoples living in the vast drainage of the Niger and of the Congo, although the Kalahari Desert and Zimbabwe are not ignored. Three photographs will make plain why this book is a pleasure to the mind. You can see the same wooden mask, an object made by the Fang of Gabon, that someone gave to Maurice Vlaminck in Paris in 1905. When André Derain saw it, he was "speechless" and "stunned," and he bought it from Vlaminck. Derain showed it to Picasso and to Matisse. "The revolution of twentieth-century art was under way." You can see a splendid four-foot bronze figure, elegant as a Bodhisattva, held by the Nupe on Jebba Island in the Niger until it was stolen last July. You can also compare the work of a contemporary Yoruba master carver making wooden twin figures with the copies made by his three apprentices.

There is a final chapter on African art today, in its vigor both West and East. Art is beyond the usual scope of these reviews, but Willett has given so genetic and so contextual a treatment that his small book transcends the discipline of art history to become an indispensable part of the history of the skills and ideas of mankind. It is a real bargain in dollars and in a reader's time.

A HISTORY OF π (PI), by Petr Beckmann. The Golem Press, Boulder, Colo. ($6.30). This cheerful work, not very thick but with plenty of illustrations, is rather like one of the more allusive and historical of Martin Gardner's columns. It draws its material largely from the standard sources in the history of mathematics—Carl B. Boyer, Thomas L. Heath, Dirk J. Struik—but it enriches even them by a knowing use of the similar Russian literature and by not a few original pieces of work by the author himself, who is an electrical engineer with one mathematics text in a more conventional vein already to his credit.

One will find a listed BASIC program—14 lines—that instructs the computer to perform the famous original Buffon and Laplace Monte Carlo evaluation of pi by throwing a needle onto ruled paper and counting the intersections. That a value for pi is entered into the program itself to tell the machine how to distribute the needle direction randomly in angle only brings out the circularity of the digital study of such an analogue process—the pun included. Professor Beckmann knows of this weakness, and he uses the example only to illustrate the method. (Twelve thousand needle throws yield pi to barely three correct decimal places.) There is a handsome facsimile Japanese manuscript page of the year 1698 displaying the rearrangement method, which cuts a circle into pie slices (pi slices?) and then nests them alternately point to point to build a wavy kind of rectangle with dimensions half the circumference by the radius. Thus πr^2 was found for the circle's area in Japan as it was by Leonardo da Vinci. The speculation here is that the method was known to antiquity.

We see mathematics from Euclid and Archimedes to Euler and modern times in the little mirror of pi. "Euler's mass annihilation of all problems connected with the evaluation of π gave a complete answer to the question of its numerical value." It was only in the 1880's, however, that analysis first proved pi to be transcendental—"worse" than irrational. Still circle-squarers did not give up; one of the dottiest, a citizen of Cleveland, published a book on his solution in an edition of thousands in 1931.

Here too is the famous bill of the Indiana State Legislature, No. 246, 1897 (it died in the Senate after passing in the

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House), which states by implication that pi is 3⅛. There are mnemonic rhymes for a couple of dozen digits of pi, given in English, French and German. The decimal expansion is cited only to 200 places, which seems a bit of a pity. Almost a decade ago the *Journal of Computing Science* carried pi to 100,000 verified decimal places, providing a useful table of quasi-random digits. (We are promised that the second edition of the book, due in the fall, will give 10,000 of them.) The 200 places, however, were first found in 1844 in two months' work by the 20-year-old calculating prodigy Johann M. Z. Dase. He was given the series expansion for the arc tangent and a well-known formula for $\pi/4$ as the sum of three arc-tangent terms. The great Gauss years later got Dase support for computing large factor tables, but Dase died at 37 with his tables half-done.

The author is a man of positive opinions ("History relates of certain men and institutions that I admire, and others that I detest"), and he freely vents his crotchets. Rome was the capital of thugs, Aristotle ignorant and tiresome, and medieval scribes besmirched their parchments with "superstitious garbage." If one can put up with such invective here and there, he will find the book a useful source of results and drolleries. Historians will have the last word.

