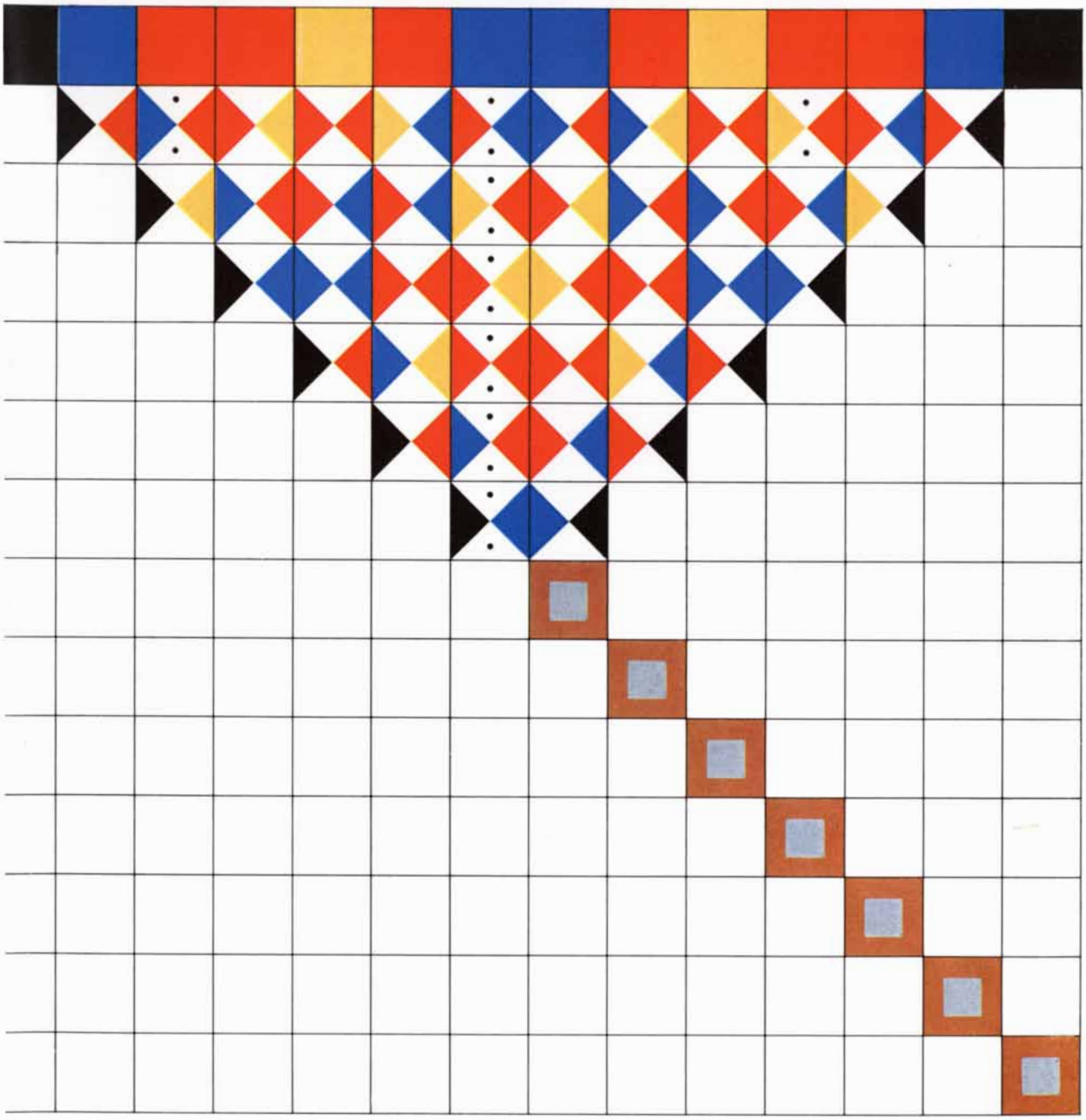
SCIENTIFIC AMERICAN



CELLULAR AUTOMATON

ONE DOLLAR

February 1971

She's riding over one of the biggest

This Dutch housewife was born the year oilmen began drilling near her home town.

When she went to high school, they were still drilling and still hadn't had any luck.

But the drilling went on for good reason. Holland had very little domestic oil and urgently needed more energy for industry.

In 1959, after thirteen years of drilling and some two hundred dry holes, Jersey's Dutch affiliate and its partner finally struck something big. Not oil. But gas. Ten thousand feet under the local sugar beet fields, they found the largest single source of energy ever discovered in Europe.

This discovery, called the Groningen Field, has caused quite a stir on Holland's home front. Old-fashioned coal stoves are disappearing and practically all gas-operated appliances have been converted to natural gas. It took five years and about $180 million to do the job.

There's a similar story in industry. About 65 per cent of Holland's larger factories have already converted to the new fuel.

But Holland isn't alone in feeling the effects of Groningen. Over four thousand miles of pipeline now allow Holland to export gas to Germany, Belgium and France, where it runs

things that ever happened to Europe.

steel mills, power plants, breweries and even heats sidewalk cafes.

Visit the Groningen Field today and it's difficult to believe that you are standing on top of one of the biggest things that ever happened to Europe.

Pipelines are buried. Digging scars have been healed by re-seeding. And hundreds of trees have been planted around the main compressor station. Not just for their beauty. But to muffle noise and preserve the peace.

Seagulls still soar over this lonely station. Cows graze and people camp nearby. All as if nothing had happened.

We are rather proud of this.

Standard Oil Company (New Jersey)

Esso

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.

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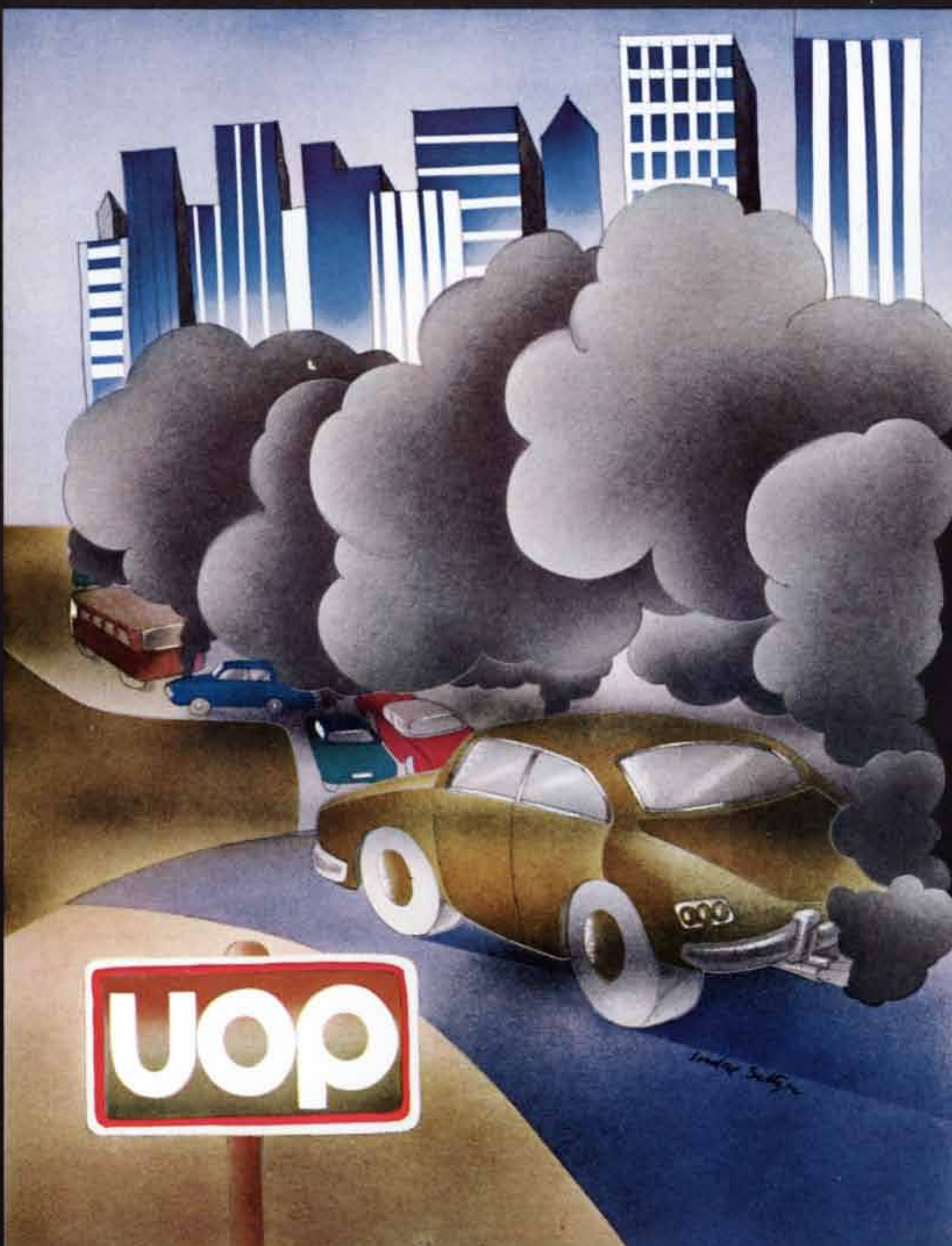
UOP is the nation's leading supplier of processes and technology for the petroleum industry to produce automotive fuels and for desulphurizing other petroleum products. In a related area the company manufactures a broad line of industrial air and water pollution control equipment.



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Established 1845 **SCIENTIFIC AMERICAN** February 1971 Volume 224 Number 2

ARTICLES

DEPARTMENTS

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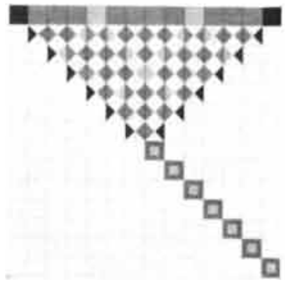

THE COVER

The design on the cover shows how a palindrome—a phrase that reads the same in either direction—can be recognized as such by a cellular automaton, a system of uniform cells whose states change according to specified rules. The palindrome TOO HOT TO HOOT is symbolized in the top line, with the *T*, *O* and *H* represented by blue, red and yellow respectively. The configuration changes in successive rows as certain transition rules are applied (see "Mathematical Games," page 112). The two dots in the left-hand cell in the seventh row from the top signify recognition of the palindrome; thereafter the right-hand cell changes to an "accept" state (*nested squares*), which persists until the edge of the cellular space is reached. The automaton, a pattern-recognition machine devised by Alvy Ray Smith III, is one application of cellular automata theory, which has generated a number of mathematical games as well as more theoretical applications.

THE ILLUSTRATIONS

Cover illustration by Alan D. Iselin

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Whatever became of what's-his-face?

The impressive doors yawn wide. A young man still in his twenties, bright and enthusiastic, resumé in hand, walks in. The doors close, and swallowed within the corporate yawn, he becomes quietly anonymous.

Multiply the scene by the thousands each year. Engrave a company, or governmental, or educational or institutional name on the doors. Cast the principal players as male or female, black or white, young or not-so-young; it doesn't seem to matter very much.

Because in a very short time they all begin to look and act anonymous anyway.

Sure, our young man was out to lick the world when he was hired, but that was before he knew he had to lick the organization first.

If the organization is rigid with inflexibilities and staffed with supervisors who know how to say no but not yes, he is likely to seek a more invigorating climate. Worse yet, he may just give up, keep his eyes open and mouth shut, and begin twenty years of payments on a little retirement cottage.

It doesn't have to be that way.

Must every organization undergo corporate hardening of the arteries? Not so, we say.

Preventive medicine starts with something as basic as respect for the worth of the individual, practiced as well as preached.

When Harvey's promotion opens up a slot, we don't look for a replica of Harvey to plug in.

(Because who, in all the world, is exactly like Harvey?)

Corporate life can be beautiful.

We start by defining the job objectives. Then we give the job, along with plenty of latitude in achieving those objectives, to the individual whose skills, experience, character, and *attitude* most impress us.

The way he sets about getting results, we have reasoned, ought to be no less his responsibility than the results themselves. Given enough freedom and flexibility, he may do a few great things that Harvey never thought of. Or reject a few unnecessary things that Harvey always did.

It's not just good works, it's good business.

We think there's nothing that motivates people quite as effectively as treating them as individuals whose ideas are important.

When our people invent a fantastic new product such as videotape, it doesn't happen by accident. When they invent a lightweight adhesive strong enough to replace rivets in an airplane, it's not by chance.

It's because they are as dedicated to their company, their jobs and the spirit of discovery, as we are dedicated to the principle of individual worth.

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In the end, one kind of dividend is paid to our employees, another to our customers, and another to our stockholders.

Simply because at 3M, everybody is somebody.

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LETTERS

Sirs:

In his interesting and colorful review of the etiology of rickets [SCIENTIFIC AMERICAN, December, 1970] W. F. Loomis repeatedly stresses the point that calciferol is a hormone rather than a vitamin, and that the name "vitamin D" not only is a misnomer but also has been misleading on a conceptual basis.

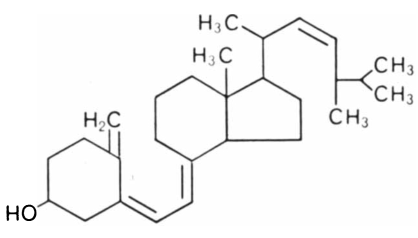
The facts set forth by Loomis are of course well known to nutritionists. Some of us can remember the unfolding in the 1920's of the fascinating story that set forth the dual nature of the antirachitic factor as supplied either by ultraviolet radiation or by diet. Loomis' contention is that because vitamin D_3 is synthesized in one tissue and translocated to others, vitamin D is not a vitamin any more than the thyroid hormone is. This tenet, however, would also make a hormone out of ascorbic acid, because in all species except primates and the guinea pig it is synthesized in the liver and translocated for utilization in fibrous tissues and the vascular endothelium. The same definition of a hormone might also include nicotinic acid, because of its endogenous production from the amino acid tryptophan.

Loomis wrongly identifies vitamin D_3 as calciferol, which is actually vitamin D_2 and has the structural formula shown below.

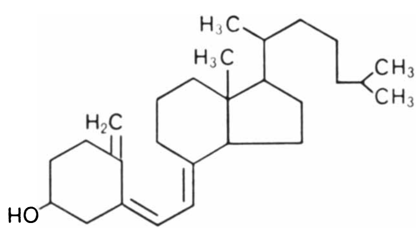
The discovery that there are dietary sources of antirachitic factor was what placed it in the vitamin category. This was a great contribution to public health because it led to improvement of the diet. Simultaneously the knowledge spread widely that ultraviolet radiation was also antirachitic. This was not ignored or forgotten, as Loomis states repeatedly. As an example, in poultry husbandry the use of windows made of a material that allowed the transmission of ultraviolet radiation was introduced at about the same time that fish oil was added to poultry diets. And in pediatrics the clinician had two strings to his bow, sunlight and vitamin D. He used them both.

THOMAS H. JUKES

Department of Nutritional Sciences
University of California
Berkeley, Calif.



Calciferol, vitamin D_2



Vitamin D_3

Sirs:

Tom Jukes is correct that many metabolites are neither vitamins nor hormones. Classically a hormone is defined as "a chemical substance produced in an organ, which, being carried to an associated organ by the blood stream, excites in the latter organ a functional activity" (*The American Illustrated Medical Dictionary*). Calciferol fits this definition. In addition, disease results from the presence of too much as well as too little calciferol in the system, a fact that recently induced the British to reduce by half the amount of ergocalciferol added to milk the better to walk the tightrope between rickets on the one hand and infantile hypercalcemia on the other.

Jukes is wrong in holding that calciferol exists in the normal diet of men and animals; it is almost completely absent in all nonfish diets that are not artificially fortified with the steroid. The misnomer "vitamin D" has led to the misconception that rickets was caused by an inadequate diet; both recent Europeans and prehistoric Neandertal men developed rickets from inadequate exposure to solar ultraviolet (see "Was Virchow Right about Neandertal?" by Francis Ivanhoe; *Nature*, Vol. 227, No. 5258, page 577, 1970). Quoting from textbooks that list rickets under vitamin-deficiency diseases only shows how wrong the textbooks can be on the nature of the disease.

The unique nature of the physiological steroid made by the skin and present in cod-liver oil has been known for nearly 35 years; it alone deserves the name calciferol. All artificial man-made analogues of the natural compound deserve derivative names such as ergocalciferol, which is made by artificially irradiating a fungal steroid with ultraviolet light, a view that is reinforced by the fact that ergocalciferol ("vitamin D_2") is less than 1 percent as effective as calciferol itself in preventing rickets in chicks.

Finally, Jukes states that "in pediatrics the clinician had two strings to his bow, sunlight and vitamin D. He used them both." The recent appearance of infantile hypercalcemia in Britain referred to above suggests that pediatricians had better not use both strings at the same time; hypercalcemia may result. In fact, it can be argued that the level of calciferol put artificially into milk should be decreased during the summer in rural populations as well as decreased the nearer one is to the Equator. The physiological aim should be to keep the sum of solar ultraviolet and calciferol artificially added to milk a constant.

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NAME

NEW ADDRESS

OLD ADDRESS

SCIENCE/SCOPE

When Canada's TELESAT satellite communications system goes into operation in mid-1973, it will include two satellites in synchronous orbit and an initial network of 30 to 40 earth stations. Each satellite will provide 12 radio-frequency channels, each of which can carry one color television signal or up to 960 voice channels. Heavy route stations at Victoria, B.C. and Toronto, Ont. will serve major population centers, while smaller television reception stations will serve isolated communities in Canada's Far North.

TELESAT will be the world's first domestic commercial synchronous satellite system. Three satellites are being built by Hughes and two major Canadian associate contractors, Northern Electric Co. Ltd. and Spar Aerospace Products Ltd.

Radar for the U.S. Air Force's F-15 single-seater air superiority fighter is a lightweight, advanced design of high reliability, optimized for one-man operation. It detects and tracks small, high-speed targets at all altitudes down to treetop level, and provides the central computer with accurate tracking information for effectively launching the F-15's missiles or firing its 20-mm. gun. For close-in dogfighting, the radar automatically acquires the target on the pilot's head-up display. Hughes was chosen to develop the radar by McDonnell Douglas, the F-15 prime contractor.

Amphibious landings, air and ground beachhead operations, and other tactical situations will be simulated on a new test bed facility Hughes is developing for the U.S. Marine Corps. The test system utilizes standard off-the-shelf commercial data processing and display equipment, and is regarded as a more flexible, economical way to investigate and evaluate various subsystems than building complete prototypes of them. The Marine Corps will use test results to determine the extent of automation required for electronic command-and-control systems for the mid-70s and beyond.

The first-round hit capability of the M60A1 tank will be markedly increased by a new solid-state ballistic computer system Hughes is developing for the U.S. Army. It will also enable the tank commander or gunner to instantly select the best type of ammunition for a specific combat condition. The computer will include a self-test capability and provide for automatic fault isolation to minimize field maintenance. Hughes will build six working prototype computer systems under a one-year contract.

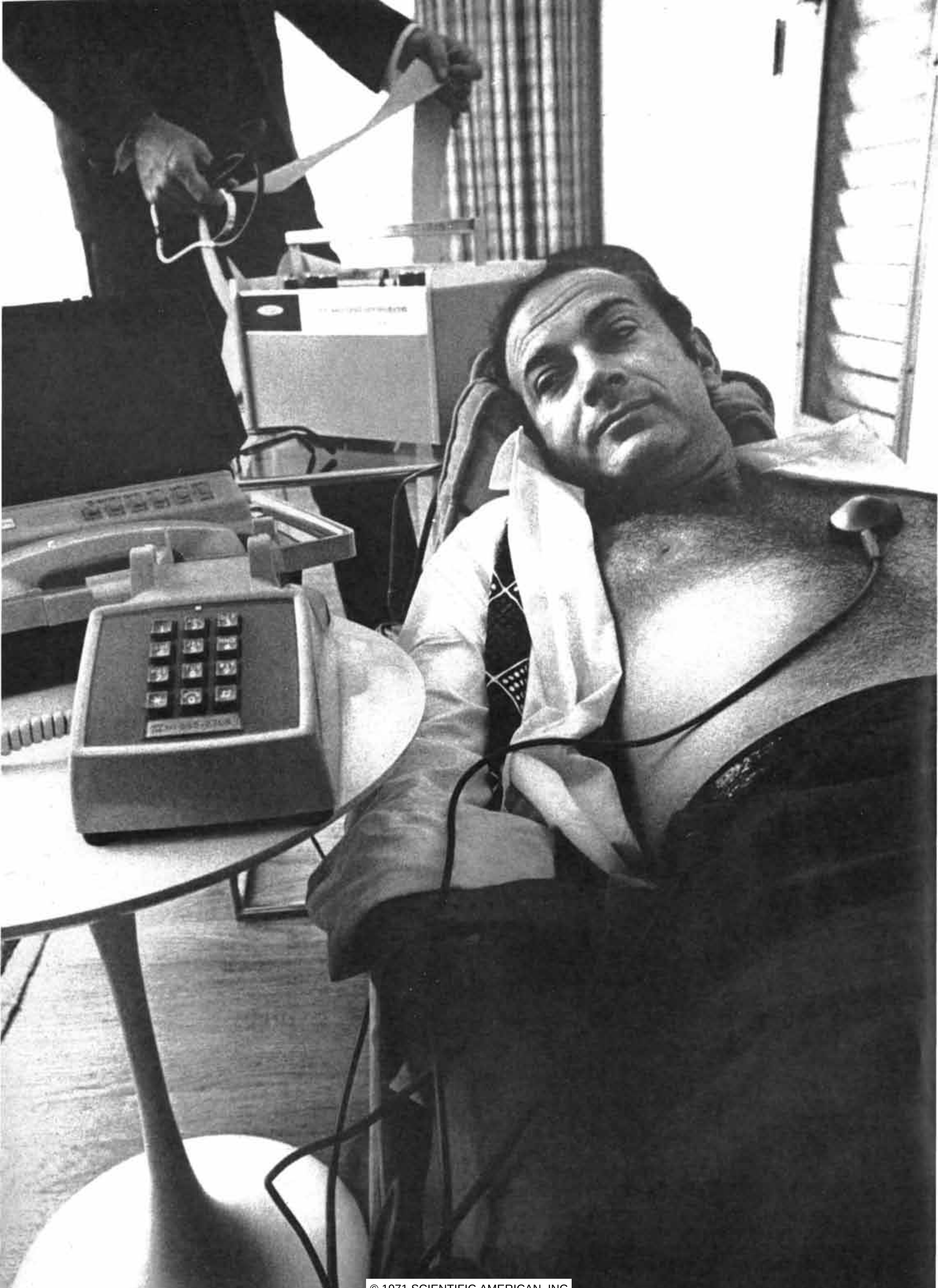
Airborne radar transmitter design engineers are needed now at Hughes. Must have specific fire-control-system, doppler, pulse-compression, microwave, and power-supply experience. Also needed: solid state microwave engineers with experience ranging from UHF to millimeter frequencies, and in the design and use of related circuits. Both positions require accredited degree, at least 3 years of specific experience, and U.S. citizenship. Write: Mr. Robert A. Martin, Hughes Aerospace Engineering Divisions, 11940 W. Jefferson Blvd., Culver City, CA 90230. An equal opportunity M/F employer.

A versatile anti-tank combination was demonstrated recently when the U.S. Army's Cheyenne helicopter made the first air launch of a TOW missile with a warhead. The target, a World War II tank, was destroyed. Additional TOW missiles were fired from both hover and high-speed flight, including post-launch maneuvering before TOW impact. Built for the Army by Hughes, TOW is a tube-launched, optically-tracked, wire-controlled missile designed to destroy tanks, armored vehicles, and field fortifications.

Creating a new world with electronics

HUGHES

HUGHES AIRCRAFT COMPANY



50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

FEBRUARY, 1921: "'Ever since a year ago announcement was made that a rocket was under development which should in principle be capable of reaching great altitudes, even as great as interplanetary distances, there have been numerous articles of more or less authenticity. Mr. Morrell states in the *Graphic* that "bodies when they speed through the air are subject to friction against the air which is sufficient to generate tremendous heat" and that "the rocket will generate a red heat for most of the first 100 miles." As a matter of fact, the velocity of the rocket must of necessity be small where the air is dense, being under 2,000 ft./sec. for the first 20 miles, at which height the pressure becomes but 1 per cent that at sea level. Even at a 95-mile elevation the velocity would be but slightly over two miles per second, where the air has an estimated density of but four one hundred millionths that at sea level. The speed of 6.4 miles per second, of which Mr. Morrell speaks as causing the rocket to "vanish in an incandescent wisp of flame and smoke," would not be reached until an altitude of over 700 miles had been attained, at which height there must exist practically a complete vacuum.'—R. H. Goddard"

"Public attention has been widely and deservedly attracted during the past month to a notable achievement of observational astronomy—no less an advance than the actual measurement of the diameter of a fixed star. With a high magnifying power all stars appear as minute disks, but the size of these disks depends not on the star but on the telescope. They are mere optical effects, inevitably produced by the influence upon the waves of light of the circular aperture through which the light enters the telescope. The greater the aperture of the telescope is, the smaller will be this 'diffraction pattern'; but even with the largest instruments it remains of such a size as to conceal from us those fine details which often we would most desire to observe—such as the existence of very close double stars and in particular the actual disks of the stars themselves. Professor Michelson, by a brilliant application of the interferometer, has added the solution of this problem to the scientific advances which this apparatus has permitted. The apparatus which has just been put into use at Mount Wilson, as an attachment to the 100-inch telescope, permits of a maximum separation of 20 feet between the interferometer mirrors. With this apparatus it has been determined that the diameter of the star Betelgeuse is probably fully three times as great as the earth's distance from the sun —in round numbers about 300,000,000 miles, fully as big as the whole orbit of Mars."

"The creator of the French liquid air industry, M. Georges Claude, has just made a new and important discovery in the industrial synthesis of ammonia. The method requires neither complicated apparatus nor vast installations. The inventor deals with pressures of several hundred atmospheres in order to unite nitrogen with hydrogen, pressures which artillerists alone were handling up to now, in guns of heavy caliber. What distinguishes the Claude method of synthetic manufacture of ammonia from the process invented by the German Haber is the incontestable superiority of its yield. With an equal volume the Claude tubes produce 25 times as much as the colossal installations in which the German chemist carries on his manufacture."

"A movement is being started to provide Russian scientists and men of letters with literature which they miss so sorely. A certain amount of scientific research and some literary work still goes on notwithstanding the Bolsheviki, who are losing some of their hostility to scientific and literary work, and what is left of the once flourishing scientific life of Russia has now been brought together into two special rationing organizations which ensure at least the bare necessities of life."

SCIENTIFIC AMERICAN

FEBRUARY, 1871: "The results of the last census, just published by the Census Bureau at Washington, give the total population of all the states and territories of the Union by the enumeration of 1870, as compared with that of 1860. The total population of the U.S. in 1870 was 38,538,180, an increase in 10 years of 7,094,859. All the Western states show heavy percentages of increase, the Southern and Middle states a small increase, while New England is almost at a standstill."

"The newly invented 'flying machine,' of which our readers have heard so much during the past year or two, was recently tried again, and according to the San Francisco *Bulletin* with considerable success. When everything was tightened and got in good running order, and the propeller arranged to cause elevation, it was just quarter of one o'clock. The fire for raising steam was kindled, and in one minute and a quarter steam was opened. At 13 minutes to one the machine was cut loose, and the propellers started. She then rose most gracefully in the air, amid the cheers of the crowd who had gathered to witness the ascension. The machine was guided by cords attached to both ends of the balloon and in the hands of persons on the ground. She ascended 50 feet and sailed along about a block, when she was pulled down to have her boiler replenished. Again she rose, this time to a height of about 200 feet. All the machinery connected with it worked to the perfect satisfaction of the inventor, who intends to place it on exhibition at some place, of which notice will be given. The name given her is 'America.' "

"The causes which led to the just-concluded war between France and Germany have been sufficiently discussed; the causes of the defeat of France and the effect which the triumph of the German arms will have upon Europe and the world at large are more fruitful themes. Many will attribute the Prussian success to superiority of numbers. Others will see in it only a triumph of one breech-loading gun over another. Others will see deeper reasons in the difference of the character of the two nations and, searching for the cause of the difference, will find it in their systems of education, which on the one hand has created a nation of educated soldiers and on the other has led to the mental, moral and physical degeneration of a nation once the terror of all Europe. In this war the Prussians have won 800,000 prisoners, including the Emperor and the marshals of France, 6,000 cannon, 112 eagle standards and a large quantity of stores, munitions and small arms. And all of this has been done in a time so short that history may be searched in vain for a precedent. The humiliation of the French nation is complete; the military pride of Germany may be stimulated in equal proportion."

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Max, National's computer, knows where every one of our cars is every minute. When we tell you you've got a car, we know it's going to be there. (National is the only car rental company that can make that statement.)

Parts of our Travelmax program you see. What you don't see are the constant improvements Travelmax makes in our airport procedures that get you to your car faster than ever before.

Add all this up, and it gives you the most advanced reservation system in the car rental industry. When your business is making the customer No. 1, that's the way you do things.

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- S&H Green Stamps
- We feature GM cars: Chevrolet, Pontiac, Oldsmobile, Buick and Cadillac
- 800-328-4567 toll free

THE AUTHORS

J. JULIAN CHISOLM, JR. ("Lead Poisoning"), is associate professor of pediatrics at the Johns Hopkins University School of Medicine and associate chief hospital physician in pediatrics for the Baltimore City Hospitals. He was graduated from Princeton University in 1944 and obtained his M.D. at Johns Hopkins in 1946. He has remained there except for a year as senior assistant resident in pediatrics at Babies Hospital in New York. "My major research interests in addition to lead poisoning," he writes, "have been proximal renal tubular function and acute intermittent porphyria. Many of the biochemical features of these disorders overlap the biochemical features of lead poisoning. I am also interested in the social aspects of pediatrics and particularly in the care of foster children. I have some interest in the delivery of health care to rural children. At the moment I have had to drop these other interests in order to concentrate my efforts on lead poisoning. No doubt this will open up considerations concerning the toxicity of other trace metals."

MALVIN A. RUDERMAN ("Solid Stars") is professor of physics at Columbia University. He did his undergraduate work at Columbia, where he was graduated in 1945, and took his Ph.D. at the California Institute of Technology. From 1953 to 1964 he taught at the University of California at Berkeley. He then spent several years as professor of physics at New York University before returning recently to Columbia. He says he "likes providing theoretical solutions to problems involving phenomena and states of matter not accessible in the laboratory. Such theories tend to survive much longer."

JAMES A. TUCK ("The Iroquois Confederacy") is assistant professor of anthropology at the Memorial University of Newfoundland. His original interest was botany, in which he received his bachelor's degree at Syracuse University. He then turned to anthropology, obtaining his Ph.D. at Syracuse in 1969. "I have worked throughout the northeast," he writes, "including New York, New England and the Atlantic Provinces. My first researches investigated the development of the Onondaga Iroquois since the 12th century. Subsequent researches have led progressively northward to Newfoundland, where we have investigated numerous Eskimo and Indian sites." A book by Tuck, *Onondaga Iroquois Prehistory: A Study in Settlement Archaeology,* is scheduled for publication later this year by the Syracuse University Press.

WILLIAM C. GOUGH and BERNARD J. EASTLUND ("The Prospects of Fusion Power") are with the division of research of the U.S. Atomic Energy Commission. Gough, who obtained his bachelor's and master's degrees in electrical engineering from Princeton University, has been with the AEC since 1953, working mainly on civilian and military power reactor programs. For his work over the past 10 years on the commission's research program in controlled thermonuclear fusion and plasma physics he was awarded the sustained superior performance certificate of the AEC. During the academic year 1966–1967 he held a Government sabbatical at the Kennedy School of Government of Harvard University, where he studied the interaction of science and public policy. Eastlund took his bachelor's degree in physics at the Massachusetts Institute of Technology in 1960 and his Ph.D., also in physics, at Columbia University in 1965. He joined the AEC in 1966.

A. O. D. WILLOWS ("Giant Brain Cells in Mollusks") is professor of zoology at the University of Washington. He writes: "I was born in Canada and am still a Canadian citizen. I came to the U.S. in 1959 to study physics at Yale and then made a switch to physiology in 1963 when I began graduate school at the University of Oregon. It was there that I became interested in the neurophysiological basis of behavior. If the truth be known, nudibranch mollusks first attracted my eye because they are often beautiful creatures to look at. I collected many to add color to the laboratory and discovered *Tritonia*'s unusual brain cells nearly by accident. I spend a great deal of time at the Friday Harbor Laboratories on San Juan Island in Washington, where I do most of my research and indulge my interest in animal behavior generally by collecting and studying examples from the great diversity found there. I enjoy scuba diving and flying small aircraft, and I am an active proponent of Zero Population Growth, a national organization dedicated to reducing the growth of our population to zero."

D. L. SLOTNICK ("The Fastest Computer") is professor of computer science and director of the Center for Advanced Computation at the University of Illinois. He received his bachelor's and master's degrees in mathematics from Columbia University in 1951 and 1952 respectively and then worked for two years at the Institute for Advanced Study. In 1956 he obtained his Ph.D. in applied mathematics (celestial mechanics) at New York University. He spent the next 10 years in industry in various engineering activities, going to the University of Illinois in 1965. Slotnick writes: "I have written far too many articles and book chapters and hold a number of patents, including the basic patent on parallel computers. I live on a small farm where I raise horses, ride them and pick my two little girls and occasionally my wife up out of the sawdust. I have a compulsion to plant trees; I have indulged it some 9,000 times on my 40 acres. I read too much and listen to and occasionally play music."

ARTHUR K. SOLOMON ("The State of Water in Red Cells") is professor of biophysics at the Harvard Medical School, where he has been head of the Biophysical Laboratory since 1946. He is also secretary general of the International Organization for Pure and Applied Biophysics and chairman of the biophysics program at Harvard University. Solomon received his Ph.D. at Harvard in 1937 and his D.Phil. at the University of Cambridge in 1947. His early work involved the application of radioactivity to biological measurements. More recently he has been concerned with obtaining an understanding of the roles of structure and composition in controlling the permeability of biological membranes. Solomon's article is his third in SCIENTIFIC AMERICAN.

LADISLAO RETI ("Leonardo on Bearings and Gears") is professor emeritus of medical history at the University of California at Los Angeles. He has also been engaged for many years in the field of the history of technology. Born in Italy, he received his degree in chemical engineering from the Technical University of Vienna and his Ph.D. in chemistry from the University of Bologna. He spent many years in South America, where he founded and directed several chemical industries and taught industrial chemistry at the University of Santa Fe in Argentina. His work in the history of technology has centered on the Renaissance and Leonardo; he has written extensively on the subject and is the editor of the facsimile edition of the Leonardo manuscripts recently found in the National Library in Madrid.

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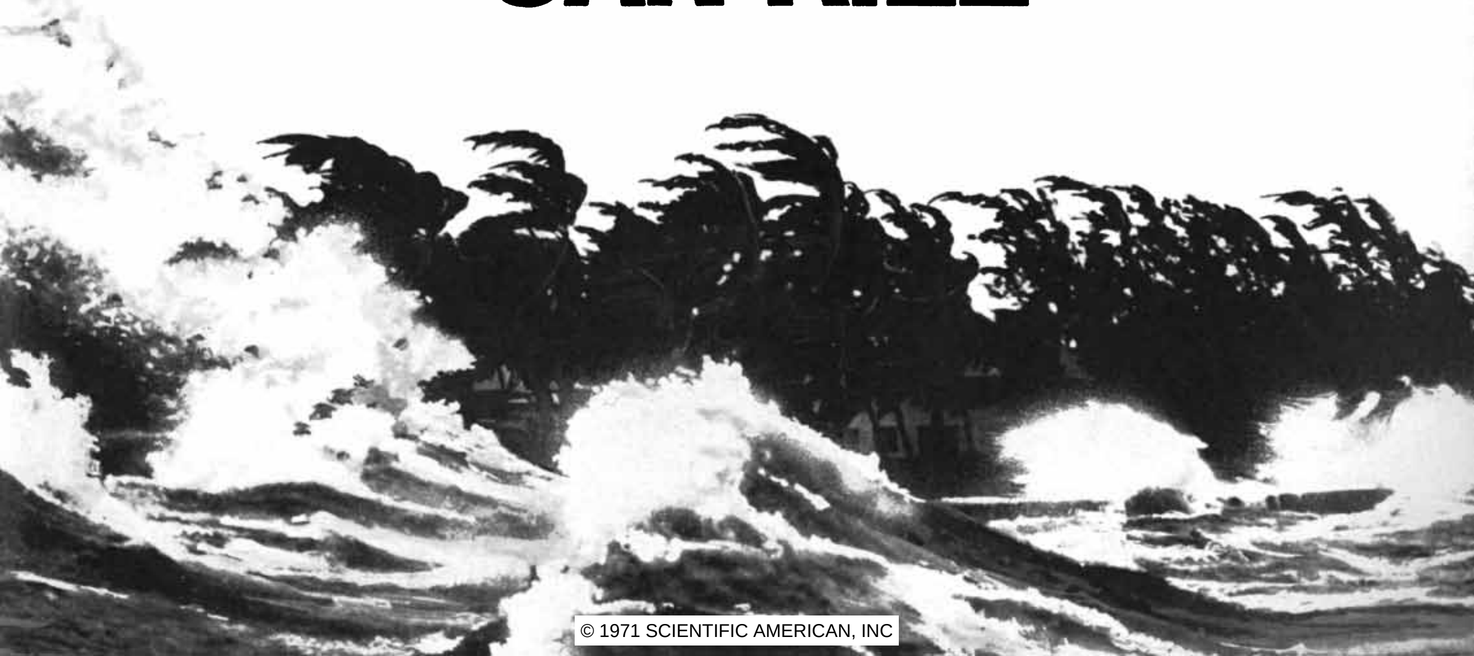

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Established 1845 SCIENTIFIC AMERICAN February 1971 Volume 224 Number 2

Lead Poisoning

Among the natural substances that man concentrates in his immediate environment, lead is one of the most ubiquitous. A principal cause for concern is the effect on children who live in decaying buildings

by J. Julian Chisolm, Jr.

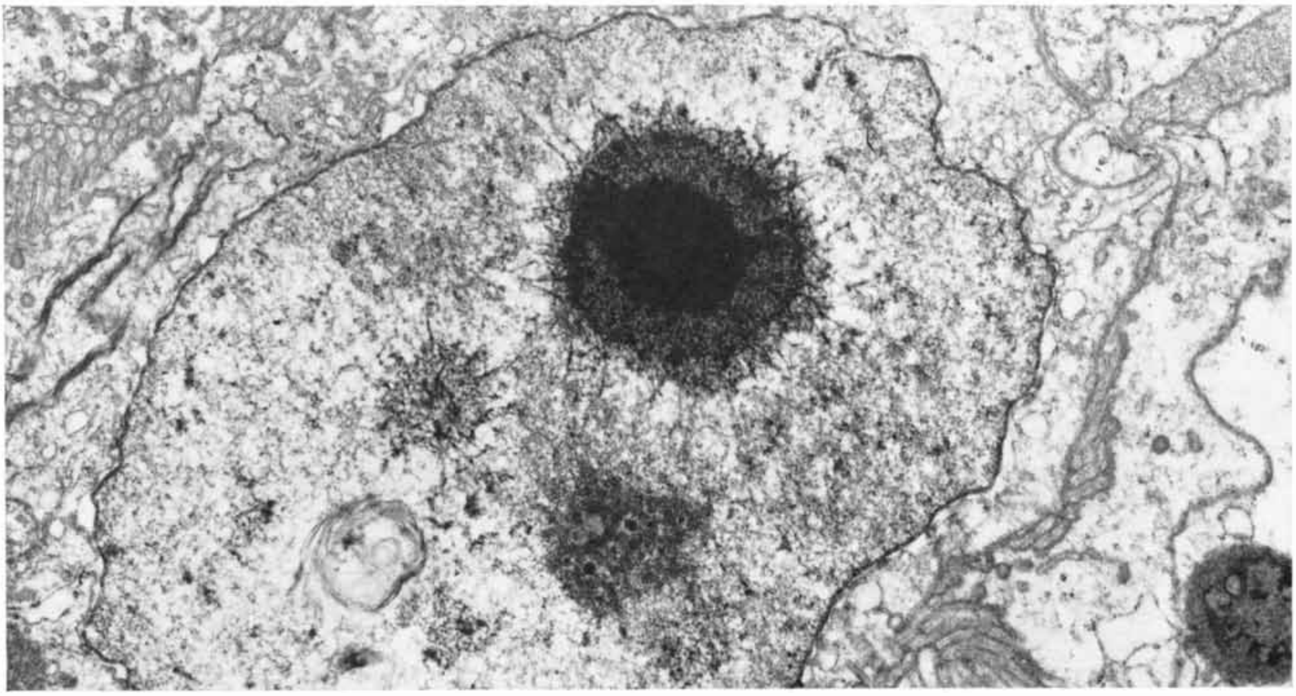
Lead has been mined and worked by men for millenniums. Its ductility, high resistance to erosion and other properties make it one of the most useful of metals. The inappropriate use of lead has, however, resulted in outbreaks of lead poisoning in humans from time to time since antiquity. The disease, which is sometimes called "plumbism" (from the Latin word for lead) or "saturnism" (from the alchemical term), was first described by the Greek poet-physician Nicander more than 2,000 years ago. Today our concerns about human health and the dissemination of lead into the environment are twofold: (1) there is a need to know whether or not the current level of lead absorption in the general population presents some subtle risk to health; (2) there is an even more urgent need to control this hazard in the several subgroups within the general population that run the risk of clinical plumbism and its known consequences. In the young children of urban slums lead poisoning is a major source of brain damage, mental deficiency and serious behavior problems. Yet it remains an insidious disease: it is difficult to diagnose, it is often unrecognized and until recently it was largely ignored by physicians and public health officials. Now public attention is finally being focused on childhood lead poisoning, although the difficult task of eradicating it has just begun.

Symptomatic lead poisoning is the result of very high levels of lead in the tissues. Is it possible that a content of lead in the body that is insufficient to cause obvious symptoms can nevertheless give rise to slowly evolving and long-lasting adverse effects? The question is at present unanswered but is most pertinent. There is much evidence that lead wastes have been accumulating during the past century, particularly in congested urban areas. Increased exposure to lead has been shown in populations exposed to lead as an air pollutant. Postmortem examinations show a higher lead content in the organs of individuals in highly industrialized societies than in the organs of most individuals in primitive populations. Although no population group is apparently yet being subjected to levels of exposure associated with the symptoms of lead poisoning, it is clear that a continued rise in the pollution of the human environment with lead could eventually produce levels of exposure that could have adverse effects on human health. Efforts to control the dissemination of lead into the environment are therefore indicated.

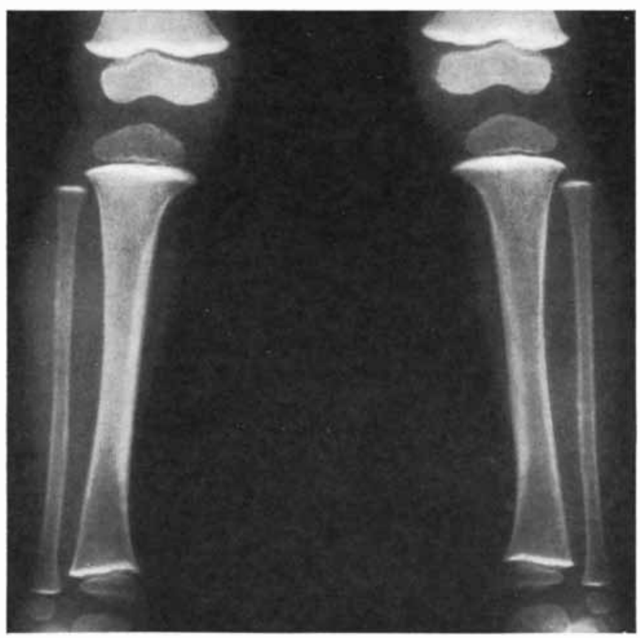
The more immediate and urgent problem is to control the exposure to lead of well-defined groups that are known to be directly at risk: young children who live in dilapidated housing where they can nibble chips of leaded paint, whiskey drinkers who consume quantities of lead-contaminated moonshine, people who eat or drink from improperly lead-glazed earthenware, workers in certain small-scale industries where exposure to lead is not controlled. Of these the most distressing group is the large group of children between about one and three to five years of age who live in deteriorating buildings and have the habit of eating nonfood substances including peeling paint, plaster and putty containing lead. (This behavior is termed pica, after the Latin word for magpie.) The epidemiological data are still scanty: large-scale screening programs now in progress in Chicago and New York City indicate that between 5 and 10 percent of the children tested show evidence of asymptomatic increased lead absorption and that between 1 and 2 percent have unsuspected plumbism. Small-scale surveys in the worst housing areas of a few other cities reveal even higher percentages.

There is little doubt that childhood lead poisoning is a real problem in many of the older urban areas of the U.S. and perhaps in rural communities as well. Current knowledge about lead poisoning and its long-term effects in children is adequate to form the basis of a rational attack on this particular problem. The ubiquity of lead-pigment paints in older substandard housing and the prevalence of pica in young children indicate, however, that any effective program will require the concerted and sustained effort of each community. Furthermore, the continued use of lead-pigment paints on housing surfaces that are accessible to young children and will at some future date fall into disrepair can only perpetuate the problem.

Traces of lead are almost ubiquitous in nature and minute amounts are found in normal diets. According to the extensive studies of Robert A. Kehoe and his associates during the past 35 years at the Kettering Laboratories of the University of Cincinnati, the usual daily dietary intake of lead in adults averages about .3 milligram. Of this, about 90 percent passes through the intestinal tract and is not absorbed. Kehoe's data indicate that the small amount absorbed is also excreted, so that under "normal" conditions there is no net retention of lead in the body. In addition the usual respiratory intake is estimated at between five and 50 micrograms of lead per day. These findings must be recon-



EXCESS LEAD complexed with protein forms inclusion bodies in the nuclei of certain cells in lead-poisoned animals and man. In an electron micrograph made by Robert A. Goyer and his colleagues at the University of North Carolina School of Medicine the nucleus of a cell from a proximal renal tubule of a lead-poisoned rat is enlarged 15,000 diameters. The large structure with a dense core and a filamentous outer zone is an inclusion body; below it to the left is a smaller one. The dark area below the large body is the nucleolus.



X-RAY PLATES may show evidence of lead ingestion or of an excessive body burden of the metal. The abdominal X ray (*left*) shows a number of bright opaque particles in the large intestine: bits of lead-containing paint that had been eaten by the 18-month-old subject. The X ray of the same child's legs (*right*) shows bright "lead lines": excess lead stored at the ends of the long bones.

ciled with postmortem analyses, which indicate that the concentration of lead in bone increases with age, although its concentration in the soft tissues is relatively stable throughout life. The physiological significance of increasing storage in bone is not entirely clear, but it has caused considerable concern. It is quite clear that as the level of intake of lead increases, the rate of absorption may exceed the rate at which lead can be excreted or stored in bone. And when the rates of excretion and storage are exceeded, the levels of lead in the soft tissues rise. Studies in adults indicate that as the sustained daily intake of lead rises above one milligram of lead per day, higher levels of lead in the blood result and metabolic, functional and clinical responses follow [*see illustration on pages 22 and 23*]. The reversible effects abate when the rate and amount of lead absorbed are reduced again to the usual dietary range.

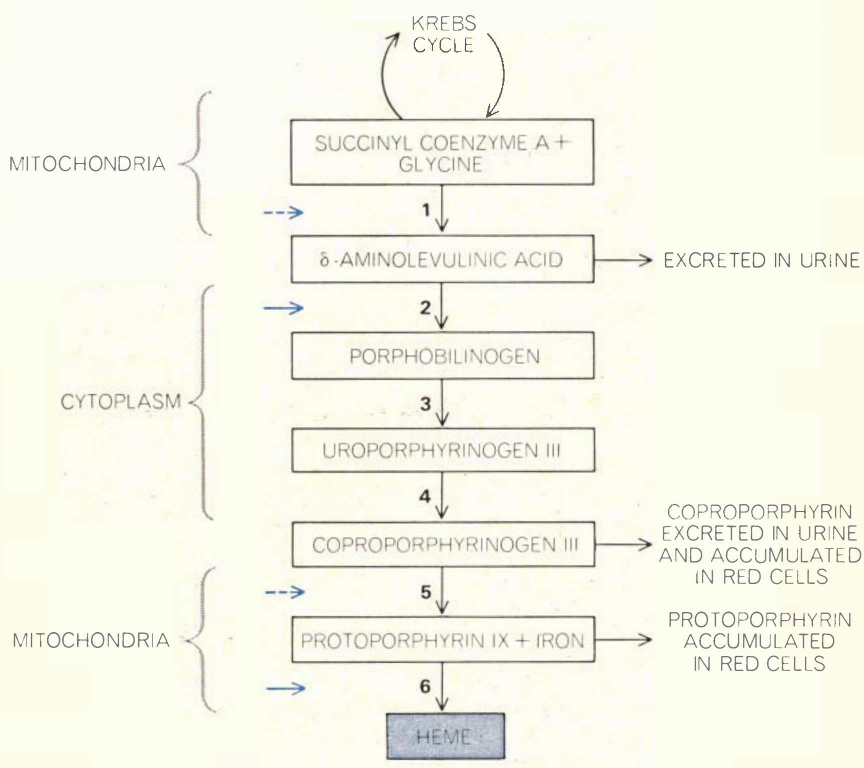
As far as is known, lead is not a trace element essential to nutrition, but this particular question has not been adequately examined. Some of the adverse effects of lead on metabolism have nonetheless been studied in considerable detail. These effects are related to the concentration of lead in the soft tissues. At the level of cellular metabolism, the best-known adverse effect of lead is its inhibition of the activity of enzymes that are dependent on the presence of free sulfhydryl (SH) groups for their activity. Lead interacts with sulfhydryl groups in such a way that they are not available to certain enzymes that require them. In the living organism, under most conditions, this inhibition is apparently partial. Inhibitory effects of lead on other aspects of cellular metabolism have been demonstrated in the test tube. Such studies are preliminary. Most of the effects reported are produced with concentrations of lead considerably higher than are likely to be encountered in the tissues of man, so that speculation about such effects is unwarranted at this point.

The clearest manifestation of the inhibitory effect of lead on the activity of sulfhydryl-dependent enzymes is the disturbance it causes in the biosynthesis of heme. Heme is the iron-containing constituent that combines with protein to form hemoglobin, the oxygen-carrying pigment of the red blood cells. Heme is also an essential constituent of the other respiratory pigments, the cytochromes, which play key roles in energy metabolism. The normal pathway of heme synthesis begins with activated succinate (produced by the Krebs cycle, a major stage in the conversion of food energy to biological energy) and proceeds through a series of steps [*see illustration below*]. Two of these steps are inhibited by the presence of lead; two others may also be inhibited, but at higher lead concentrations.