THE SOURCES OF INVENTION, by John Jewkes, David Sawers and Richard Stillerman. W. W. Norton & Company, Inc. ($2.75). In 1958 the three learned authors published the first edition of this enlightening study, with specific case histories, from the automatic transmission to the zipper, showing the complex nature of the process of technological innovation and arguing strongly that the race is not now, and never was, to the large team laboratory alone. Individual inventors—who are by no means to be thought of as being mainly daft but brilliant self-taught loners but came as often from the Massachusetts Institute of Technology and the Technische Hochschule of Munich in the 19th century as they do now—play an indispensable role, frequently augmented by a driving development by the big firms. This paperbound second edition holds to the same view, and it has added 10 new cases, including digital computers, phototypesetting and oxygen steelmaking. It is a strong argument, although not one beyond doubt. One feels there have been important changes since William Perkin and Rudolf Diesel, hard as it seems to name them definitely.

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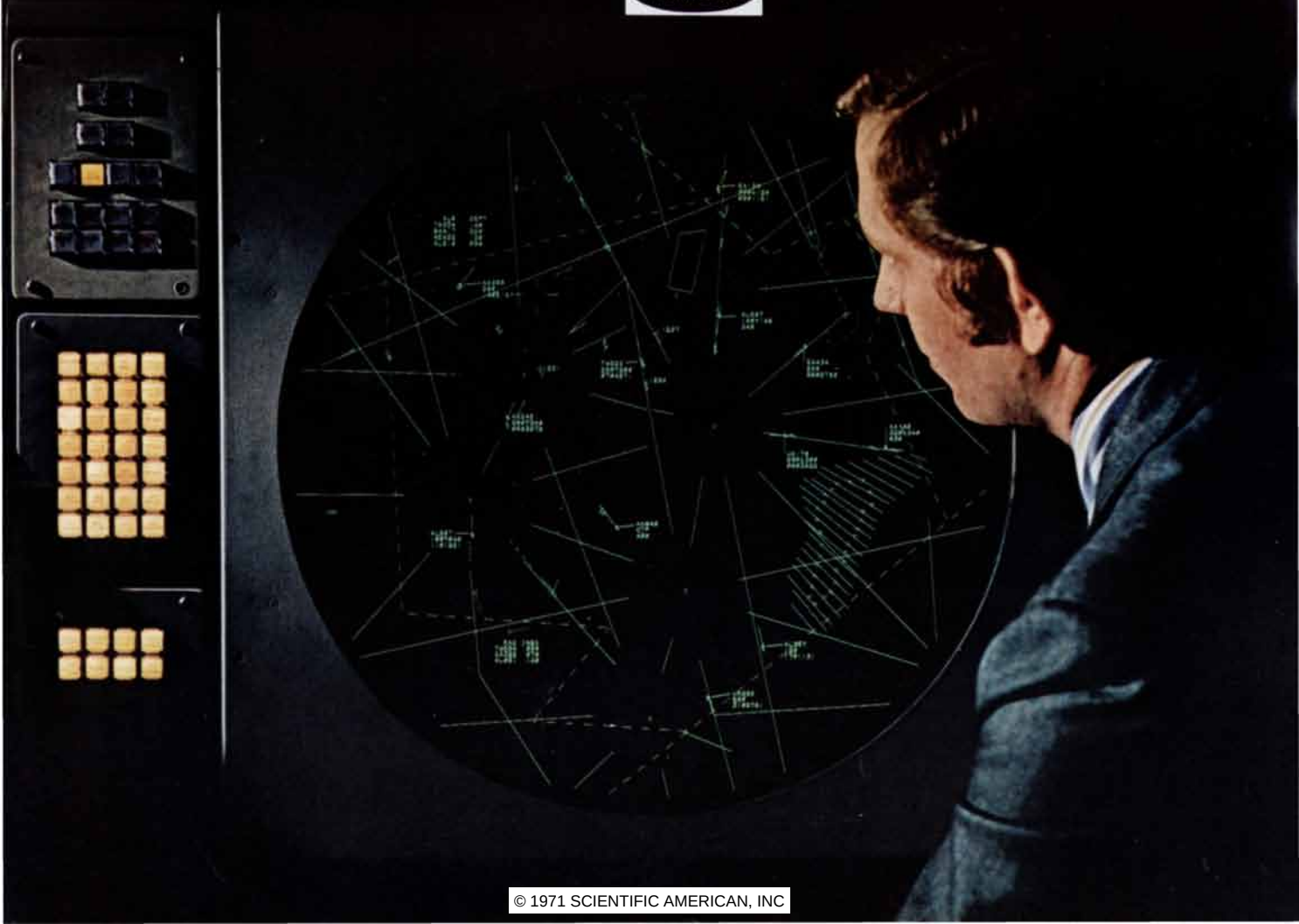

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