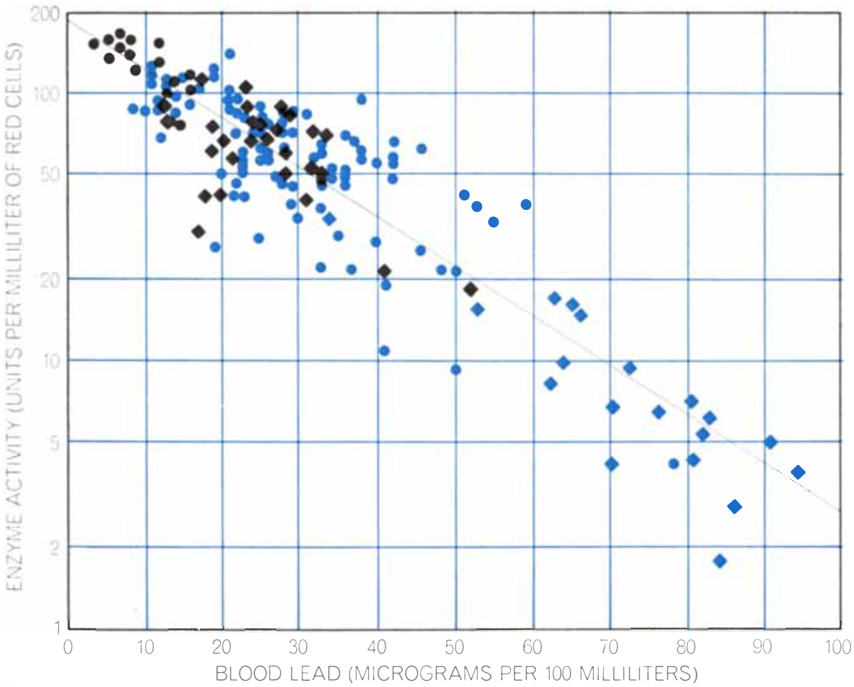
Lead is implicated specifically in the metabolism of delta-aminolevulinic acid (ALA) and in the final formation of heme from iron and protoporphyrin. Both of these steps are mediated by enzymes that are dependent on free sulfhydryl groups for their activity and are therefore sensitive to lead. The two steps at which lead may possibly be implicated are the formation of ALA and the conversion of coproporphyrinogen to protoporphyrin. Although the exact mechanism is not known, coproporphyrin (an oxidized product of coproporphyrinogen) accumulates in the urine and the red cells in lead poisoning. Whatever the mechanisms, the increased excretion of ALA and coproporphyrin is almost al-

PATIENTS	LEAD OUTPUT (MILLIGRAMS PER 24 HOURS)		
	MEAN	MEDIAN	RANGE
UNEXPOSED CONTROLS	.132	.157	.012–.175
HOUSEHOLD CONTROLS	.832	.651	.087–1.93
INCREASED LEAD ABSORPTION, NO SYMPTOMS	2.16	1.11	.116–9.60
LEAD POISONING, WITH AND WITHOUT BRAIN DAMAGE			
DURING EXPOSURE:	44.0	27.0	5.040–104.0
AFTER TREATMENT:	.362	.240	.062–0.850

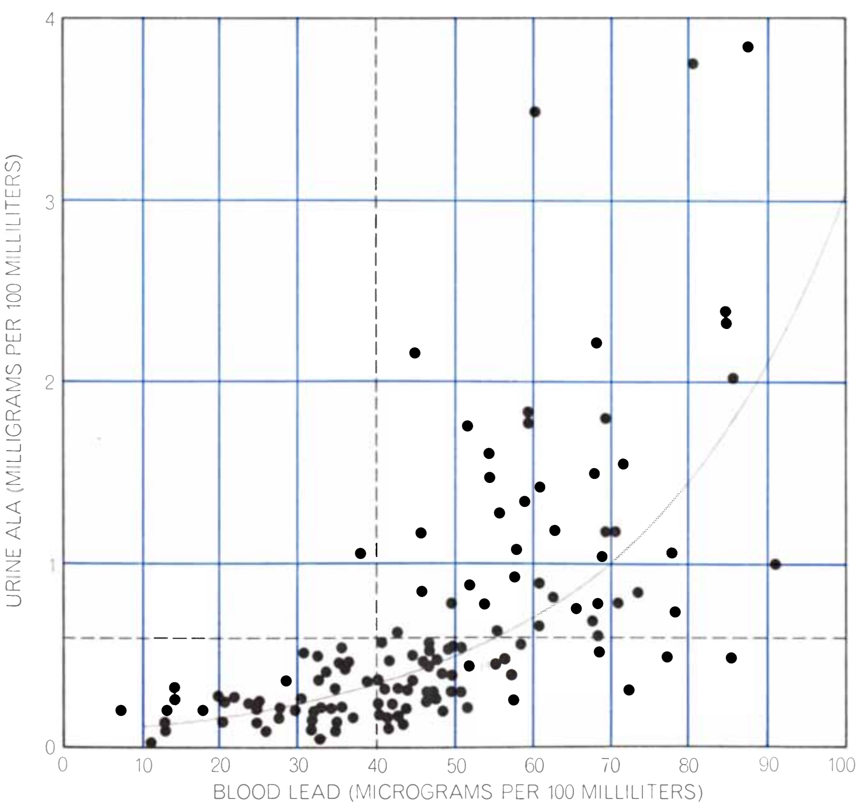
EXCRETION OF LEAD in feces is an index of exposure to lead. These results of a study by the author and Harold E. Harrison illustrate the massive exposures seen in lead poisoning. Unexposed controls were children with no known exposure to lead. The other groups were children with increased lead absorption (high blood lead), children with lead poisoning and members of their households with neither high blood values nor overt symptoms.



BIOSYNTHESIS OF HEME, a constituent of hemoglobin, is inhibited by lead, resulting in accumulation of intermediates in the synthetic pathway. Of six steps in the pathway, the first and the last two take place in mitochondria, the others elsewhere in the cell cytoplasm. Lead inhibits two steps (*solid colored arrows*) and may inhibit two others (*broken arrows*).



CORRELATION between blood lead and the activity of delta-aminolevulinic acid dehydrase, an enzyme inhibited by lead, was shown by Sven Hernberg and his colleagues at the University of Helsinki. The vertical scale is logarithmic. The values are well correlated, as indicated by the straight regression line, over a wide range of blood-lead levels in groups with different lead exposures: students (*black dots*), automobile repairmen (*black squares*), printshop employees (*colored dots*) and lead smelters and ship scrappers (*colored squares*).



ENZYME SUBSTRATE, delta-aminolevulinic acid (ALA) accumulates in the urine when lead inhibits enzyme activity. Stig Selander and Kim Cramér found that a decrease in lead below about 30 micrograms does not produce a comparable decrease in ALA, suggesting that an enzyme reserve may be involved. Broken lines show presumed normal values.

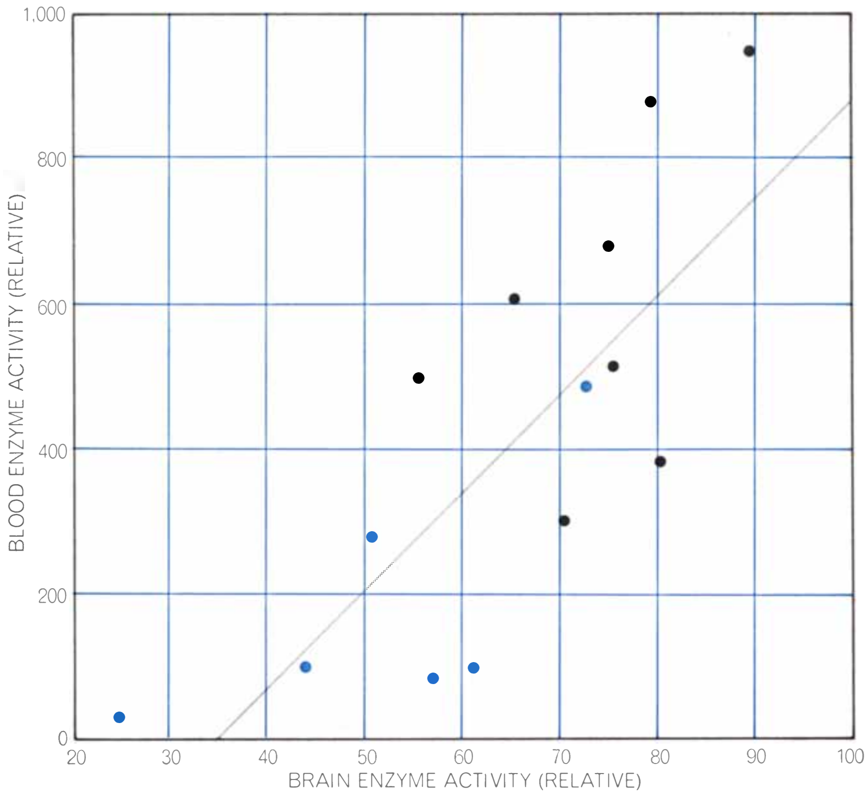
ways observed before the onset of symptoms of lead poisoning, and the presence of either is therefore important in diagnosis.

The enzyme that catalyzes ALA metabolism is ALA dehydrase. A number of investigators, including Sven Hernberg and his colleagues at the University of Helsinki and Abraham Goldberg's group at the University of Glasgow, have studied the extent to which varying levels of lead in the blood inhibit ALA-dehydrase activity in red blood cell preparations in the laboratory. They have shown a direct relation between the concentration of lead in blood and the activity of the enzyme. Moreover, they find that there seems to be no amount of lead so small that it does not to some extent decrease ALA-dehydrase activity; in other words, there appears to be no threshold for this effect [*see top illustration at left*]. If that is so, however, one would expect to see a progressive increase in the urinary excretion of the enzyme's substrate, ALA, beginning at very low blood-lead levels. This does not seem to be the case. Stig Selander and Kim Cramér in Sweden, correlating blood-lead and urine-ALA values, found that the first measurable increase in urine ALA is observed only after blood lead rises above approximately 30 micrograms of lead per 100 milliliters of whole blood [*see bottom illustration at left*]. The apparent inconsistency between the effect of lead on the activity of an enzyme in the test tube and the accumulation of the enzyme's substrate in the body might be explained by the presence of an enzyme reserve. This hypothesis is consistent with the functional reserve exhibited in many biological systems.

Almost all the information we have on the effect of lead on the synthesis of heme comes from observations of red blood cells. Yet all cells synthesize their own heme-containing enzymes, notably the cytochromes, and ALA dehydrase is also widely distributed in tissues. The observations in red blood cells may therefore serve as a model of lead's probable effects on heme synthesis in other organ systems. Even so, the degree of inhibition in a given tissue may vary and will depend on the concentration of lead within the cell, on its access to the heme synthetic pathway and on other factors. For example, J. A. Millar and his colleagues in Goldberg's group found that ALA-dehydrase activity is inhibited in the brain tissue of heavily lead-poisoned laboratory rats at about the same rate as it is in the blood [*see illustration on opposite page*]. When these workers used amounts of lead that produced an average blood-lead level of 30 micrograms per 100 milliliters of blood, the level of ALA-dehydrase activity in the brain did not differ significantly from the levels found in control rats that had not been given any added lead at all. It is now established experimentally that lead does interfere with heme synthesis in tissue preparations from the kidney, the brain and the liver as well as in red cells but the concentrations of lead that may begin to cause significant inhibition in these organs are not yet known.

Only in the blood is it as yet possible to see a direct cause-and-effect relation between the metabolic disturbance and the functional disturbance in animals or people. In the blood the functional effect is anemia. The decrease in heme synthesis leads at first to a decrease in the life-span of red cells and later to a decrease in the number of red cells and in the amount of hemoglobin per cell. In compensation for the shortage, the blood-forming tissue steps up its production of red cells; immature red cells, reticulocytes and basophilic stippled cells (named for their stippled appearance after absorbing a basic dye) appear in the circulation. The presence of stippled cells is the most characteristic finding in the blood of a patient with lead poisoning. The stippling represents remnants of the cytoplasmic constituents of red cell precursors, including mitochondria. Normal mature red cells do not contain mitochondria. The anemia of lead poisoning is a reversible condition: the metabolism of heme returns to normal, and the anemia improves with removal of the patient from exposure to excessive amounts of lead.

The toxic effect of lead on the kidneys is under intensive investigation but here the story is less clear. In acute lead poisoning there are visible changes in the kidney and kidney function is impaired. Again the mitochondria are implicated: their structure is visibly changed. Much of the excess lead is concentrated in the form of dense inclusions in the nuclei of certain cells, including those lining the proximal renal tubules. Robert A. Goyer of the University of North Carolina School of Medicine isolated and analyzed these inclusions and found that they consist of a complex of protein and lead [*see upper illustration on page 16*]. He has suggested that the inclusions are a protective device: they tend to keep the lead in the nucleus, away from the vulnerable mitochondria. Involvement of the mitochondria is also suggested by the fact that lead-poisoned kidney cells consume more oxygen than normal cells in laboratory cultures, which indicates



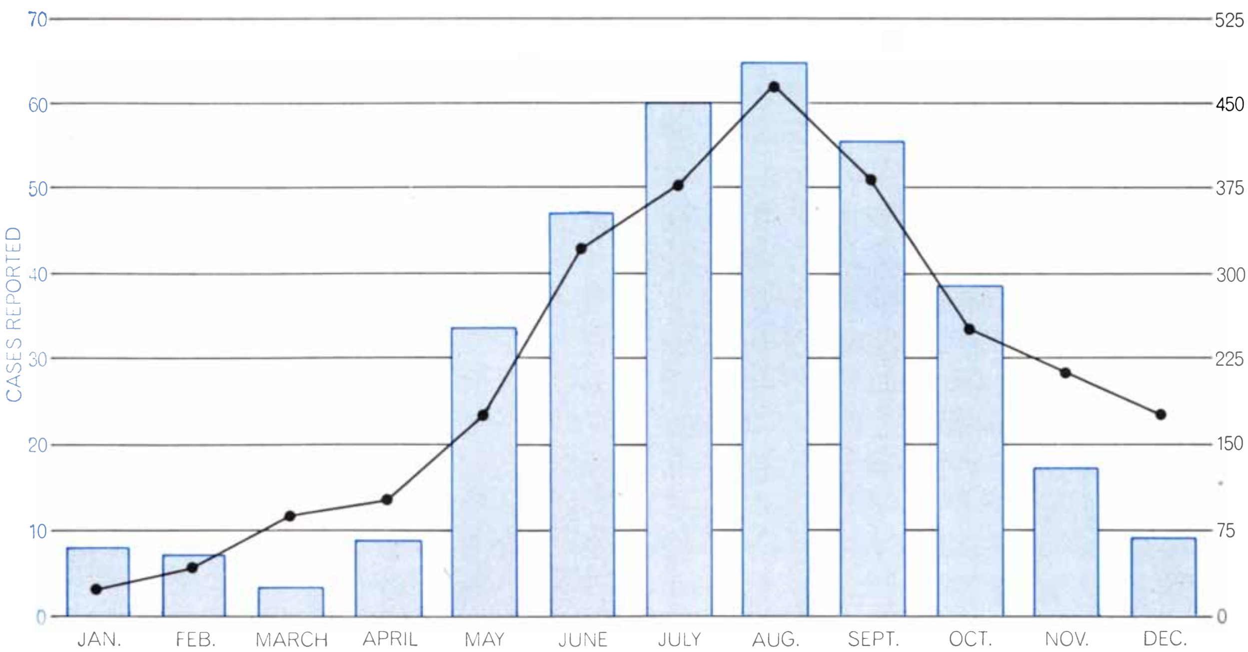
CORRELATION between the activity of ALA dehydrase in the blood and in the brain of normal rats (*black dots*) and lead-poisoned rats (*colored dots*) suggests that the enzyme may be implicated in brain damage, according to J. A. Millar and his colleagues. These data are for severely poisoned rats; in others with blood-lead values of about 30 micrograms per 100 milliliters of blood, brain enzyme activity was not significantly less than in controls.

that their energy metabolism is affected.

Kidney dysfunction, apparently due to this impairment in energy metabolism, is expressed in what is called the Fanconi syndrome: there is an increased loss of amino acids, glucose and phosphate in the urine because the damaged tubular cells fail to reabsorb these substances as completely as normal tubular cells do. The excessive excretion of phosphates is the important factor because it leads to hypophosphatemia, a low level of phosphate in the blood. There is some evidence that, when phosphate is mobilized from bone for the purpose of maintaining an adequate level in body fluids, lead that is stored with relative safety in the bones may be mobilized along with the phosphate and enter the soft tissues where it can do harm. The effect of acute lead poisoning on the kidney can be serious but, like the effect on blood cells, it is reversible with the end of abnormal exposure. Furthermore, the Fanconi syndrome is seen only at very high levels of lead in blood (greater than 150 micrograms of lead per 100 milliliters of blood) and only in patients with severe acute plumbism.

In the central nervous system the toxic effect of lead is least understood. Little is known at the metabolic level; most of the information comes from clinical observation of patients and from postmortem studies. Two different mechanisms appear to be involved in lead encephalopathy, or brain damage: edema and direct injury to nerve cells. The walls of the blood vessels are somehow affected so that the capillaries become too permeable; they leak, causing edema (swelling of the brain tissue). Since the brain is enclosed in a rigid container, the skull, severe swelling destroys brain tissue. Moreover, it appears that certain brain cells may be directly injured, or their function inhibited, by lead.

The effects I have been discussing are all those of acute lead poisoning, the result of a large accumulation of lead in a relatively short time. There are chronic effects too, either the aftereffects of acute plumbism or the result of a slow buildup of a burden of lead over a period of years. The best-known effect is chronic nephritis, a disease characterized by a scarring and shrinking of kidney tissue. This complication of lead poisoning came to light in Australia in 1929, when L. J. J. Nye became aware of a pattern of chronic nephritis and early death in

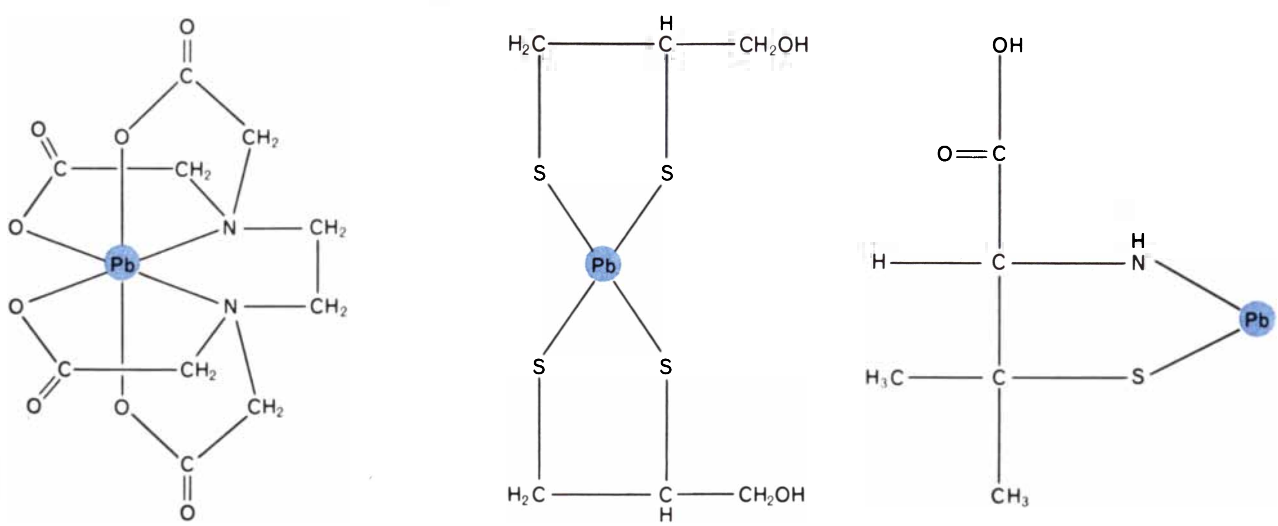


SEASONAL PATTERN of lead-poisoning cases is striking. The bars show the average number of cases reported monthly in Baltimore from 1931 through 1951 (*numbers at left*). Curve shows cases reported monthly in New York City last year (*numbers at right*).

the state of Queensland. Investigation revealed that Queensland children drank quantities of rainwater that was collected by runoff from house roofs sheathed with shingles covered with lead-pigmented paint. In 1954 D. A. Henderson found that of 352 adults in Queensland who had had childhood lead poisoning 15 to 40 years earlier, 165 had died, 94 of chronic nephritis. Chronic lead nephropathy, which is sometimes accompanied by gout, is also seen in persistent, heavy moonshine drinkers and in some people who have had severe industrial exposure. In all these cases, however, the abnormal intake of lead persists for more than a decade or so before the onset of nephropathy. Most of the patients have a history of reported episodes of acute plumbism, which suggests that they have levels of lead in the tissues far above those found in the general population. Furthermore, there is the suspicion that factors in addition to lead may be involved.

The other known result of chronic overexposure to lead is peripheral nerve disease, affecting primarily the motor nerves of the extremities. Here the tissue damage appears to be to the myelin sheath of the nerve fiber. Specifically, according to animal studies, the mitochondria of the Schwann cells, which synthesize the sheath, seem to be affected. Various investigators, including Pamela Fullerton of Middlesex Hospital in London, have found that conduction of the nerve impulse may be impaired in the peripheral nerves of industrial workers who have had a long exposure to lead but who have no symptoms of acute lead poisoning.

These findings and others raise serious questions. It is clear that a single attack of acute encephalopathy can cause pro-



CHELATING AGENTS used in treating lead poisoning bind lead atoms (*Pb*) firmly in one or more five-member chelate rings. Diagrams show lead chelates formed by EDTA (*left*), BAL (*middle*) and d-penicillamine (*right*). The last structure is still hypothetical.

found mental retardation and other forms of neurological injury that is permanent. Similarly, in young children repeated bouts of symptomatic plumbism can result in permanent brain damage ranging from subtle learning deficits to profound mental incompetence and epilepsy. Can a level of absorption that is insufficient to cause obvious acute symptoms nevertheless cause "silent" brain damage? This question remains unanswered, in part because of the difficulty in recognizing mild symptoms of lead poisoning in children and in part because the experimental studies that might provide some answers have not yet been undertaken.

POPULATION	EXPOSURE (MICROGRAMS PER CUBIC METER OF AIR)	MEAN BLOOD LEAD (MICROGRAMS PER 100 GRAMS)
RURAL U.S.	0.5	16
URBAN U.S.	1.0	21
DOWNTOWN PHILADELPHIA	2.4	24
CINCINNATI POLICEMEN	2.1	25
CINCINNATI TRAFFIC POLICEMEN	3.8	30
LOS ANGELES TRAFFIC POLICEMEN	5.2	21
BOSTON AUTOMOBILE-TUNNEL EMPLOYEES	6.3	30

RESPIRATORY EXPOSURE to lead is reflected in the mean blood-lead values of various groups, according to John R. Goldsmith and Alfred C. Hexter of the California Department of Public Health. Groups apparently exposed to more lead in the air have generally higher blood-lead values; whether these indicate higher body burdens of lead is not known.

Classical plumbism—the acute disease—is seen today primarily in children with the pica habit. Before discussing these cases in some detail I shall briefly take up two other current environmental sources of lead: earthenware improperly glazed with lead and lead-contaminated alcoholic beverages.

Michael Klein and his colleagues at McGill University recently reported two cases of childhood lead poisoning, one of which was fatal, that they traced to an earthenware jug in which the children's mother kept a continuously replenished supply of apple juice. The slightly acidic juice was leaching lead out of the glaze, the thin layer of glassy material fused to the ceramic surfaces of the jug. The investigators thereupon tested 117 commercial earthenware food and beverage containers and 147 samples made with 49 different commonly used glazes in the McGill ceramics laboratory. Excessive amounts of lead—more than the U.S. maximum permissible amount for glazes of seven parts per million—were leached out of half the vessels. (The maximum permissible amount should probably be reevaluated, since past methods of testing have not taken account of such variables as the quantity of the food or beverage consumed, its acidity, the length of time it is stored and whether or not it is cooked in the pottery.) As the McGill report points out, the danger of poisoning from lead-glazed pottery has been rediscovered periodically since antiquity. The Greeks knew about the danger but the Romans did not; they made the mistake of storing wine in earthenware. James Lind, who in 1753 recommended lemon or lime juice as a preventive for scurvy, also warned that the juices should not be stored in earthenware jugs. Now the index of suspicion has fallen too low: one physician poisoned himself recently by drinking a cola beverage (and 3.2 milligrams of lead) every evening for two years from a mug his son had made for him. Do these cases represent isolated occurrences? How many other people are similarly exposed? Clearly the first step is the testing of earthenware and a reevaluation of its fabrication and use for food and drink.

In the manufacture of moonshine whiskey, lead solder is used in the tubing of distillation units. Moreover, discarded automobile radiators that contain lead often serve as condensers. Lead is therefore found in most samples of confiscated moonshine. Lead encephalopathy, nephritis with gout and other lead-related conditions have been reported in moonshine consumers, largely in the southeastern part of the U.S. The problem of diagnosis is complicated by the fact that the symptoms of acute alcoholism and acute lead poisoning are similar in many ways. (Again there is a historical record. The McGill report noted that the Massachusetts Bay Colony forbade rum distillation in leaded stills in 1723 in an effort to prevent "dry gripes," an intestinal condition. In 1767 Sir George Baker blamed "the endemic colic of Devonshire" on the use of lead-lined troughs in the making of apple cider.)

Childhood lead poisoning in the U.S. is seen almost exclusively in children of preschool age who live in deteriorated housing built before 1940 (when titanium dioxide began to replace lead in the pigment of most interior paints). The causative factors are commonly a triad: a dilapidated old house, a toddler with pica and parents with inadequate resources (emotional, intellectual, informational and/or economic) to cope with the family's needs. The three factors interact to increase the likelihood that the child will eat chips of leaded paint. A chip of paint about the size of an adult's thumbnail can contain between 50 and 100 milligrams of lead, and so a child eating a few small chips a day easily ingests 100 or more times the tolerable adult intake of the metal! In one study conducted some years ago at the Baltimore City Hospitals and the Johns Hopkins Hospital, Harold E. Harrison and I found that the average daily fecal excretion of lead by children with severe plumbism was 44 milligrams. In a group of normal unexposed children we found a daily fecal lead excretion of less than .2 milligram of lead. In other words, pica for leaded paint results in genuinely massive exposures. And when the abnormal intake ceases, it may be several months or years before blood-lead levels return to normal.

The repeated ingestion of leaded-paint chips for about three months or longer can lead to clinical symptoms and eventually to the absorption of a potentially lethal body burden of lead. During the first four to six weeks of abnormal ingestion there are no symptoms. After a few weeks minor symptoms such as decreased appetite, irritability, clumsiness, unwillingness to play, fatigue, headache, abdominal pain and vomiting begin to appear. These, of course, are all quite nonspecific symptoms, easily ignored as behavior problems or blamed on various childhood diseases. In a few weeks the lassitude may progress to intermittent drowsiness and stupor; the vomiting may become persistent and forceful;

brief convulsions may occur. If the exposure to lead continues, the course of the disease can culminate abruptly in coma, intractable convulsions and sometimes death.

This picture of fulminating encephalopathy is commonest in children between 15 and 30 months of age; older children tend to suffer recurrent but less severe acute episodes and are usually brought to the hospital with a history of sporadic convulsions, behavior problems, hyperactivity or mental retardation. The symptoms tend to wax and wane, usually becoming more severe in summer. (Some 85 percent of all lead-poisoning cases are reported from May through October. This remarkably clear seasonal pattern is still not understood. It may be due at least in part to the fact that the ultraviolet component of sunlight increases the absorption of lead from the intestine.)

The symptoms of even acute encephalopathy are nonspecific, resembling those of brain abscesses and tumors and of viral and bacterial infections of the brain. Diagnosis depends, first of all, on a high level of suspicion. To make a positive diagnosis it is necessary to show high lead absorption as well as the adverse effects of lead. This requires the measurement of lead in blood and other specialized tests. Mild symptoms may be found in the presence of values of between 60 and 80 micrograms of lead per 100 milliliters of blood. As the blood-lead level rises above 80 micrograms the risk of severe symptoms increases sharply. Even in the absence of symptoms, in children blood-lead levels exceeding 80 micrograms call for immediate treatment and separation of the child from the source of lead.

Treatment is with potent compounds known as chelating agents (from the Greek *chēlē*, meaning claw): molecules that tend to bind a metal atom firmly, sequestering it and thus rendering it highly soluble [see "Chelation," by Harold F. Walton; SCIENTIFIC AMERICAN, June, 1953]. Chelating agents remove lead atoms from tissues for excretion through the kidney and through the liver. With chelating agents very high tissue levels of lead can be rapidly reduced to levels approaching normal, and the adverse metabolic effects can be promptly suppressed. Initially two agents are administered by injection: EDTA and BAL. (EDTA, or edathamil, is ethylenediaminetetraacetic acid; BAL is "British Anti-Lewisite," developed during World War II as an antidote for lewisite, an arsenic-containing poison gas.) After the lead level has been reduced another agent, d-penicillamine, may be administered orally as a follow-up therapy.

Before chelating agents were available about two-thirds of all children with lead encephalopathy died. Now the mortality rate is less than 5 percent. Unfortunately the improvement in therapy has not substantially reduced the incidence of brain damage in the survivors. Meyer A. Perlstein and R. Attala of the Northwestern University Medical School found that of 59 children who developed encephalopathy, 82 percent were left with permanent injury: mental retardation, convulsive disorders, cerebral palsy or blindness. This high incidence of permanent damage suggests that some of these children must have had recurrent episodes of plumbism; we have found that if a child who has been treated for acute encephalopathy is returned to the same hazardous environment, the risk of permanent brain damage rises to virtually 100 percent. In Baltimore, with the help of the Health Department and through the efforts of dedicated medical social workers, we are able to make it an absolute rule that no victim of lead poisoning is ever returned to a dangerous environment. The child goes from the hospital to a convalescent home and does not rejoin his family until all hazardous lead

	I NO DEMONSTRABLE EFFECTS	II MINIMAL SUBCLINICAL EFFECTS DETECTABLE	III COMPENSATION	IV FUNCTIONAL INJURY (SHORT, INTENSE EXPOSURE)
METABOLIC EFFECTS	NORMAL	URINARY ALA MAY INCREASE	INCREASE IN SEVERAL METABOLITES IN BLOOD AND URINE	FURTHER INCREASE IN METABOLITES
FUNCTIONAL EFFECTS BLOOD	NONE	NONE	REDUCED RED CELL LIFE-SPAN. INCREASED PRODUCTION	REDUCED RED CELL LIFE-SPAN WITH OR WITHOUT ANEMIA (REVERSIBLE)
KIDNEY FUNCTION	NORMAL	NORMAL	SOMETIMES MINIMAL DYSFUNCTION	FANCONI SYNDROME (REVERSIBLE)
CENTRAL NERVOUS SYSTEM	NONE	NONE	?	MINIMAL TO SEVERE BRAIN DAMAGE (PERMANENT)
PERIPHERAL NERVES	NONE	NONE	?	POSSIBLE DAMAGE
SYMPTOMS	NONE	NONE	SOMETIMES MILD, NON-SPECIFIC COMPLAINTS	ANEMIA, COLIC, IRRITABILITY, DROWSINESS; IN SEVERE CASES, MOTOR CLUMSINESS, CONVULSIONS AND COMA
RESIDUAL EFFECTS	NONE	NONE	NONE KNOWN	RANGE FROM MINIMAL LEARNING DISABILITY TO PROFOUND MENTAL AND BEHAVIORAL DEFICIENCY, CONVULSIVE DISORDERS, BLINDNESS

EFFECTS OF LEAD are associated in a general way with five levels of exposure and rates of absorption of the metal. Level I is associated with blood-lead concentrations of less than 30 micrograms of lead per 100 milliliters and Level II with the 30–50 microgram range. Level III, at which compensatory mechanisms apparently minimize or prevent obvious functional injury, may be associated with concentrations of between 50 and 100 micrograms. Level IV is usually associated with concentrations greater than 80 micrograms but impairment may be evident at lower levels, particularly if compensatory responses are interfered with by some other disease state.

sources have been removed or the family has been helped to find lead-free housing. Cases of permanent brain damage nevertheless persist. It appears that even among children who suffer only one episode, are properly treated and are thereafter kept away from lead, at least 25 percent of the survivors of lead encephalopathy sustain lasting damage.

Clearly, then, treatment is not enough; the disease must be prevented. Children with increased lead absorption must be identified before they become poisoned. Going a step further, the sources of excessive lead exposure must be eliminated.

Baltimore has taken a "case-finding" approach to these tasks. Free diagnostic services were established by the city Health Department in the 1930's. Physicians took advantage of the services, and increasing numbers of cases were discovered. Since 1951 the removal of leaded paint has been required in any dwelling where a child is found with a blood-lead value of more than 60 micrograms. The number of cases reported each year rose for some time as diagnostic methods and awareness improved, but recently it has leveled off. In order to reach children before they are poisoned, however, more is required than case-finding; what is needed is a screening program that examines entire populations of children in high-risk areas of cities. Chicago undertook that task in the 1960's. Last year New York City inaugurated a new and intensive screening program in which children are being tested for blood lead in hospitals and at a large number of neighborhood health centers; an educational campaign has been launched to bring lead poisoning and the testing facilities to public notice. As in Baltimore, a blood-lead finding of more than 60 micrograms results in an examination of the child's home. If any samples of paint and plaster contain more than 1 percent of lead, the landlord is ordered to correct the condition by covering the walls with wallboard to a height of at least four feet and by removing all leaded paint from wood surfaces; if the landlord does not comply, the city undertakes the work and bills him. Before the new program was begun New York was screening about 175 blood tests a week; by the end of the year it was doing about 2,000 tests a week. Whereas 727 cases of lead poisoning were reported in the city in 1969, last year more than 2,600 were reported. As Evan Charney of the University of Rochester School of Medicine and Dentistry has put it, "the number of cases depends on how hard you look."

Screening is complicated by technical difficulties in testing both children and dwellings. The standard dithizone method of determining blood lead requires between five and 10 cubic centimeters of blood taken from a vein—a difficult procedure in very small children—and the analysis is time-consuming. What is needed is a dependable test that can be carried out on a drop or two of blood from a finger prick. A variety of approaches are now being tried in several laboratories in order to reach this goal; as yet no microtest utilizing a drop or two of blood has been proved practical on the basis of large-scale use in the field. Several appear to be promising in the laboratory, so that field testing in the near future can be anticipated. As for the checking of dwellings, the standard method is laborious primarily because it requires the collection of a large number of samples. Several different portable instruments are under development, including an X-ray fluorescence apparatus that gives a lead-content reading when it is pointed at a surface, but these devices have not yet been proved reliable in the field.

Since World War II the incidence of lead poisoning (usually in the form of lead palsy) among industrial workers, which was once a serious problem, has been reduced by various control measures. The danger is now limited primarily to small plants that are not well regulated and to home industries.

There is increasing concern over environmental lead pollution. Claire C. Patterson of the California Institute of Technology has shown that the levels of lead in polar ice have risen sharply since the beginning of the Industrial Revolution. Henry A. Schroeder of the Dartmouth Medical School has shown that the burden of lead in the human body rises with age, and that this rise is due almost entirely to the concentration of lead in bone. Although man's exposure to lead in highly industrialized nations may come from a variety of sources, the evidence points to leaded gasoline as the principal source of airborne lead today. These observations have occasioned much speculation. It is nonetheless clear that a further rise in the dissemination of lead wastes into the environment can cause adverse effects on human health; indeed, concerted efforts to lower the current levels of exposure must be made, particularly in congested urban areas.

At the moment there is no evidence that any groups have mean blood levels that approach the dangerous range. Some, however, do have levels at which a minimal increase in urinary ALA, but nothing more, is to be expected. This includes people whose occupation brings them into close and almost daily contact with automotive exhaust. These observations emphasize the need to halt any further rise in the total level of exposure. A margin of safety needs to be defined and maintained. This will require research aimed at elucidating the effects of long-term exposure to levels of lead insufficient to cause symptoms or clear-cut functional injury. With regard to respiratory exposure, it is still not clear what fraction of the inhaled particles reaches the lungs and how much of that fraction is actually absorbed from the lung. Still another important question is the storage of lead in bone. Can any significant fraction of lead in bone be easily and quickly mobilized? If so, under what circumstances is it mobilized? There are more questions than answers to the problems posed by levels of lead only slightly higher than those currently found in urban man. Much research is required.

With regard to childhood lead poisoning, however, we know enough to act. It is impermissible for a humane society to fail to do what is necessary to eliminate a wholly preventable disease.

V FUNCTIONAL INJURY (CHRONIC OR RECURRENT INTENSE EXPOSURE)
INCREASE ONLY IN CASE OF RECENT EXPOSURE
POSSIBLE ANEMIA (REVERSIBLE)
CHRONIC NEPHROPATHY (PERMANENT)
SEVERE BRAIN DAMAGE, PARTICULARLY IN CHILDREN (PERMANENT)
IMPAIRED CONDUCTION (MAY BE CHRONIC)
MENTAL DETERIORATION, SEIZURES, COMA, FOOT OR WRIST DROP
MENTAL DEFICIENCY (OFTEN PROFOUND), KIDNEY INSUFFICIENCY, GOUT (UNCOMMON), FOOT DROP (RARE)

What one can say is that the risk of functional injury increases as the concentration of lead in the blood exceeds 80 micrograms per 100 milliliters. The residual effects persist after blood-lead levels return to normal.

SOLID STARS

Much of the matter in white-dwarf stars and pulsars (neutron stars) is under such enormous pressure that it must be considerably more rigid than normal steel

by Malvin A. Ruderman

Twinkle, twinkle, little star,
How I wonder what you are,
Up above the world so high,
Like a diamond in the sky.

Children have long been charmed by the notion that a star is a twinkling jewel embedded in the black night sky. Their parents may smile indulgently, having been taught that stars are really spheres of incandescent gas. During the past decade, however, it has become apparent that in some cases the child's picture is closer to the truth: the core of certain dense stars and the outer layer of still denser ones are now believed to be solid matter. Some stars probably consist mainly of carbon in exotic crystalline form. A parent would be a spoilsport indeed if he refused to regard such an object as a twinkling celestial diamond.

In the very densest stars one can expect phenomena and forms of matter that cannot be studied directly in terrestrial laboratories. Curiously this is not because of our inability to reproduce stellar temperatures of many millions of degrees but rather because the behavior of ultradense matter resembles that expected in some forms of ordinary matter near and even below the lowest temperatures that have ever been achieved on the earth. A description of matter when it is ultradense depends on combining theory and experiments in diverse fields: the cryogenic phenomena of superfluidity and superconductivity, phase transitions between solids and liquids, proton- and neutron-scattering data obtained with large cyclotrons, the still imperfect marriage of relativity and quantum mechanics expressed in relativistic quantum field theory and even the interaction of "strange" particles produced in accelerators of the highest energy.

The central region of a dying star contains the densest matter known in the universe. After the star has exhausted the nuclear fuel that enabled it to shine for billions of years it will, according to present theory, suffer one of three fates.

It may contract forever, approaching but never reaching a radius of a few kilometers and a density exceeding 10^{16} grams per cubic centimeter. It is then one of the "black holes" predicted by the general theory of relativity: objects so compact that even light cannot escape their gravitational pull. The black hole is the destiny of all stars whose terminal mass considerably exceeds the mass of the sun. No black hole has ever been observed, but then it is not clear by which of its properties an astronomer might observe it.

Stars lighter than about 1.2 solar masses can die as white dwarfs: stars only about the size of the earth but whose central density can reach 10^8 grams per cubic centimeter (a pea weighing more than a truck). In white dwarfs the enormous contracting pull of gravity is balanced by the pressure created by rapidly moving electrons. Even in objects cooled to absolute zero a residual electron motion persists. This motion is a consequence of the exclusion principle, enunciated by Wolfgang Pauli in 1925, which "forbids" electrons from getting close to one another (as they must when matter is compressed) unless they move rapidly. The greater the compression, the faster the motion and the greater the resulting pressure. This quantum-mechanical kinetic energy electrons possess when they are near similar neighbors is termed degeneracy energy. Exactly the same kind of motion contributes the pressure that makes ordinary solids and liquids difficult to compress. Without it all familiar forms of condensed matter would collapse.

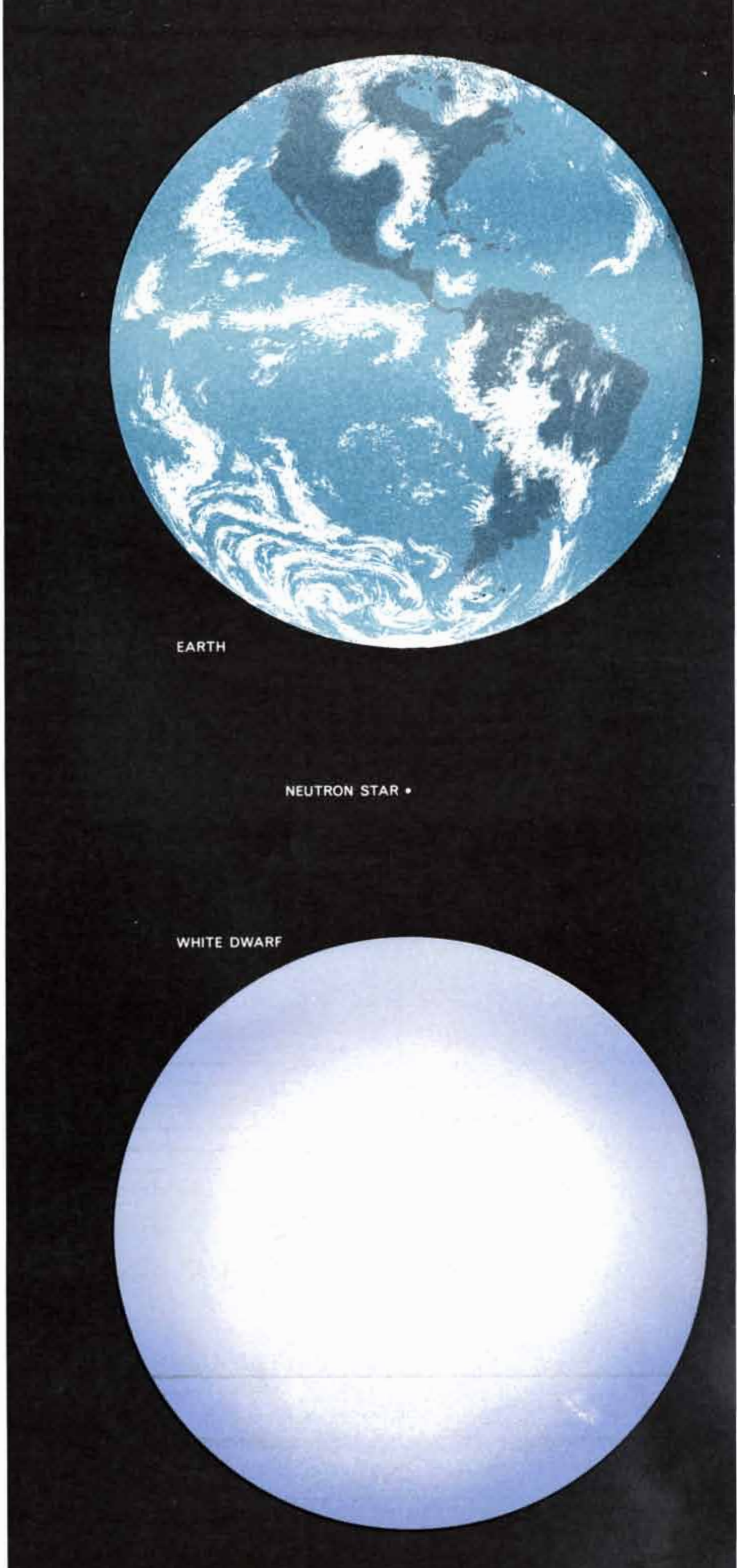
A third possible fate can befall stars whose mass lies between one-tenth and something less than twice the mass of the sun. They can become neutron stars: stellar corpses in which the pull of gravity is balanced by the same combination of forces that keeps ordinary atomic nuclei from collapsing in spite of the pull of nuclear attractive forces. This combination consists of the degeneracy energy of nucleons (similar to the degeneracy energy of electrons) and short-range nuclear repulsive forces. For such forces to be effective, matter must be compressed until it approaches the density of matter within an atomic nucleus: at least 10^{14} grams per cubic centimeter (all the people in the world compressed into a single raindrop). Neutron stars, which were first predicted theoretically nearly 40 years ago, are expected to have a radius of only about 10 kilometers. Within the past few years radio and optical astronomers have apparently discovered rapidly rotating neutron stars. They are the pulsars, neutron stars rotating and beaming radiation to us at rates between 30 times per second and once every few seconds [see "The Nature of Pulsars," by Jeremiah P. Ostriker; SCIENTIFIC AMERICAN, January]. Perhaps as many as 100 million of the 100 billion stars in our galaxy have burned themselves out and collapsed into neutron stars.

There seems to be no possibility whatever of reproducing the densities of white dwarfs and neutron stars in the laboratory; the present limit of laboratory densities is comparable to the density at the center of the moon. There are, however, compelling reasons for believing that matter at ultrahigh densities is much simpler than ordinary matter, so that many of its properties are predictable from theory alone. An ordinary piece of iron is quite complicated. Nearly all the electrons closely surround individual iron nuclei to which they are attached in orbits much like those in free, isolated iron atoms. A very few shared valence electrons are responsible for most of the metal's chemical and metallurgical properties.

As iron is compressed, this structure ultimately becomes much simpler. When its density reaches 10^5 grams per cubic centimeter, all the electrons in neighboring atoms are pressed so close together that their degeneracy energy exceeds the Coulomb, or electrical, force that binds the negatively charged electrons to the positively charged nuclei. Instead of clustering around their parent nuclei, the electrons distribute themselves more or less uniformly throughout the internuclear space [*see top illustration on page 27*]. So great is the energy of these degenerate electrons that they are only slightly affected by the Coulomb forces of the nuclei: their orbits are virtually straight lines. The entire swarm of electrons behaves like a homogeneous negatively charged sea that is unresponsive to the motions and positions of the positively charged nuclei embedded in it.

The forces the nuclei "feel" are then mainly the strong Coulomb repulsion of neighboring nuclei. In normal terrestrial matter this repulsion is effectively much weaker, in part because the nuclei are spaced at greater distances but chiefly because most of the large positive charge of a neighboring nucleus is canceled by the negative charge of the electrons in orbit around it.

In superdense matter the Coulomb repulsion among nuclei tends to force the nuclei to arrange themselves in a regular crystalline lattice, just as atoms in ordinary matter do when the temperature is low enough [*see bottom illustration on page 27*]. The atomic lattices of ordinary solid matter dissolve (melt) when the thermal kinetic energy of the atoms reaches a critical value sufficient to move them around easily; the value defines the



RELATIVE SIZES of the earth, a neutron star and a white dwarf are illustrated at the right. A typical white dwarf has about the same radius as the earth, approximately 6,000 kilometers, but its mass is comparable to that of the sun. Neutron stars are equally massive but are thought to have a radius of only 10 or 15 kilometers. The dot representing the neutron star was made several times too large to ensure visibility; the period at the end of this line would still be twice too large.

melting point of the particular solid. For ordinary matter the melting point does not exceed a few thousand degrees. Because of the great magnitude of the internuclear Coulomb repulsion in superdense matter, the temperature needed to melt the lattice is extraordinarily high. For iron compressed to a density of 10^8 grams per cubic centimeter the melting point exceeds 100 million degrees.

The melting temperature of superdense matter depends on the nuclear electric charge, or atomic number (the number of protons in a nucleus), as well as the density. In 1935, soon after the nature of white dwarfs was understood, Subrahmanyan Chandrasekhar of the University of Chicago showed how the central density of a white dwarf could be determined from either its mass or its radius alone. But the atomic number of the nuclei in the core, whether they are carbon or iron or something in between, depends on how the star evolved, and this cannot yet be discovered solely from observation. It is therefore difficult to say categorically whether or not particular white dwarfs have a solid center. Nevertheless, the observation that many have a mass sufficient to produce a density well above 10^6 grams per cubic centimeter, together with central temperatures below 10 million degrees, makes it very likely that many of the white dwarfs have a core in which the nuclei are frozen in crystalline lattices.

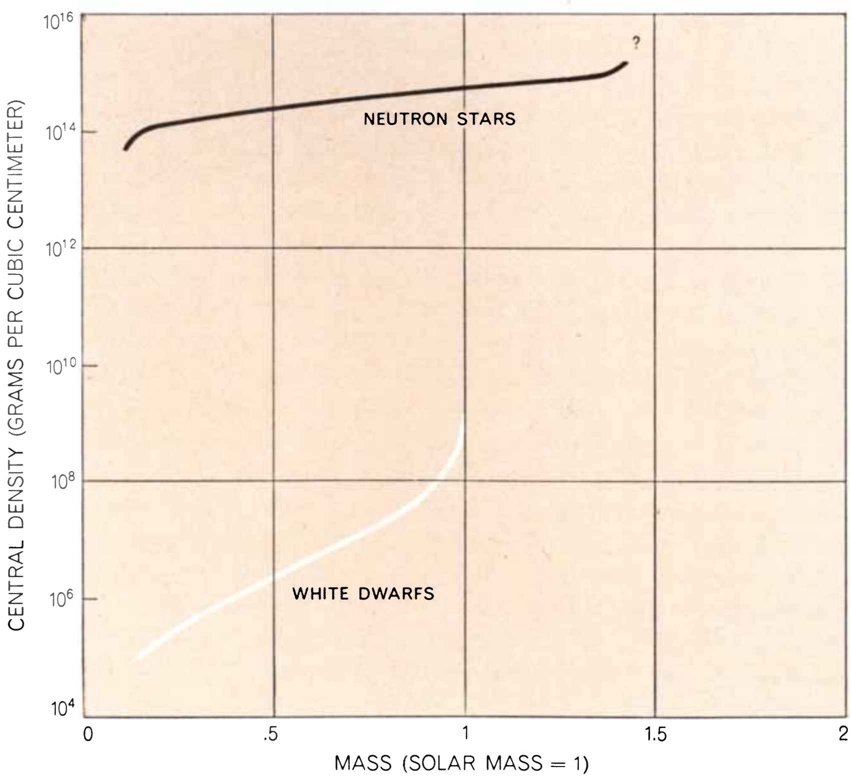
So far there are no observations either to support or to refute this possibility. Hugh M. Van Horn of the University of Rochester has suggested that the heat liberated in the cooling star when its core is changing from a gas to a liquid to a solid may be detectable as a lengthening of the time during which the surface temperature remains high. The effect, however, is slight and the observations are inconclusive.

When matter in a contracting star is compressed to densities beyond 10^8 grams per cubic centimeter, the velocity of the electrons approaches the velocity of light. The electron energy becomes so great that normal nuclei are no longer stable in the electron sea. When these energetic electrons collide with the protons bound in the nucleus, some of the protons are converted into neutrons. (When an electron and a proton combine to form a neutron, a low-energy neutrino escapes.) The more highly matter is compressed, the more this reaction proceeds; the number of free electrons is steadily reduced as the number of neutrons in the nuclei steadily increases [*see top illustration on page 28*].

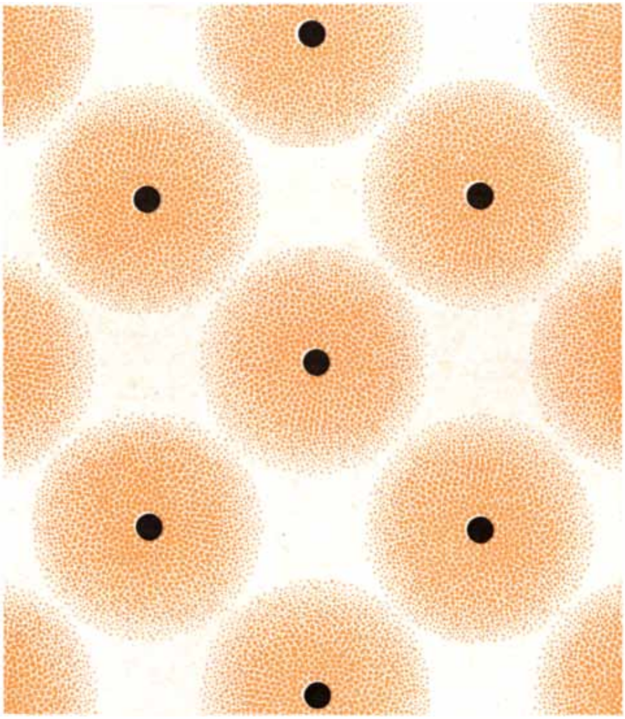
As electrons are removed from the electron sea, the electron pressure that had balanced the crushing inward pull of gravity in the white-dwarf star is no longer sufficient to enable a stable star to form with such matter as its core. When the density exceeds 3×10^{11} grams per cubic centimeter, the nuclei have become so rich in neutrons that some of the neutrons begin to evaporate into the electron sea. Such matter consists of a uniform electron sea interpenetrated by a uniform neutron sea in which nuclei rich in neutrons are embedded. At still higher densities the evaporated internuclear neutrons become the main constituent of matter, in which electrons and a few nuclei are still embedded. At a density near 3×10^{14} grams per cubic centimeter the nuclei rather suddenly disappear. The few protons that still remain no longer cluster into nuclei but spread themselves uniformly through the matter as the electrons and the much more abundant neutrons do.

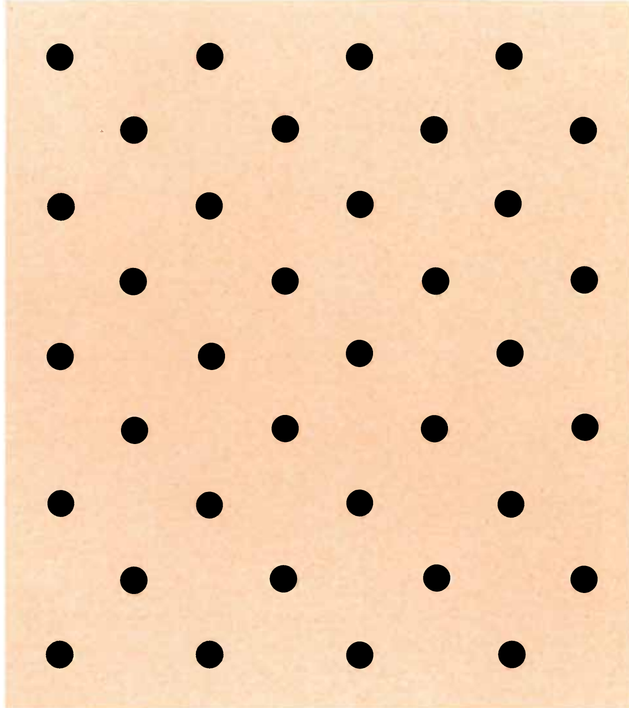
At densities near or exceeding 3×10^{14} grams per cubic centimeter the degeneracy pressure of the neutrons and their mutual repulsion at short distances causes the neutron fluid to become virtually incompressible [*see bottom illustration on page 28*]. Its resistance to compression is 10^{22} times that of ordinary steel. Such a fluid can again supply the pressure needed to counterbalance the pull of gravity in the central region of a shrinking star that has now become a true neutron star, finally stabilized at a diameter of perhaps 10 kilometers.

If one were to examine a cross section of this strange object, one would find that the density rises from zero at the surface to about 10^8 grams per cubic centimeter within about a meter of the surface [*see bottom illustration on page 29*]. The next kilometer or so would consist of matter compressed to a density (10^8 to 3×10^{14} grams per cubic centimeter) where the neutron-rich heavy nuclei exist. Typical atomic numbers of the most stable nuclei in these regions are around 42 (molybdenum) up to about 140 (elements far heavier than any yet created on the earth) near the core. At the temperature expected in such stars the nuclei would be arranged in a rigid crystalline lattice. The melting temperature of the lattice can exceed 10^{10} degrees, which is almost two orders of magnitude higher than the probable temperature of a neutron star. No matter how hot the star may have been when it was formed, processes involving neutrino

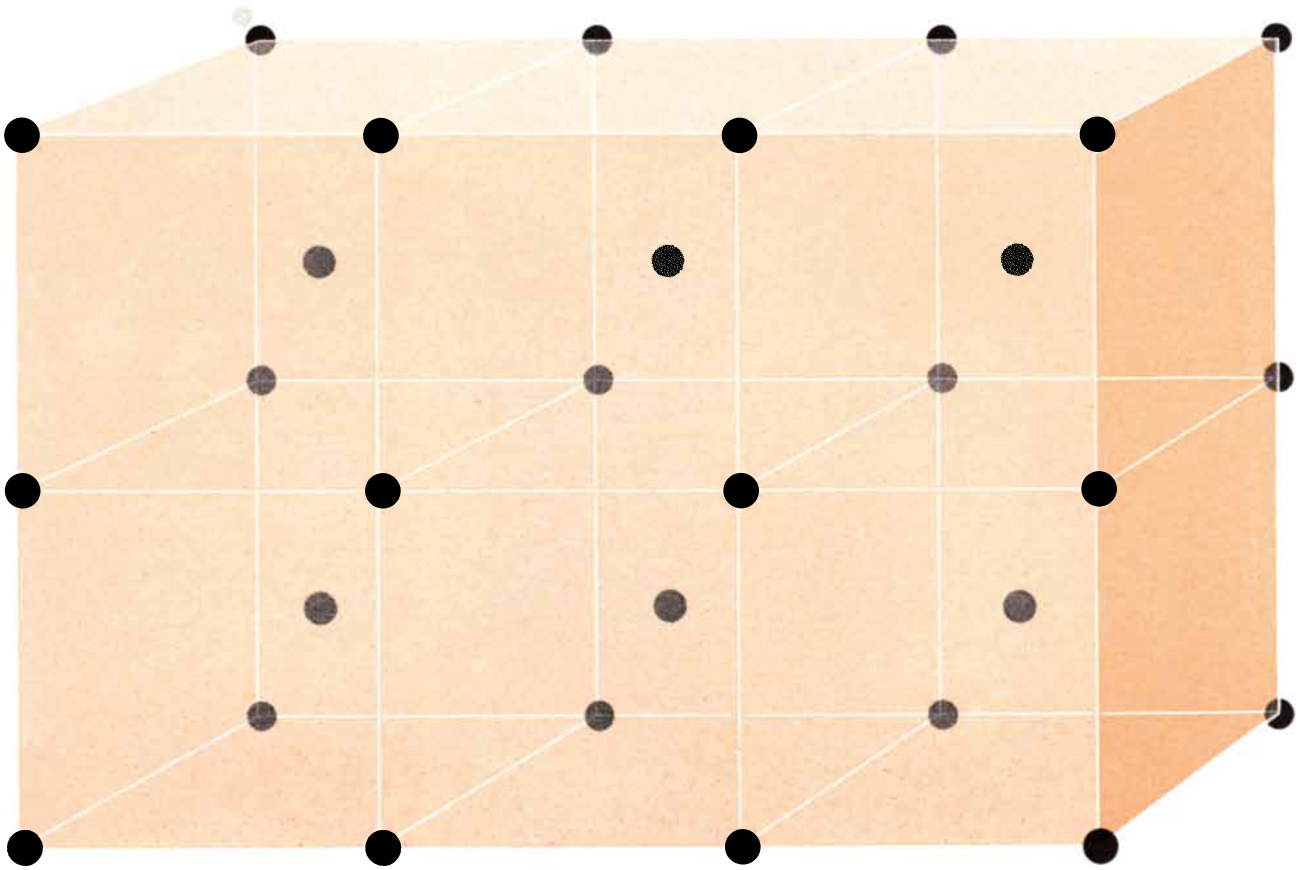


CENTRAL DENSITIES of neutron stars exceed those of white dwarfs by factors ranging from 100,000 to a billion. A density of 10^8 grams per cubic centimeter corresponds to the mass of a truck in the volume of a pea. Objects with central densities between about 10^9 and almost 10^{14} grams per cubic centimeter would be unstable; hence the gap in the chart.

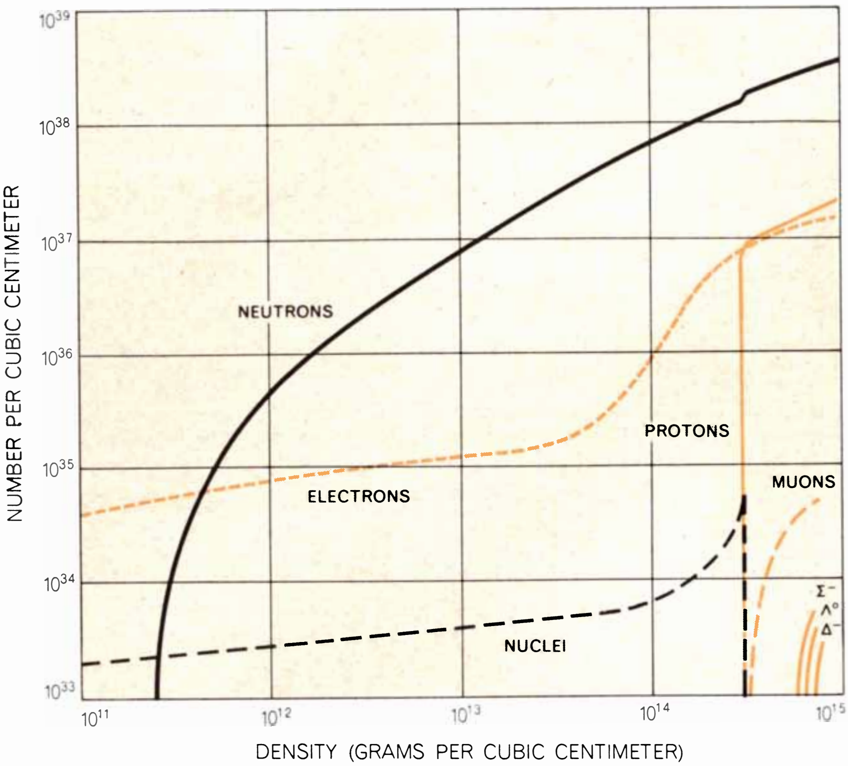




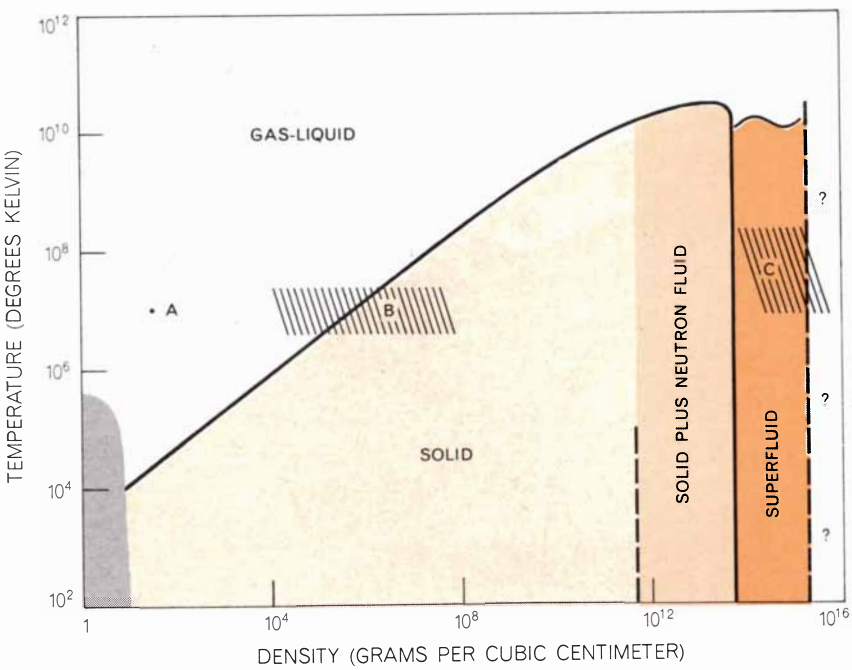
DISTRIBUTION OF ELECTRONS in a normal solid (*left*) and in a superdense solid (*right*) is markedly different. In a normal solid virtually all the electrons (*color*) surround the nuclei (*black dots*) of the parent atoms. Because the positive charges of the nuclei are essentially neutralized by the surrounding cloud of negative electrons, not much energy is needed to make the nuclei move. In a superdense solid the electrons tend to spread themselves uniformly throughout the matter. Since the nuclei are not locally neutralized they are strongly repelled by the like charges of their neighbors. As a result they tend to hold rigidly fixed positions. In normal matter the distance between nuclei is about 10,000 times their radii; in a neutron star the spacing is about 10 times the nuclear radius.



CRYSTAL-LIKE ARRANGEMENT is assumed by nuclei (*black dots*) in superdense solids for the reasons given in the illustration at the top of the page. The arrangement depicted here characterizes matter as it is thought to exist in the central region of white dwarfs and in the outer crust of neutron stars, where the densities range from about a million to 300 trillion grams per cubic centimeter.



CONSTITUENTS OF MATTER are a function of density. At a density beyond 10^8 grams per cubic centimeter electrons become so energetic they combine with the protons in nuclei to form neutrons. Beyond 3×10^{11} grams per cubic centimeter the nuclei begin to evaporate neutrons. At around 3×10^{14} grams per cubic centimeter nuclei suddenly break up into separate protons and neutrons. At still higher densities negative muons begin to replace electrons and a variety of "strange" particles (sigma minus, lambda zero, delta minus) appear.



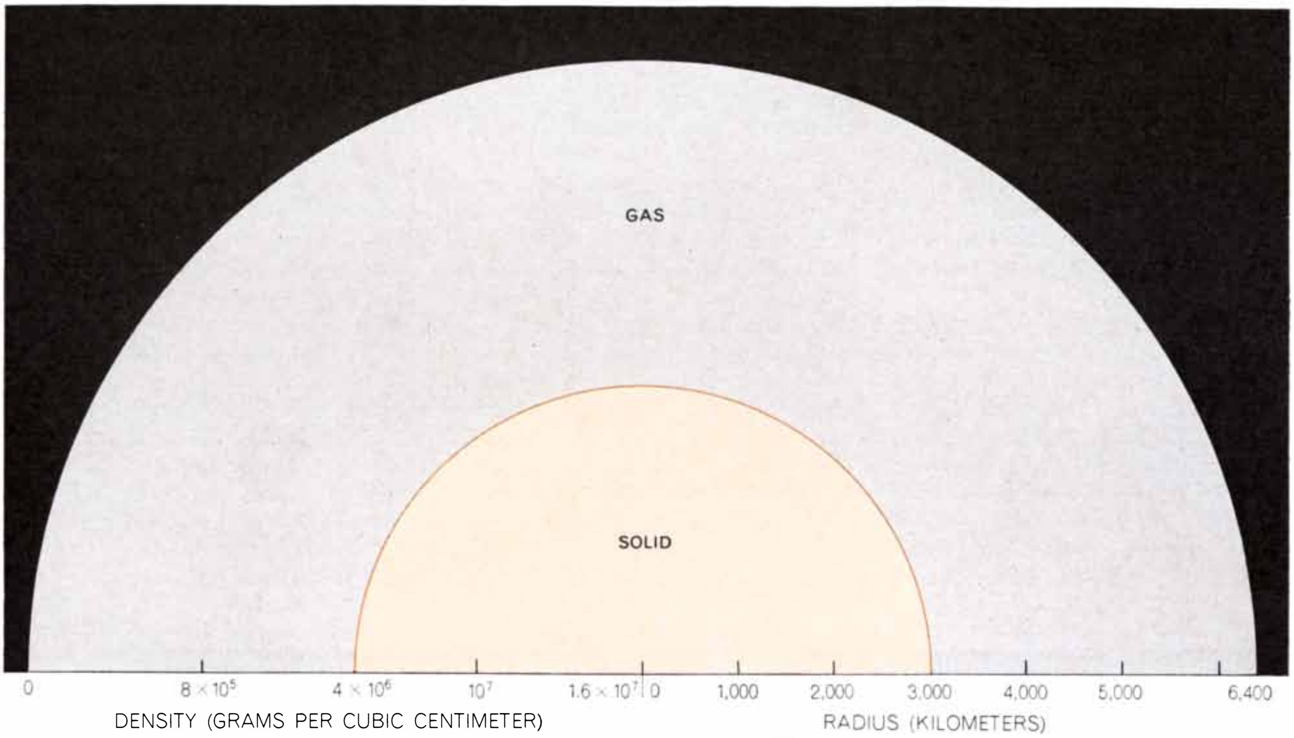
PHASE DIAGRAM shows the physical state of ultradense matter at various densities and temperatures. The nuclei are assumed to be the most stable ones at the density plotted. Beyond 3×10^{11} grams per cubic centimeter nuclear reactions tend to produce the most stable nuclei no matter what the original constituents. Point *A* indicates conditions at the center of the sun. The hatched areas indicate conditions in the central region of white dwarfs (*B*) and neutron stars (*C*). The dark gray area indicates conditions accessible in the laboratory. Theory does not predict nature of matter at 10^{16} grams per cubic centimeter.

emission will cool the star to several hundred million degrees within a few years. Therefore, except for a thin skin a meter or so thick, the outer portion of a neutron star consists of a structure made rigid by geometrically arranged nuclei. This crystalline shell is up to 10^{18} times more rigid than a piece of normal steel and 10^{20} times more incompressible. Like a jelly, it can be jiggled more easily than it can be compressed. This stellar crust, because of the high degeneracy energy of its electrons, is able to conduct electricity 10^5 times better than copper. It is also remarkably pure, since the charge and the number of neutrons in a "foreign" nucleus are rapidly altered by the surrounding electrons and neutrons.

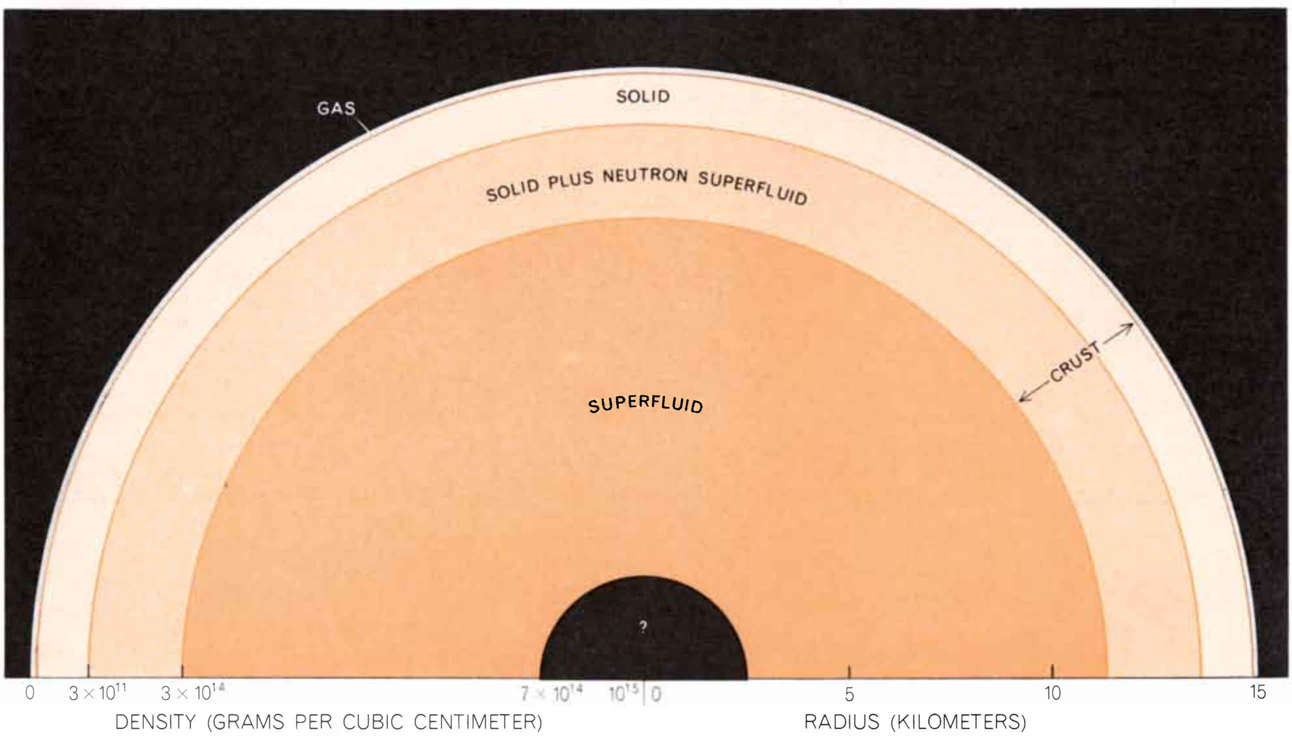
In the lightest neutron stars the crust will extend to the very center. In most, however, the crust ends a few kilometers below the surface. Below the crust the main constituent of a neutron star is the neutron fluid. The fluid is devoid of nuclei; the few protons and electrons that remain form a fluid that interpenetrates the neutron fluid. The neutron sea is probably a superfluid with properties one would expect to find in a fluid consisting of the helium isotope helium 3 when it is cooled to near absolute zero. These properties include zero viscosity (which enables superfluid helium to "climb" out of a beaker) and the ability to conduct heat much more readily than silver or copper. It is not possible in the laboratory to cool liquid helium 3 to a temperature low enough to achieve the state of matter one expects to exist in the 100-million-degree core of a neutron star.

The protons in the core, which are only a few percent as numerous as the neutrons, probably also form a superfluid. Since the protons have an electric charge, the proton superfluid will be a superconductor capable of maintaining electric currents and magnetic fields indefinitely. Only the electrons in the superfluid neutron-proton sea are expected to behave like those in normal matter. Their degeneracy energy is so enormous, however, that they travel at about 99.99 percent of the velocity of light, which means that their kinetic energy is nearly 100 times greater than their rest-mass energy.

Near the center of a neutron star, where densities may approach 10^{15} grams per cubic centimeter, neutrons and electrons possess so much energy that they will be converted into other elementary particles: baryons and mesons of the kind produced in the largest accelerators. Under terrestrial conditions these particles live less than a millionth of a second before they decay, but in



CROSS SECTION OF WHITE DWARF shows it to consist of a solid core surrounded by an envelope of gas. A white dwarf with nine-tenths the mass of the sun would have a radius of some 6,000 kilometers, about the same as the earth. The position of the solid-gas interface depends on the temperature and the nature of the nuclei present. The interface is drawn here for a typical core temperature of 10 million degrees Kelvin and for matter composed of oxygen nuclei. If the star were composed of carbon, it would just fail to be solid at the center. If the star were largely iron, it would be solid to within about 400 kilometers of the surface. An iron core would have a melting temperature of more than 100 million degrees K., or more than 10 times the typical core temperature.



CROSS SECTION OF NEUTRON STAR shows it to consist of an enigma wrapped in a superfluid wrapped in a solid crust, all covered by a few meters of gas. The core presumably consists of an exotic mixture of neutrons, protons, mesons and strange heavy particles. The surrounding superfluid consists primarily of neutrons with zero viscosity. Its properties resemble those of liquid helium 3 near absolute zero. The deeper portion of the solid crust is filled with neutrons. The outer portion resembles terrestrial matter except that it is up to 10^{18} times more rigid than steel and 10^{20} times more incompressible. A neutron star also has an intense magnetic field, 10^{12} times stronger than that of the earth. Pulsars, because of their periodic radio emission, are believed to be neutron stars.

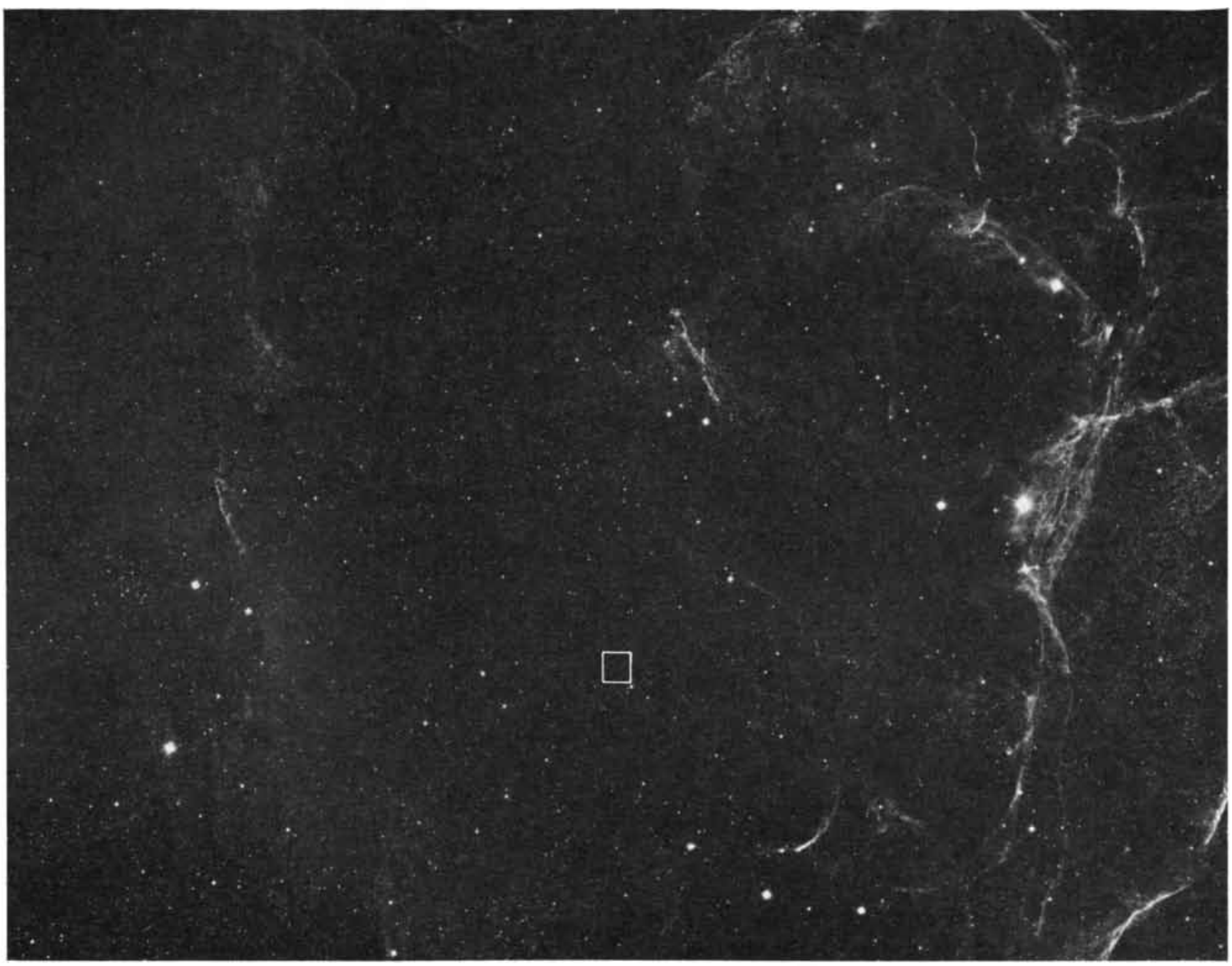
the ultradense center of a neutron star they are stable. Thus exotic particles of all kinds should coexist with neutrons, protons and electrons, forming a bizarre fluid for which we have neither sufficient experimental data nor theory to devise a quantitative model. The central core of a neutron star is a unique place in which one can expect to encounter phenomena totally outside our experience.

The laboratory analogue of a hot neutron star is a hollow spherical shell of cold steel whose thickness is about a tenth of its radius. Filling the shell is liquid helium 3 near absolute zero. At the very center of the sphere there may be a core of unknown composition and properties. To mimic the phenomena that may occur in a neutron star the shell should be a few degrees above absolute zero and the liquid helium less than a hundredth of a degree above zero.

Now that neutron stars have revealed themselves as pulsars, rotating up to 30 times per second, one can calculate that the magnetic field at the surface of a neutron star may be a trillion times larger than the magnetic field of the earth. The interior fluid probably rotates a bit faster than the external shell. Although the spinning shell is gradually decelerating, this "information" may be only slowly transmitted to the superfluid inside, which rotates essentially without friction. There is much richness in the possible phenomena and observable behavior of such a highly structured object that should help to test present ideas on neutron stars as pulsars. Gordon A. Baym, Christopher J. Pethick and David Pines of the University of Illinois and I have recently shown that certain anomalies in the rotation speed of the crust of a pulsar tend to support the description of a neutron star as a rigid container of superfluid.

There is strong evidence that the highly regular interval between the radio pulses from a pulsar is simply the time it takes a neutron star to make a complete revolution. The precision with which this time can be measured is sufficient in some cases to detect sudden changes in the rotation period as small as one part per billion. Even slight geometrical distortions in the crust of a neutron star can have a significant effect on the pulse rate.

Because the crust of a neutron star should have considerable strength, the star can maintain a shape that is slightly different from the shape of a rotating gaseous fluid bound by its own gravita-

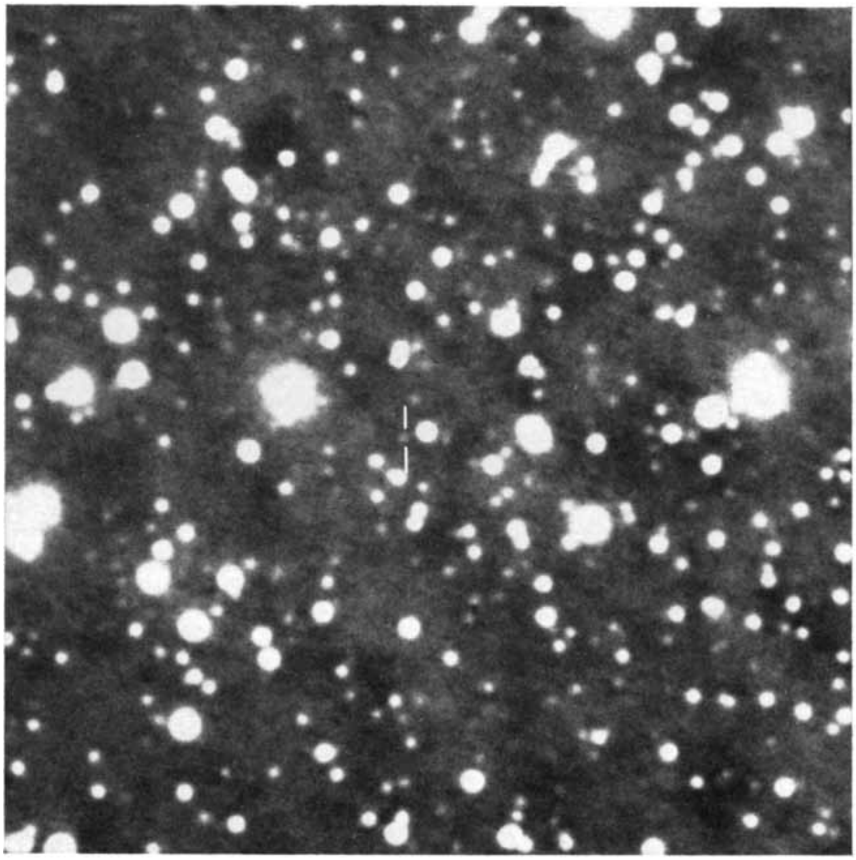


REGION CONTAINING PULSAR in the constellation Vela is shown in this plate made at the Cerro Tololo InterAmerican Observatory in Chile by Bart J. Bok. Because the plate was exposed in the ultraviolet region of the spectrum it clearly reveals the wisplike remnants of the supernova explosion that presumably produced the pulsar, identified by its coordinates as PSR 0833–45. Radio observations made by George S. Downs and Paul E. Reichley of the Jet Propulsion Laboratory disclose that the pulsar lies in the center of the region indicated by the white square. Only one pulsar, NP 0532 in the Crab Nebula, has been positively identified in photographs made with optical telescopes. An object that is a candidate for the Vela pulsar is shown in the picture on the opposite page.

tional attraction. Presumably the crust solidified soon after the star was formed, when its rotation rate was close to maximum. As the rotation rate decreases there will be a reduction in centrifugal force and a consequent tendency for the star's shape to be more spheroidal than it was at first. The rigid crust, however, tends to resist this shape adjustment. It is rather difficult to estimate how much the crust can be stressed before it breaks.

It seems probable that the crust of a neutron star is strong enough to allow a maximum variation in surface position of somewhere between a hundredth of a centimeter and one centimeter. In other words, the fantastic gravitational pull of the star (100 billion times stronger at its surface than the gravitational pull of the earth) is very effective in keeping the shape of the star quite close to spherical. As a result no neutron-star mountains should be more than a few centimeters high, and even these might quickly melt. To climb a one-centimeter Everest on a pulsar, however, would take a man the energy of 100 lifetimes. Nevertheless, in spite of the very small geometrical distortions the crust could tolerate, some of the effects of such distortions may be observable.

If the crust should crack as the result of accumulated strains producing a starquake, the event could be detected unambiguously if the readjustment in surface position were to exceed a few ten-thousandths of a centimeter. This change, slight as it is, would be accompanied by a comparably small change in rotation speed for angular momentum to be conserved. Indeed, small sudden increases have been observed in the period of two young, rapidly rotating neutron stars, one at the center of the Crab Nebula and the other within the supernova remnant in the constellation Vela [*see illustrations on these two pages*]. If these rotation changes are interpreted as starquakes, they correspond to surface movements of about one centimeter in the Crab Nebula pulsar and a hundredth of a centimeter in the Vela pulsar. Although other explanations may yet prevail, we at least have the possibility that these or similar occurrences portend the beginning of neutron-star seismology. (J. A. Wheeler of Princeton University has quipped that since the study of the earth's crust is called geology, the study of a star's crust should be called astrology.)



POSSIBLE VELA PULSAR is marked by the two vertical lines in this composite photograph made with an image intensifier attached to the 60-inch telescope at the Cerro Tololo observatory. The faint 22nd-magnitude star is located almost exactly at the pulsar's computed radio position, but it has not been shown that the candidate is actually blinking. The picture is a composite of 75 separate plates made by Hong-Yee Chiu and Stephen P. Maran of Goddard Space Flight Center and C. Roger Lynds of Kitt Peak National Observatory.

The existence of a thick solid crust around a neutron star may have significant observable effects on pulsar behavior that are much subtler than the possible production of starquakes. In ways not yet understood the radio signals from pulsars are almost certainly generated by the magnetic field that rotates with the neutron star. Through this field the star couples to the medium around it and "feels" the torque that gradually decreases its rotation rate. The fact that the magnetic field threads through the rigid crust of the rotating neutron star and is anchored to it rather than to the gaseous-liquid matter found in the outer layers of less dense stars may be quite relevant to the precisely maintained periods of pulsars. The magnetic field cannot drift with respect to the stellar surface (as sunspots do), so that the field and its effects can remain unchanged after tens of millions of rotations.

Because crust rigidity can slightly distort the shape of a rotating neutron star it can cause a slow stellar wobble like that of a slightly aspherical spinning top. Peter Goldreich of the California Institute of Technology has pointed out that an extremely small wobble would be sufficient to keep the stellar magnetic field from roughly aligning itself along the stellar axis of rotation as the spinning star gradually slows up. An aligned field would not vary in the aspect it presents to us as the star rotates, so that it would be difficult to understand why the pulsar's signal changes so much during each rotation. (The necessary minimum shape distortion from crust rigidity to prevent alignment is only about 10^{-5} centimeter.)

A complete interpretation of pulsar observations will probably depend in part on a more reliable and detailed description of properties of neutron star crusts than is currently available. To know how the star can be expected to wobble, how it may stabilize its magnetic field and when its crust may crack, it will be necessary to learn more about crustal strength and ductility and how the crust relaxes under stress. All of this suggests that the twinkling pulsar—with its jewel-like crust surrounding a superfluid core that in turn can possess a center with unknown properties—may have the most remarkable architecture of any object in the universe.

THE IROQUOIS CONFEDERACY

This alliance of Woodland Indian tribes played a significant role during the European colonization of North America. Excavations in New York now cast new light on their origins and social evolution

by James A. Tuck

Among the Indians in the American Northeast none affected the lives of the European colonists more than the few thousand who lived near Lake Ontario and spoke the Iroquoian language. With firearms acquired in the 17th century, first from the Dutch and then the English, an alliance of five Iroquois tribes forayed east into the maritime provinces of Canada and west as far as the Illinois River. They crushed the nearest of their traditional Algonkian-speaking enemies and even destroyed Iroquois-speaking tribes that did not belong to their confederacy. Since the Algonkians were allies of the French, the Iroquois did much to help the English win control of Canada in the 18th century. Then they fought for both sides during the War of Independence.

The role played by these "Romans of the New World," as the historian Francis Parkman called them, seems out of all proportion to the slim resources at their disposal. How did the Iroquois manage to accomplish so much? The question has made Iroquois prehistory a controversial subject; a leading scholar in the field has remarked that more ink has been spilled over the Iroquois than over any other aboriginal American people. Yet the five tribes of the confederacy never had more than 12,000 members, and probably had considerably fewer. Their fighting men numbered only some 2,200.

Some scholars have maintained that the Iroquois came originally from Georgia and the Carolinas. That area was the home of the "civilized" Cherokees, who spoke an Iroquoian language and whose ready adoption of European ways was considered an indication of their superiority to other Indians. It has also been suggested that the Iroquois came from the north, moving down the valley of the St. Lawrence under pressure from the advancing Algonkians. One source even places the Iroquois homeland in the Pacific Northwest. Not until recently has it been realized that the Iroquois culture might simply have arisen in the area where the European colonists first encountered it.

Today it is clear that the actual origin is the last one. Archaeological evidence collected at more than a score of sites over the past two decades shows that the Onondagas—the key tribe in the confederacy—developed into full-fledged Iroquois from a preceding level of pre-Iroquois culture in the years after A.D. 1000 without ever leaving a 25-by-15-mile area in upper New York State near modern Syracuse. What is true of the Onondagas must surely hold for the other tribes in the confederacy: the Oneidas and Cayugas immediately to the east and the west, the Senecas of the Genesee valley farther to the west and the Mohawks of the Mohawk valley farther to the east.

What is known about the Iroquois in Colonial times is helpful in interpreting their prehistory. Like most of the other aboriginal inhabitants of the region, they were representatives of the Late Woodland period of Northeastern prehistory. Farmers and hunters, they lived in villages in forest clearings, protected from raiders by one or more palisades made of saplings. In the clearing beyond the palisade the women of the village raised corn, beans, squashes and tobacco. The women also collected wild plant foods and the men hunted and fished. Except for dogs, domestic animals were unknown. Inside the palisade stood several "longhouses," which were long indeed: typically they were 25 feet in width and 50 to 100 feet in length. This was the traditional Iroquois form of house, consisting of a framework of saplings covered with sheets of bark. It was divided into apartments that were usually occupied by closely related families. Running down the middle of the house was a corridor where the families living on each side shared fireplaces.

Each of the five tribes of the confederacy occupied two or more such villages, usually only a few miles apart. Village affairs were supervised by a local council. Above the local council was a tribal council, which generally met in the largest village. The tribes were banded together in a "Great League of Peace," the formal name for the confederacy, which was governed by a council of 50 sachems representing all the tribes. Iroquois religious observations marked both the events of the agricultural cycle (with such occasions as a "planting festival" and a "green corn festival") and the progress of the seasons (exemplified by an annual "wild strawberry festival" and similar events).

As a tribe whose leader was prominent in founding the Great League of Peace, the Onondagas were traditionally at the center of confederacy affairs. The tribe was "keeper of the central fire," and the name of their tribal leader, Atotarho, was adopted by an Onondaga when he rose to be sachem. Thus it seems likely that the trends and events of Onondaga

INDIAN VILLAGE on a hilltop near Syracuse, N.Y., is seen in the photograph on the opposite page during excavation. It is a 14th-century Iroquois site known as Furnace Brook. Unpainted stakes mark the excavators' grid. Colored stakes locate post molds: the dark humus of rotted saplings that once formed house walls and inner partitions. Dominating the scene is the outline of a structure that was 22 feet wide and 210 feet long: an Iroquois longhouse.

SAVAGE RITUAL at a 15th-century Iroquois village site known as Bloody Hill is evidenced by a bathtub-shaped pit discovered by a Syracuse University team in 1967. A fire burning under the stones transformed the pit into a platform suitable for roasting.

CLOSE-UP OF PIT during its excavation shows pieces of broken and cut human bone. Arrows point to knife marks. Part of a skull was also unearthed. Evidently an adult male had been cooked and eaten. The incident preceded the founding of the Onondaga tribe.

prehistory parallel those of the other tribes. All five tribes must have been subjected to much the same environmental and social pressures. Indeed, the career of the Onondagas probably reflects the events taking place among many of the Indians of the American Northeast in the era following the introduction of the cultivation of corn, beans and squashes around 1000 B.C.

The Late Woodland culture of the pre-Iroquois inhabitants of New York is named Owasco after a site at Owasco Lake near the center of the state. The earliest Owasco village that is pertinent to Onondaga prehistory lies some eight miles north of Skaneateles Lake and is known as the Maxon-Derby site. (This site and others, by the way, take their names from the local landowner or from local topographic features.) The Maxon-Derby site was excavated in 1959 and 1960 by William A. Ritchie of the New York State Museum in Albany. The site covers two acres and includes the floors of seven houses. Two separate carbon-14 analyses show that the village was occupied around A.D. 1100. Apparently it had no palisade of the kind that surrounded the villages of historical times.

The outlines of the seven houses can be traced partially or completely by rows of post molds: dark patches of humus in the subsoil that mark the position of the saplings that once formed the frame. Most of the houses were small, with parallel sides and rounded ends, but two of them appear to be precursors of the Iroquois longhouse: they were 25 feet wide and 60 feet long. The hearths in these larger houses, however, were along one wall rather than in a central corridor. The fact that the houses had several hearths suggests that they sheltered several related families.

The food remains at the Maxon-Derby site included the bones of mammals, birds and fish, the debris of wild plants and charred kernels of corn. Among the artifacts were triangular stone arrow points, bone tools and fired-clay tobacco pipes. All these objects in one way or another foreshadow Iroquois forms. The most abundant artifacts at the site were fragments of pottery; their rims had been decorated with impressions made by the edge of a paddle wrapped with cord.

A second Owasco village, known as the Chamberlin site, is some three miles southeast of the Maxon-Derby site. Early historical records indicate that it was once surrounded by a low ring of earth, which has now disappeared. A field party from Syracuse University excavated the site under my direction in the summer of 1967. Carbon-14 analysis indicates that the village was occupied around A.D. 1290, some two centuries later than the Maxon-Derby village. The pottery showed a corresponding degree of development, although it still clearly represented the late phase of Owasco culture.

The Chamberlin houses in particular show advances along Iroquois lines. Although the hearths are still next to one wall, the houses are more than 80 feet long. I suspect that the obliterated ring of earth once formed the base of a defensive palisade, which may mean that by the end of the 13th century village defense was becoming an important consideration.

Remains at still a third village site only a little east of the Chamberlin site show the transition from the Owasco culture to the nascent culture of the Iroquois. This is the Kelso site, excavated by Ritchie in 1963. The Kelso site actually consists not of one village but of two overlapping villages. Both were heavily fortified; the palisade of one consisted of three concentric rings of saplings. Some of the Kelso houses were small and oval, but the longhouses were nearly 130 feet in length and the hearths are along a central corridor with a door at each end. Although the overlapping outlines of the palisades show there had been two villages, only a single carbon-14 date was obtained. This is A.D. 1390, just a century later than the Chamberlin date. Not only the form of the Kelso longhouses but also the details of decoration on tobacco pipes and pottery allow the site to be assigned to the earliest phase of the full Iroquois culture.

On the basis of the available evidence the connection among the three sites is not entirely clear. It is nonetheless possible that the three villages, considering their closeness in time and space and the similarity of their artifacts, were occupied successively by a single community. Periodic relocations could have been motivated by the need for new supplies of firewood, for new hunting grounds and perhaps for new soil for horticulture.

Four village sites that are comparable in age to the first three and that also reflect the transition from the Owasco culture to the Iroquois are located among the tributaries to Lake Onondaga, some 15 miles farther east. The first of these sites, the Cabin site, was apparently a small, undefended hilltop village. A large trash heap on the steep slope next to the village yielded a wealth of artifacts. These are primarily fragments of pottery but also include triangular arrow points, tobacco pipes of late Owasco style, bone awls, pins, scrapers and fish-spear points, and a bangle fashioned from the toe bone of a deer [*see top illustration on pages 38 and 39*]. Another find was a tiny stylized clay effigy of a human face. This may foreshadow the later practice of wearing life-size effigy masks, which became an important feature of Iroquois religious ritual in historical times. No absolute date has been established for the Cabin site, but the inventory of artifacts suggests that it was occupied between A.D. 1250 and 1300.

Four miles to the north are the remains of a two-acre village known as the Furnace Brook site. It is not quite contemporaneous with the Kelso site to the west but, like the Kelso villages, it was completely surrounded by a palisade. Two carbon-14 determinations show that Furnace Brook was occupied between A.D. 1300 and 1370. Some of its houses are small and reminiscent of the ones at the Maxon-Derby site, but Furnace Brook has a longhouse that is of unusual dimensions for the period. It was 22 feet wide and 210 feet long; a door at each end opened on a central corridor where the hearths were located. The artifacts unearthed at Furnace Brook show that, like the Kelso site, it belongs to the earliest phase of the full Iroquois culture.

A third village site less than two miles away is Howlett Hill. It has the well-defined remains of three longhouses. The largest is also of unusual dimensions: it is 334 feet long [*see illustration on page 37*]. Analysis of charcoal from a post mold of this house yields a carbon-14 date of A.D. 1380, which suggests that the Howlett Hill village may have been a successor to the Furnace Brook one. The increase in longhouse size (the largest at Howlett Hill is a third longer than the largest at Furnace Brook) clearly reflects a similar increase in the number of occupants. In any case, the people of both villages had progressed beyond the Owasco culture to the Iroquois.

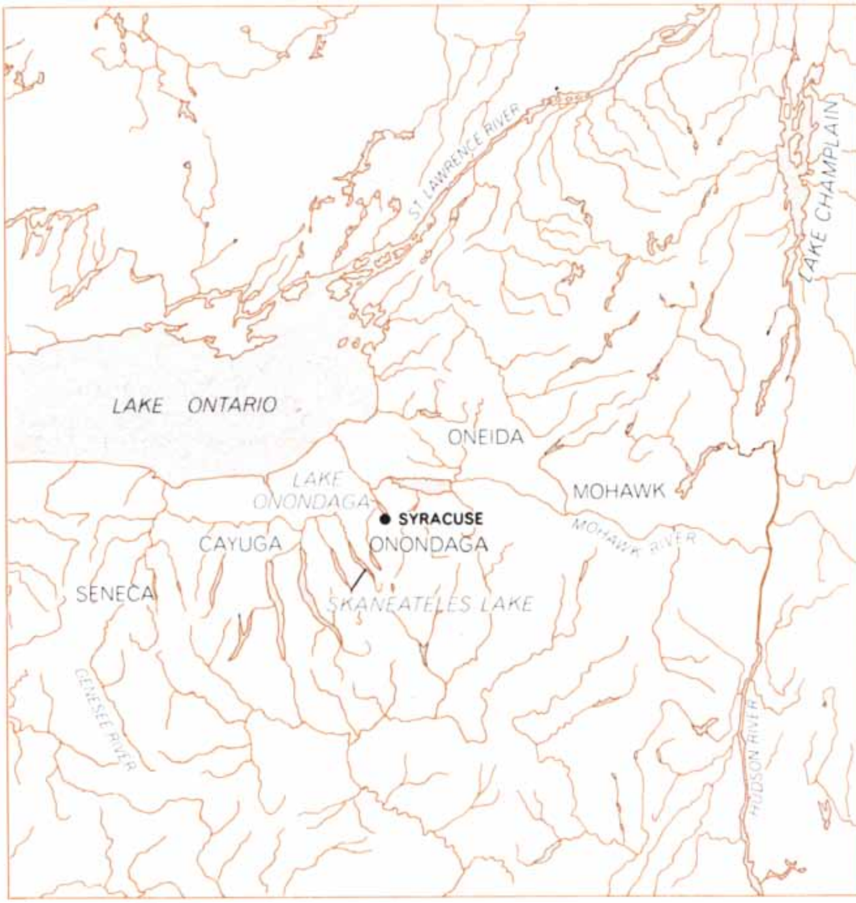
The last of the villages in the vicinity of Lake Onondaga is known as the Schoff site. It was partly excavated by our Syracuse University group in 1967, and it proved to have the longest of all the longhouses: it extended almost exactly 400 feet. A limited number of artifacts unearthed at the village include trumpet-shaped tobacco pipes and pottery with incised neck decorations. Both suggest that the villagers had attained the phase of Iroquois cultural development that follows the nascent phase. Analysis of material from the site has provided a carbon-14 date of A.D. 1410.

I have already suggested that the

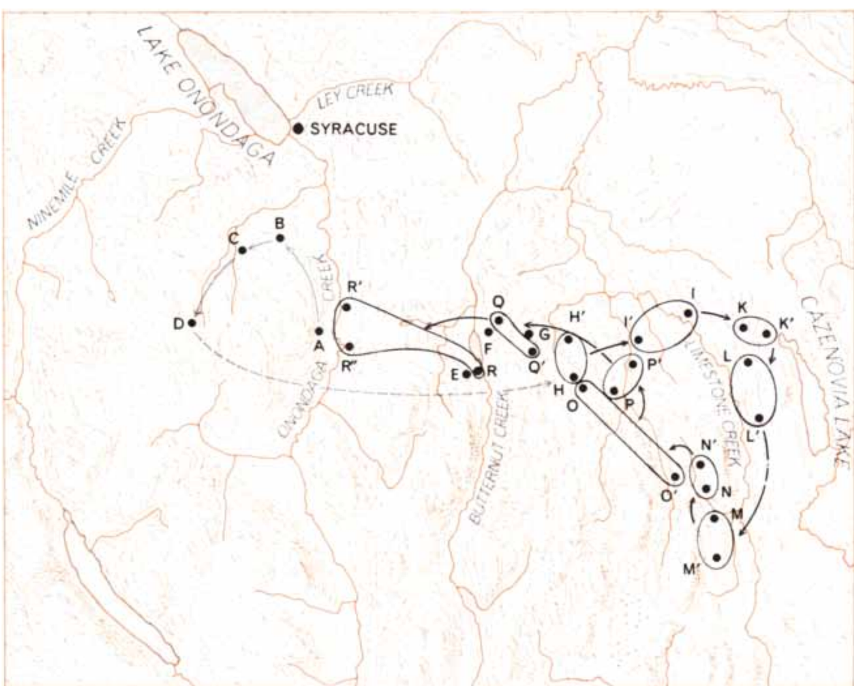
three western sites could have been the successive residences of a single social group. The probability that another single group successively occupied the four central sites is stronger. The four villages are close to one another, and their successive occupation—if I am right—represents a series of moves into fresh territory first from south to north and then south again. Moreover, the three most recent villages are separated in time by no more than a century, and the progressive increase in the size of their longhouses might reflect the natural increase in the group's numbers. Lastly, certain aspects of the assemblage of artifacts at these sites, notably a high percentage of pottery vessels with incised neck decorations compared with the low percentage of this kind of decoration at other sites, suggest a degree of cultural continuity that may be characterized as a "microtradition."

The sequence of sites from Cabin to Schoff therefore appears to reflect the activities of a single group. The group's next move apparently was to abandon the Lake Onondaga watershed altogether. In spite of long and intensive reconnaissance and the excavation of test pits in a zone extending for miles in all directions from the Schoff site, no trace of a successor village has been found. The trail does not, however, grow completely cold.

The largest number of sites in the Onondaga region are found in the area east of Syracuse. The record preserved in these eastern sites extends from nascent Iroquois times through the period of European contact and up to the final decades of the 18th century. Three of the earliest sites in the eastern group are roughly contemporaneous with the Howlett Hill and Schoff sites in the cen-

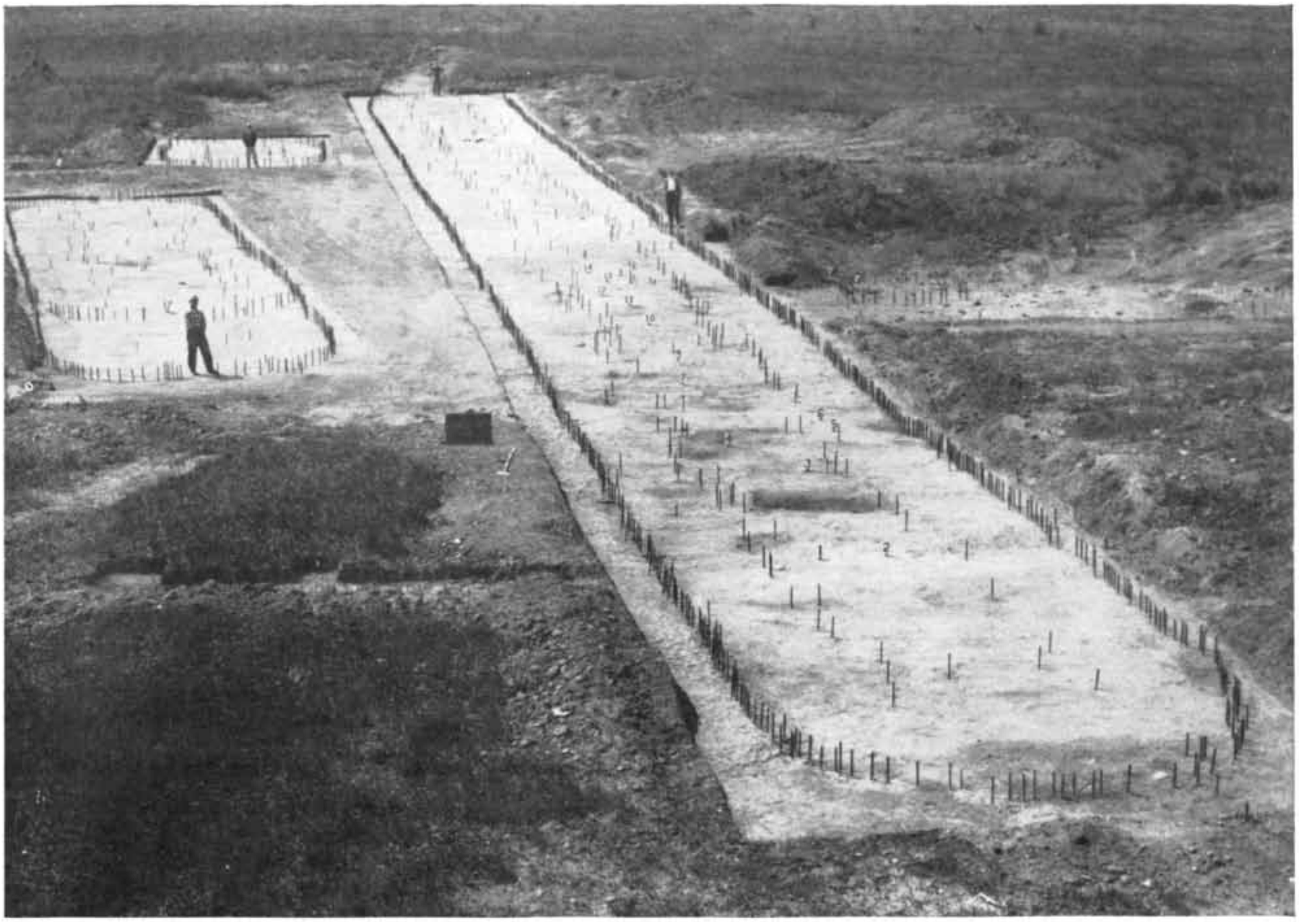


FIVE TRIBES of the Iroquois confederacy were, from west to east, the Senecas, the Cayugas, the Onondagas, the Oneidas and the Mohawks. At the beginning of the 18th century their power extended from Maine to Illinois and from southern Ontario to Tennessee. The Tuscaroras became the sixth after being ousted by white settlers in the Carolinas.



A	CABIN	L'	ATWELL
B	FURNACE BROOK	N	CHASE
C	HOWLETT HILL	N'	QUIRK
D	SCHOFF	M	SHELDON
E	COYE II	M'	DWYER
F	KEOUGH	O	CARLEY
G	BLOODY HILL	O'	POMPEY CENTER
H	BURKE	P	INDIAN HILL
H'	CHRISTOPHER	P'	INDIAN CASTLE
I	NURSERY	Q	JAMESVILLE PEN
I'	CEMETERY	Q'	WESTON
K	BARNES	R	TOYADASSO
K'	MCNAB	R'	UPPER VALLEY OAKS
L	TEMPERANCE HOUSE	R"	LOWER VALLEY OAKS

VILLAGE SITES occupied by the Indians who eventually founded the Onondaga tribe are identified by letters on this map. Arrows indicate successive occupations. The period runs from the end of the 13th century through the 18th. Establishment of two adjacent villages (*H–H'*) late in the 15th century marks the foundation of the tribe. Thereafter the tribe usually occupied pairs of villages.



LARGER LONGHOUSE, at the Howlett Hill site, is 334 feet in length. Closely set stakes outline the house wall. Other stakes within the house show where its inner structural supports stood. Numbered placards locate 16 hearths that lined a central corridor.

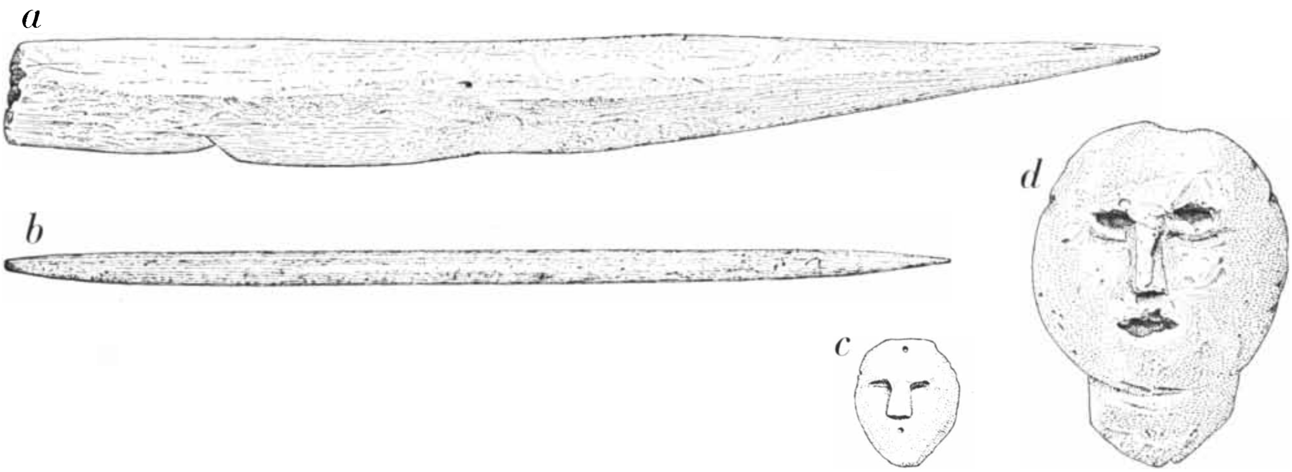
tral group; the earliest of them is known as Coye II. Like the Kelso site in the west and Howlett Hill in the central group, Coye II is a village that was occupied by people at the nascent phase of Iroquois cultural development. This is evidence that still a third social group in the Onondaga region participated in the transition from the Owasco to the Iroquois culture.

Two sites slightly later than Coye II are Keough and Bloody Hill. Both were small villages. No absolute date is available for Keough but a carbon-14 analysis of material from Bloody Hill places its time of occupation around A.D. 1420. The percentages of similar artifacts of various kinds from both sites are nearly identical, suggesting that the villages were occupied at about the same time.

Bloody Hill has also yielded evidence that ritual torture and cannibalism, which were familiar in historical times, were an established part of the Iroquois culture in the 15th century. In the summer of 1967 our digging exposed a large pit shaped somewhat like a bathtub: it was about eight feet long, four and a half feet wide and two and a half feet deep. The soil showed signs of having been subjected to intense heat. We found that the pit had been filled with firewood, some of it logs as much as six inches in diameter, which was then ignited. A layer of boulders and cobblestones had been placed on top of the burning logs, and the blaze soon transformed the cobble pavement into a roasting platform. A few scraps of refuse were present on the platform but the principal remains on it were fragments of an adult male's skull and long bones; the bones showed the marks of cutting tools. In the light of later Iroquois practices, it is not difficult to see in these human remains the ordeal and ultimate disposition of a captured enemy. The pit is testimony to the bellicose characteristics of early Iroquois society every bit as eloquent as the village fortifications.

About two miles east of Bloody Hill are two later sites I believe contain evidence of how the village groups of the time reacted to local strife. One of these areas is known as the Christopher site. It appears to cover two acres, and thus it represents a village much larger than either Keough or Bloody Hill. I suggest that the Christopher site in fact represents a merger of the two earlier communities, probably in the interests of improved security.

The second area, called the Burke site, is another extended village. It was occupied for a considerable time and, as the relocation of its palisade and one of its longhouses indicates, it was rebuilt at least once. The real surprise at the Burke site, however, is the presence of the same pottery-decorating microtradition that was characteristic of the Schoff site and its predecessors in the central area. At Burke we seem to have picked up the trail that had vanished earlier. Not only does the Schoff microtradition reappear at Burke but also one of the Burke longhouses is almost as generous in its proportions as the houses of the central area are. Although it has not yet been fully exposed, it already measures more than 240 feet. Moreover, the forms of the arrow points and tobacco pipes at Burke indicate a gradual evolution from the forms found at Howlett Hill and Schoff. That would be natural. The only available date for the Burke site, based on a carbon-14 study of material prob-

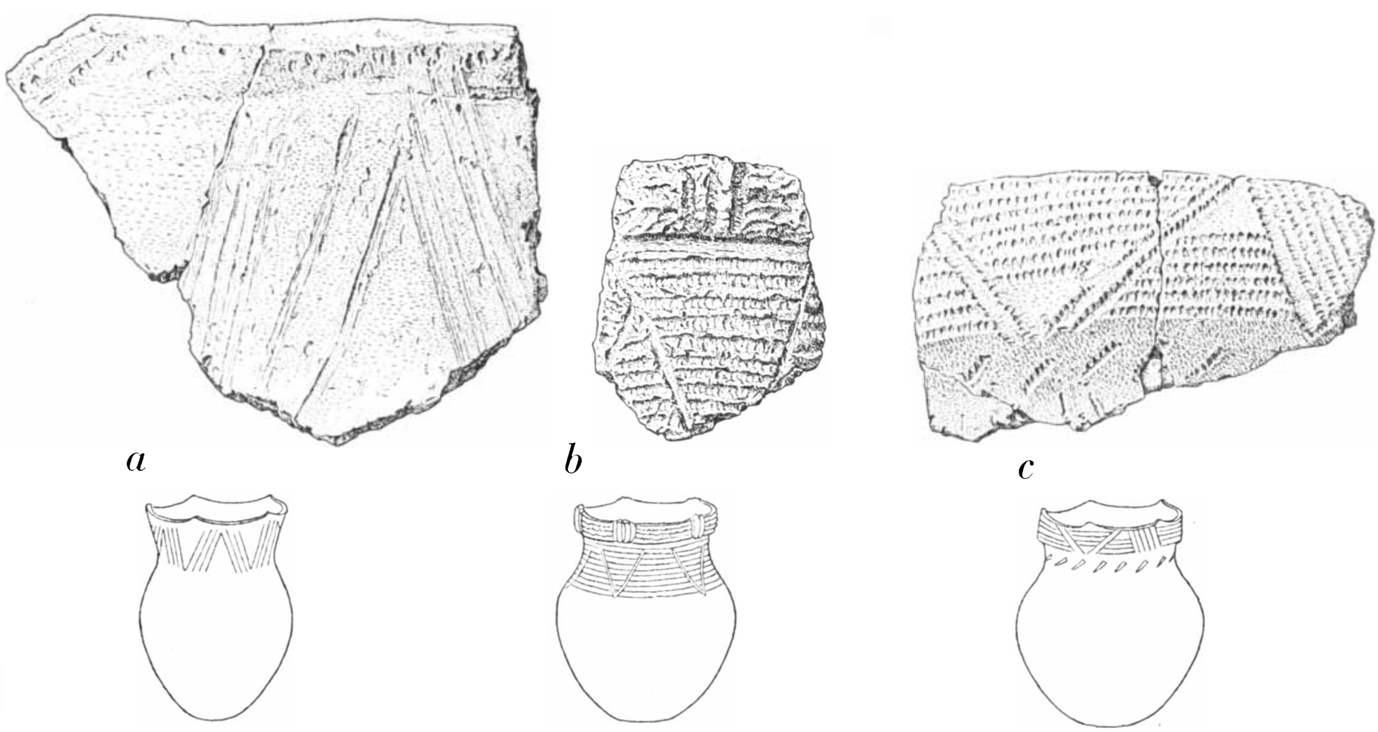


CHARACTERISTIC ARTIFACTS of the Owasco and Iroquois cultures include a bone awl (*a*), a bone point for a fish spear (*b*), an effigy of a human face modeled in clay (*d*) and a bangle fashioned from the toe bone of a deer (*e*). All are from the Cabin site,

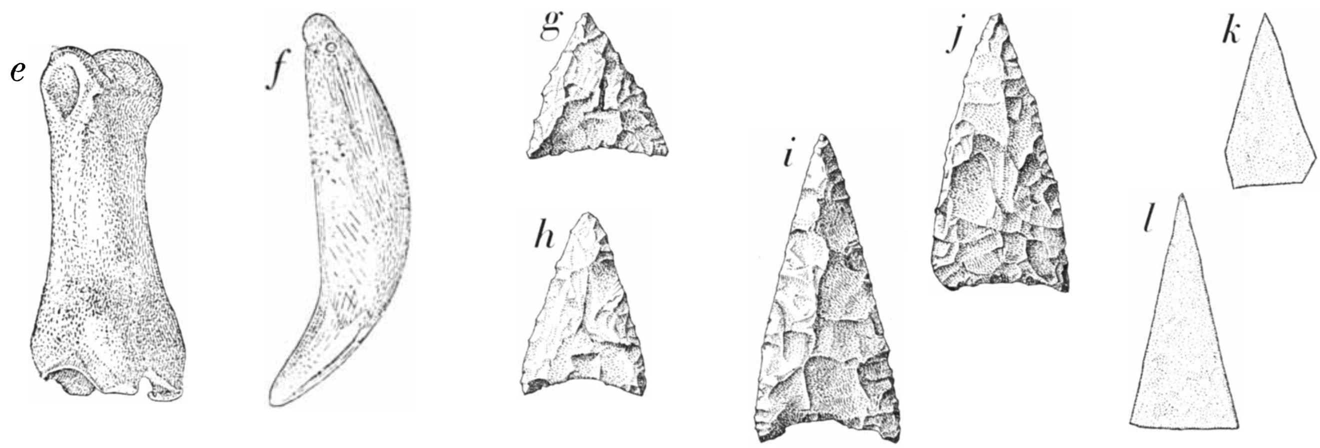
ably deposited near the end of the village's occupation, is about A.D. 1480, or almost a century later than the Schoff village.

Why would a group intent on relocation choose to settle only two miles away from a large, well-defended and strange village? The choice has implications that bear on the eventual development of the Iroquois confederacy. It is hard to imagine that two potentially hostile communities could have existed so close together without an understanding, however informal, about mutual defense. At the very least some kind of nonaggression pact would have been needed to prevent clashes that could have been disastrous for one village if not both. I interpret the evidently peaceful coexistence of the inhabitants of the Christopher and Burke sites as an arrangement that marks the founding of the Onondaga tribe. The two groups probably became closely allied between A.D. 1425 and 1450, and it appears that an Iroquois two-village system and a subsequent pattern of intertribal nonaggression alliances may have begun here.

How soon after this time the two allied villages developed a sense of common identity and took a single name is impossible to say, but it should not have been long afterward. ("Onondaga" is an Iroquois word meaning "the people on the hills.") The merger would provide most of the advantages of combining military forces while at the same time avoiding the pressure that too large a concentration of people in a single village would exert on the environment. In this simple balancing of security require-



POTTERY DECORATION was applied principally to the neck of cooking vessels by incising lines in the clay or pressing it with a paddle wrapped with cord. The decorated fragments are illustrated two-thirds actual size; the form of the entire vessel is shown schematically below. The first examples are from village sites that may have been occupied successively by the same group: the



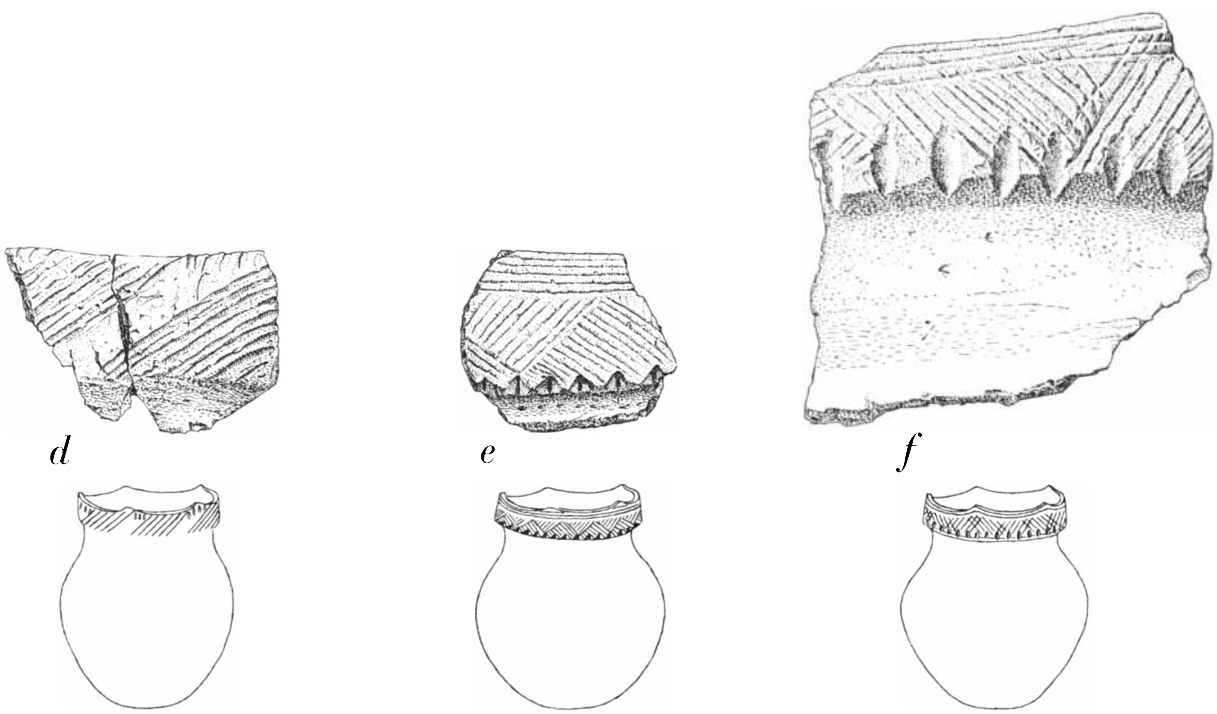
which was occupied around A.D. 1250 or 1300 by a group that was at the Owasco stage of cultural development. The smaller effigy (*c*), bear tooth (*f*) and arrow points (*g–j*) are from later Iroquois sites. Brass arrow points (*k, l*) mark the arrival of European trade goods.

ments with ecological imperatives, I believe, lies the basis of the later and larger political groupings that gave rise to the Great League of Peace.

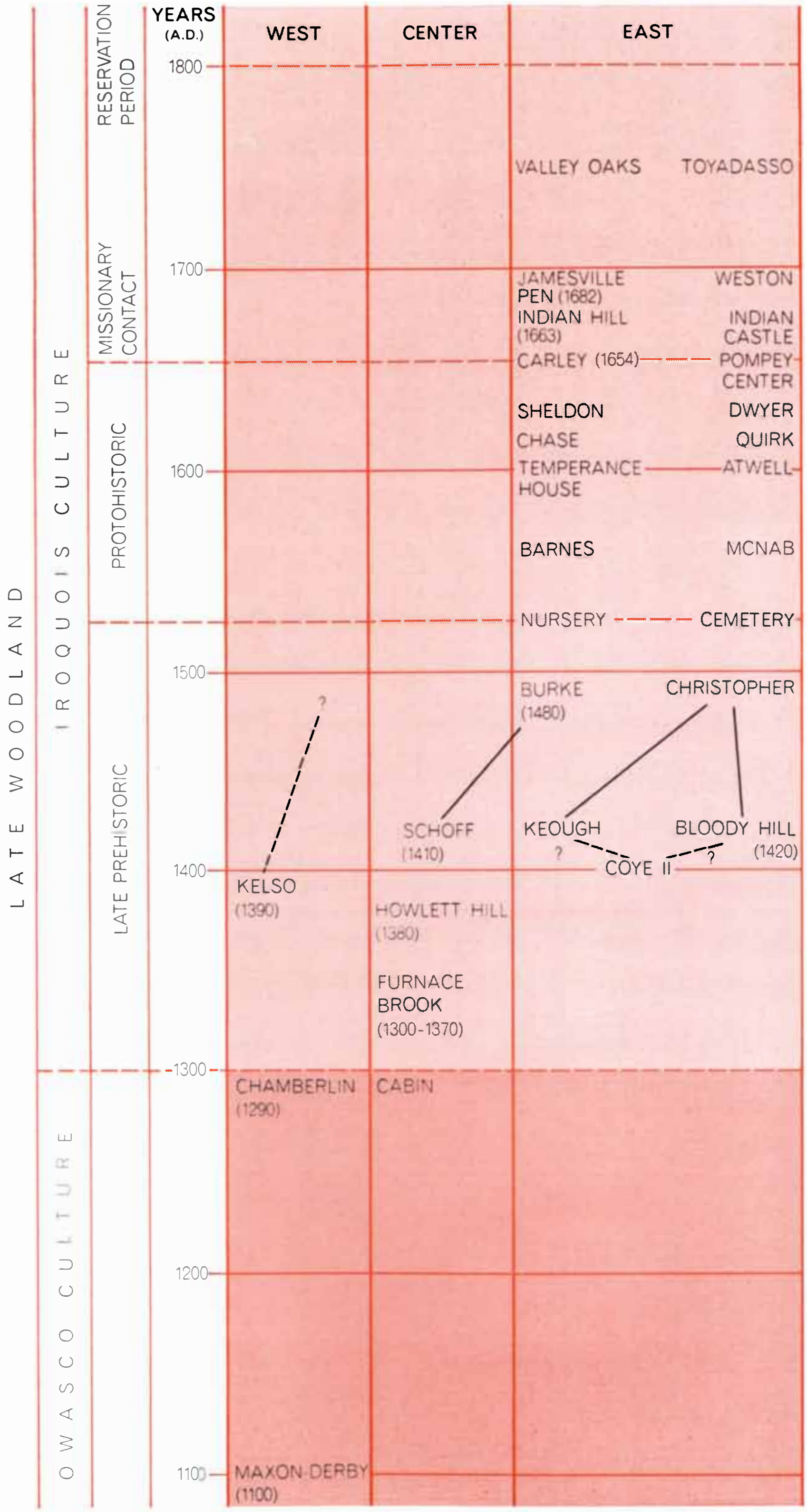
For nearly three centuries, beginning with the first removal and resettlement of the twin villages late in the 15th century, the Onondaga tribe shifted its living sites a number of times. Although the removals were surely not simultaneous on each occasion, the general pattern consisted in occupying one smaller and one larger village that were never more than a few miles apart. Before the tribe's final post-Revolution move to the Onondaga reservation, it had occupied nine such pairs of villages. To describe the 18 sites in detail would be unnecessary; a short summary will suffice to complete the record of Onondaga cultural development.

The late prehistoric period of the Iroquois lasted until late in the 16th century. During that time the Onondaga villages were successively relocated in a northeasterly direction. The next, or protohistoric, period was marked by the introduction of European trade goods, although there was no direct contact between the Iroquois and Europeans. During this time the direction of relocation was southward, along the valley of Limestone Creek. Sites with steep approaches were favored, and the villages were usually well fortified. The houses were considerably smaller than the great longhouses of earlier days; the change may be indicative of social evolution that made the traditional house obsolete.

After a few southward removes the Onondagas reached the Allegheny Plateau and began to move northward again



Cabin site (*a*), inhabited before A.D. 1300, and the Furnace Brook (*b*), Howlett Hill (*c*) and Schoff (*d*) sites, which were inhabited during the 14th century and the early 15th. The next sherd (*e*), from the Burke site, reveals its Owasco ancestry by its decoration with impressions of the edge of a cord-wrapped paddle. Finally, a fragment from the Cemetery site (*f*) exemplifies Onondaga ware.



CHRONOLOGICAL CHART shows the relative ages of selected Late Woodland Indian sites in the Syracuse area. Three of the oldest lie north of Skaneateles Lake. The artifacts they contain demonstrate a transition from the preceding Owasco culture to nascent Iroquois. The three sites may have been occupied successively by the same group, but no trace of the group is found after A.D. 1390. The four more central sites also show the transition from Owasco culture to Iroquois. Development of a "microtradition" that favors incised decoration of pot necks suggests that they were occupied successively by the same group that subsequently occupied the eastern village represented by the Burke site, where the same microtradition is present. Coalition with a third group of Iroquois villagers is suggested by the proximity of the Burke and Christopher sites. Villages are usually paired thereafter.

along the valley of Butternut Creek. Villages were still located in defensible positions, but they were no longer necessarily protected by steep slopes. A steady decay in native arts and crafts provides a measure of the growing importance of European trade goods. Stone axes, knives and arrow points disappear and metal ones take their place. By the time of the first recorded contact between the Onondagas and Europeans the native manufacture of pottery had become virtually a lost art. We may surmise that many less tangible elements of Iroquois culture had been eroded at the same rate.

On August 5th, 1654, a French missionary, Father Simon LeMoyne, entered the leading Onondaga village. As he writes, he was "singing the ambassador's song and receiving addresses of welcome." The next year two more French priests arrived; they supervised the building of a small bark chapel and started the work of Christianizing the Onondagas. Tradition has it that they came to the village now known as the Indian Hill site. Jesuit records, however, indicate that Indian Hill was not settled until about 1663, so that it is more likely that Father LeMoyne entered an earlier Onondaga village, perhaps the Carley or the Pompey Center site.

A European who came to Indian Hill in 1677 left this eyewitness description: "The Onondagoes have butt one towne, butt it is very large, consisting of about 140 houses, nott fenced; it is situate upon a hill thatt is very large, the banke on each side extending it self att least two miles, all cleared land whereon the corne is planted. They have likewise a small village about two miles beyond thatt, consisting of about 24 houses." (The latter was apparently a village to the south of Indian Hill now called the Indian Castle site.)

The visitor's words attest to the Onondaga two-village settlement pattern and also to the extensive plantings that surrounded the settlements. It further allows us to deduce that the dwellings at Indian Hill were not the traditional Iroquois longhouses; the site is much too small to have accommodated 140 houses of any great size. That the settlement Indian Hill was "nott fenced" is surprising. Evidently by this time the Onondagas no longer built the customary village palisade.

The sites of historical Onondaga villages need further study, but the archaeological work that has been done at Indian Hill so far suggests that by the 1670's European trade goods were predominant. Virtually the only items of

VILLAGE DEFENSE depended primarily on a stout palisade made of timbers brought from the nearby forest and set upright in a ring around the village. The holes indicate where the timbers stood that formed the palisade surrounding the site at Furnace Brook.

native manufacture found there (or at Jamesville Pen, the successor village to Indian Hill) are tobacco pipes.

This was the period of the confederacy's greatest influence. The Iroquois conquered the Huron Indians in 1649, the Tobacco and "Neutral" tribes in 1650, the Eries in 1656 and other groups in succeeding years. By that time the confederacy held sway from the Illinois River in the west to the Kennebec in the east and from the Tennessee River north to the Ottawa. In 1711 the British settlements in North Carolina expelled the Iroquoian-speaking Tuscaroras from their lands. The Tuscaroras moved north and were formally adopted by the Oneidas, increasing the membership of the confederacy from five tribes to six.

The confederacy sided successfully with the British in the many bloody frontier campaigns of the French and Indian Wars, but the War of Independence that followed led to its destruction. Nominally the Great League of Peace remained neutral, but each tribe was left free to choose the side it preferred. Only the Oneidas favored the cause of the Revolution. The Senecas and the Mohawks actively supported the loyalists until Revolutionary punitive campaigns in 1779 defeated them, decimated the Onondagas and brought general destruction to the Iroquois homeland.

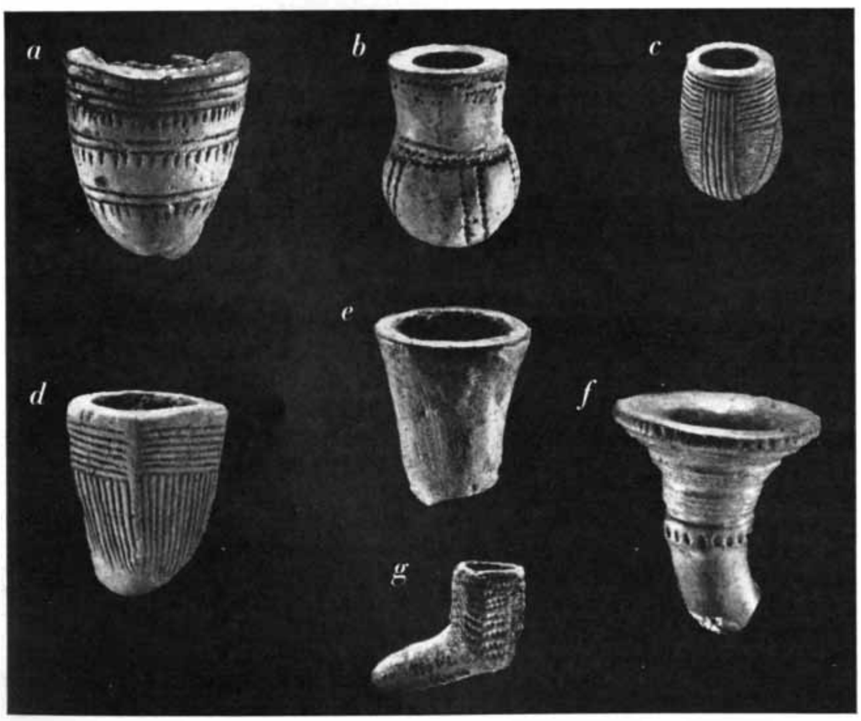
The surviving Onondagas took refuge first on a reservation near Buffalo and finally on a parcel of land near Syracuse part of which today constitutes the Onondaga Indian Reservation. Of the other tribes, the Oneidas chose a new home in Wisconsin, and many of the surviving Mohawks and Cayugas remained allied with the loyalists and moved to Canada.

In this summary of some 700 years we first find traces of the early and apparently successive activities of three small Late Woodland Indian groups in the upstate New York area where the Onondaga tribe eventually arose. Around A.D. 1400 we lose track of the westernmost group; its contributions to the Onondaga culture, if any, remain unknown. The villages successively occupied by the other two groups, however, are more easily traced. The movements of one group can be followed for a period of 200 years as it shifts from place to place in an area just west of modern Syracuse. As the group moves, its members acquire Iroquois ways and develop a concern about self-defense that may have arisen because of the increase in population pressure throughout the American Northeast that followed the introduction of agriculture.

Between A.D. 1425 and 1450 the western group leaves its ancestral domain, moves eastward and settles near a community of a similar kind that had inhabited a similar local territory for some generations. Although there is a tradition of warfare and human sacrifice, the strangers' incursion appears to have been peaceful. This strife-free event we take to mark the founding of the Onondaga tribe, the central group in the later Iroquois confederacy. From earlier mergers of small groups and from political unions such as this one, presumably aimed at nonaggression and mutual defense, there seem to have arisen such powerful Iroquois social institutions as the "medicine societies" and perhaps even the system of tribal organization in moieties, or dual groups. Both would have served a socially integrative function in newly formed communities. The medicine society gathers individuals from separate kinship groups into a single unified organization. The moiety system, in turn, ensures a system of complementary rituals and ceremonies, ranging from the exchange of marriage partners between the two halves of the tribe to burial rituals and the elevation of sachems.

The increase in nonhostile contacts between the Iroquois villages and tribes that led to the Great League of Peace can be seen in the archaeological evidence. It appears in the gradual transformation of local microtraditions into patterns that are more broadly homogeneous. This is particularly evident in certain styles of pottery among the Onondagas, the Oneidas and the Mohawks that eventually become almost identical.

The heyday of the confederacy in the 16th century must have been a relatively peaceful time. Although village fortifications testify to a continuing concern about defenses, raids from the outside could not have been nearly as disruptive as the earlier intertribal battles. Over the next two centuries, however, direct and indirect contacts with Europeans, and Iroquois involvement in European quarrels, proved fatal. These contacts brought about the collapse of the Great League of Peace, the steady erosion of the Iroquois way of life and the eventual transformation of the Romans of the New World into wards of a white man's society.



TOBACCO PIPES, a common Woodland Indian artifact, were made in a number of styles. A miniature model (*g*) shows the form of an intact pipe. The rest have lost their stems and are represented only by their bowls. The conical bowl, decorated with impressions from a cord-wrapped paddle (*a*), is from the Furnace Brook site and resembles the pipes of the preceding Owasco culture. The pot-shaped (*b*), barrel-shaped (*c*) and square bowls (*d*) are from the same site, an Iroquois village that was occupied between A.D. 1300 and 1370. A somewhat trumpet-shaped bowl (*e*) from the Bloody Hill site, which was occupied around 1420, presages the form of Iroquois trumpet pipe (*f*) popular in historical times.

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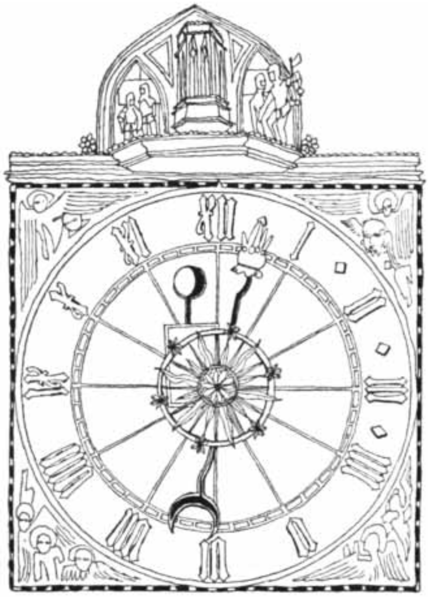
No point in naming these films here. Anybody in a position to use them in the practice of medicine knows where to ask about them if he needs to. Others have little need for the names.

SCIENCE AND



Defoliation in Chicago

At the annual meeting of the American Association for the Advancement of Science in Chicago at Christmastime a now familiar pattern emerged. Certain scientists undertook to put before the public applications of science and technology by which they are deeply troubled, and certain groups sought to confront the AAAS and its members with what they believe is their lack of concern with the social consequences of science and technology. Among the most significant topics of discussion was the military use of defoliants in Vietnam. At AAAS meetings in recent years this practice has been criticized largely on the grounds that, whatever utility it may have in military operations, it may expose the entire region and its inhabitants to grave physiological, genetic and ecological hazards. A committee report delivered at this year's meeting presented evidence that the application of defoliants has had a heavy effect on the ecology of one important area, notably degrading a complex web of ecological relationships that will need many years to recover.

Reporting the AAAS committee findings, Matthew S. Meselson of Harvard University noted that 20 percent of a 1.2-million-acre mangrove forest occupying the delta area between Saigon and the South China Sea has now been denuded of foliage by the aerial spraying of defoliants. A heretofore disregarded factor in tropical plant nutrition has prevented natural reforestation of the area, 300,000 acres whose trees are normally harvested for charcoal and whose meandering waterways once provided the inhabitants with a marketable crop of fish and shellfish.

The committee identifies the factor as "nutrient dumping." This is to say that the soil of the region contains few nutrients and its plant cover depends on the minerals released throughout the year by the decay of a steady fall of leaves and other plant debris. When the debris falls nearly all at once, as a result of spraying with defoliants, the nutrients are leached away by rainfall before they can be utilized by the plant life. The result is the starvation of the plants, and the destruction of the plant life makes the environment unfavorable for the animal life it formerly supported.

Evidence that defoliants are damaging livestock in the remote hill regions of Vietnam where rice and other crops are regularly sprayed was said to be inconclusive. Arthur H. Westing of Windham College found that poultry in his laboratory were unaffected by exposure to defoliants. Westing suggested, however, that some of the symptoms reported in Vietnamese poultry resemble those accompanying overdoses of an insecticide widely used in Vietnam for the suppression of mosquitoes. The possibility that defoliants caused birth defects among the civilian population was judged by the medical member of the committee, John D. Constable of the Massachusetts General Hospital, to be unproved.

Discussion at the meeting revealed that one major objective of the defoliation program—depriving the enemy of foodstuffs they might commandeer from farmers under their control or might cultivate themselves—had been found pointless by Government-sponsored studies, some of them undertaken years before the AAAS committee began its own investigation. A Rand Corporation analysis of interviews with prisoners and defectors, made in 1967 when the spraying program was at its peak, came to the conclusion that only 5 percent of those interviewed had depended on local produce, either commandeered or grown by themselves. A 1970 Army field study, undertaken after the use of defoliants had declined, concluded that only 1 percent of all enemy troops grew their own food.

Technology and the Law

How can a society protect itself against the unwanted side effects of technology? How can it identify potential harmful effects and weigh them against potential benefits, curb the former and promote the latter? One approach is to create new institutions for technology assessment: agencies at the Federal level, staffed by competent experts qualified to investigate areas of technological change and—having weighed the good against the bad, the opportunities against the hazards—make recommendations or even issue orders designed to prevent ill-considered change and to encourage beneficial change while minimizing any undesirable by-products. A different approach (although not a mutually exclusive one) depends on existing legal remedies in an effort to compel Government agencies and private industry to consider the effect of technological activities on the public welfare. Individuals and organizations have undertaken to litigate in the public interest. The role of advocacy and the adversary process, in courts and in public hearings, in technology assessment has been considered in a number of recent studies, including several sponsored by George Washington University's Program of Policy Studies in Science and Technology and by Harvard University's Program on Technology and Society. In a paper published by the Harvard program Milton Katz of the Harvard Law School considers the function of certain private actions in court as instruments for technology assessment.

Katz deals with torts, or wrongs that are independent of any breach of contract and for which a remedy can be sought through court action. Technology assessment is an ongoing enterprise, he points out, that proceeds whenever a company considers a new technology or a change in existing technology, and "whether or not the assessors are aware of the fact, the existing legal order infuses their calculations." That is because it is the law that determines what anticipated costs and benefits must be taken into consideration. Pollution, for example, has usually been considered a "social" or "external" cost, not an "internal" cost to the company. A court decision assessing damages for pollution makes pollution an internal cost that must affect the company's decision: its technology assessment.

Private tort actions can have an increasingly explicit role in technology assessment, Katz writes. He deals specifically with the legal doctrines of nuisance, strict product liability and liability for harm from abnormally dangerous activities. The effect of these doctrines has been to "internalize" social costs within enterprises that engender them, "and so to spur the enterprises to apply the resources of technology and management to reduce the costs." In reaching decisions and fixing damages courts have often considered the applicable technology that was utilized or that might have been utilized by a defendant; the next logical step, Katz suggests, is to consider what improvements in technology might be attained through adequate research efforts, or at least whether adequate efforts to improve the technology have been undertaken by the defendant. The infusion into tort doctrine of "enhanced concern to optimize technology assessment" would be beneficial for tort law as well as for technology assessment, he maintains. The result could be a new "theory of distinctive risk and enterprise liability" that would hold industry responsible for damages arising from its operations.

Such a development would require arrangements shielding individual enterprises from prohibitive risks of liability, he writes, for example by pooled insurance schemes. The resulting risk should be not so large as to discourage research or development but large enough to impel all firms to eliminate harmful side effects. "The accent should be kept on therapeutic deterrence and incentives, along with compensation for victims."

Intelligence and Race (Cont.)

Some light on the factors influencing intelligence is provided by a study of the I.Q. scores of 88 children each of whom had one white parent and one black parent. Sixty-one of the children had a white mother (and a black father); the remaining 27 had a black mother (and a white father). When tested at four years of age, the children of white mothers achieved a mean I.Q. score significantly higher than the children of black mothers did. The mean scores were respectively 100.9 and 93.7. In the absence of evidence that intelligence is genetically linked to the sex of the parent, the provisional interpretation is that environmental factors rather than inherited capacity are primarily responsible for the difference in the two scores.

Reporting these findings in *Science*, Lee Willerman, Alfred F. Naylor and Ntinos C. Myrianthopoulos of the National Institute of Neurological Diseases and Stroke review the pitfalls that beset efforts to compare the I.Q.'s of U.S. whites and U.S. Negroes. They point out, for example, that U.S. Negroes and U.S. whites have about 21 percent of their genes in common, and that in surveys 70 percent of U.S. Negroes report having at least one white ancestor. The authors accept the designations "white" and "Negro" as useful, however, "in providing insights concerning the occurrence of many biological and social phenomena." They undertook their study on the assumption that intelligence is "determined by additive genetic factors which are not sex-linked." Any test differences that emerged could then be regarded as environmental in origin because the mother "is the primary socializing agent during preschool years."

The subjects of the investigation were provided by a study sponsored by the National Institutes of Health involving the children born to some 42,000 women who were registered during pregnancy in 12 institutions throughout the U.S. The children are given neurological and psychological examinations at intervals during the first eight years of life. The first 88 children of racially mixed parentage to reach four years of age were given an abbreviated form of the Stanford-Binet test to measure I.Q. A study of the children's weight and length at birth and their gestation period showed that there were no significant differences between children born to white mothers and those born to Negro mothers. The number of years of education of all the parents, white and Negro, male and female, also was remarkably similar: the means ranged from 10.9 to 11.5 years. The I.Q. scores of the parents, however, were not known.

In addition to the overall difference of 7.2 points in the mean I.Q. scores favoring the children of white mothers, there were some other results of interest. For example, when the sex of the child is ignored, it is the children of the unmarried Negro mothers that have the lowest I.Q. On the other hand, if marital status is ignored, it is only the males born to Negro mothers who have a significantly low I.Q. The authors suggest that the first of these findings may be attributable to the disorganization assumed to exist in one-parent families. The second finding is consistent with other studies showing that males in general score lower than females on certain I.Q. tests. The authors conclude: "Interpretation of the race effect should be tentative since the number of interracial subjects is small. The evidence presented here suggests that environmental factors may play an important role in the lower intellectual performance of Negro preschool children."

Last of the "Monkey Laws"

Mississippi's law against the teaching of evolution, which was the last of several such state laws, has been overturned by the state's Supreme Court. The statute made it unlawful "to teach that mankind ascended or descended from a lower order of animals." The state court, citing a decision by the U.S. Supreme Court in 1968 holding unconstitutional the antievolution law in Arkansas, said that "for all practical purposes" the decision also applied to Mississippi. Tennessee's antievolution law, which had led to the celebrated Scopes trial, was repealed in 1967.

Removal of the antievolution laws does not end efforts to legally limit the teaching of evolution. Such teaching is now under attack from another direction by the Creation Research Society. The society is pressing in a number of states for action to give the doctrine of divine creation equal status with other explanations of the origin of man (see "Science and the Citizen"; SCIENTIFIC AMERICAN, January).

Death by the Mile

It is generally believed that, although the number of people who die in motor vehicle accidents in the U.S. is high, the death rate is in fact low when expressed in terms of total miles driven. Figures supporting this view are provided by the Metropolitan Life Insurance Company in its *Statistical Bulletin*, which reports that in both 1965–1966 and 1967–1968 the U.S. was the lowest among 13 major countries in deaths from traffic accidents on the basis of each 100 million miles driven. The statistic is particularly noteworthy in view of the fact that the number of motor vehicles per 1,000 population is considerably higher in the U.S. than in any of the other countries.

In 1965–1966, according to the report, the average annual death rate per 100 million miles was 5.7 in the U.S. and 23.4 in Japan, which was at the other extreme. In 1967–1968 the figures were 5.5 for the U.S. and 17.7 for Japan. For the same period the figures for the other countries were: Great Britain, 6.2; New Zealand, 7.9; Canada, 8; Norway, 8.1; Denmark, 9.7; Italy, 12.4; West Germany, 12.5; France, 13.4; the Netherlands, 14.5; Finland, 14.5, and Australia, 15.8. Notwithstanding the relatively low rate in the U.S., the report says, the large and rising number of automobile fatalities (some 56,400 in 1969) shows "the need for more drastic action to reduce the hazard. That such measures can be very effective is indicated by the experience of Finland and Great Britain, where severe legislation against driving whilst under the influence of alcohol was enacted in the late 1960's." As a result, the report notes, "the death rate per 100 million vehicle miles was lowered by as much as a quarter in Finland and by a fifth in Great Britain."

Home Remedy

In the film M*A*S*H the pious surgeon Major Burns strikes a dying soldier several sharp blows on the chest with his fist. It later becomes apparent that Burns was trying to restore the soldier's heartbeat, using what nonmedical viewers are likely to conclude is a procedure of doubtful validity. Physicians, however, recognize "chest thump" as a standard emergency measure, first advocated 50 years ago, for restoring the activity of a stopped heart. Unfortunately the maneuver rarely results in more than one or two faint beats, although repeated thumps have kept a heart beating for as long as 90 minutes.

It now turns out that a sharp blow on the patient's chest can be remarkably effective in restoring normal rhythm in cases of ventricular tachycardia, the rapid beating that often follows coronary attack and that, if not reversed, leads quickly to death. The preferred treatment for sustained ventricular tachycardia is an intravenous injection of lidocaine. If that fails, normal rhythm can usually be restored by delivering a mild and carefully timed electric shock through the chest wall, a procedure called cardioversion.

The introducer of cardioversion, Bernard Lown, and two of his colleagues, James E. Pennington and Jack Taylor, all of the Harvard School of Public Health, observed in experiments with dogs that an induced tachycardia can be terminated by shocks of less than one watt-second. This suggested to the investigators that muscles in or surrounding the heart might spontaneously convert the mechanical energy contained in a blow to the chest into a brief electrical pulse sufficient to terminate the arrhythmia. When the chest-thump procedure worked on dogs, it was used as an emergency procedure on five patients and was successful in restoring normal heart rhythm in 12 episodes of tachycardia. "In each case a brisk blow to the midsternum or left precordial area [terminated] the arrhythmia," the authors report in *The New England Journal of Medicine.* They suggest that chest thump be employed as an emergency measure in cardiac resuscitation whenever more sophisticated means, such as an electric cardioverter, are not at hand. They also suggest that where chest thump has worked in the past it did so because it terminated ventricular tachycardia and not because it restored life in a heart that had ceased to beat.

Superconducting Glass

For several years the preferred alloys for carrying the electric current in superconducting magnets have been mixtures of niobium and titanium or niobium and tin. At a temperature of 4.2 degrees Kelvin such alloys can withstand magnetic fields ranging from 100,000 to 200,000 gauss without losing their superconductivity. An unusual competitive material is now being developed by the Corning Glass Works. It consists of a porous glass that has been impregnated with an alloy of lead and bismuth at pressures of up to 70,000 pounds per square inch. Glass containing 30 to 40 percent metal can be fabricated in the form of fibers or tapes 60 microns thick, which can be wound with a radius as tight as a quarter of an inch.

J. H. P. Watson of Corning has recently produced samples of the glass in which an alloy consisting of 60 percent lead and 40 percent bismuth has remained superconducting at 4.2 degrees K. in a magnetic field of 150,000 gauss. At a still lower temperature, 2.5 degrees K., the critical field has exceeded 200,000 gauss. Before the glass can be used in superconducting magnets a way must be found to produce it in long continuous lengths. Present samples are only a few inches long.

Sea Shells from What Seashore?

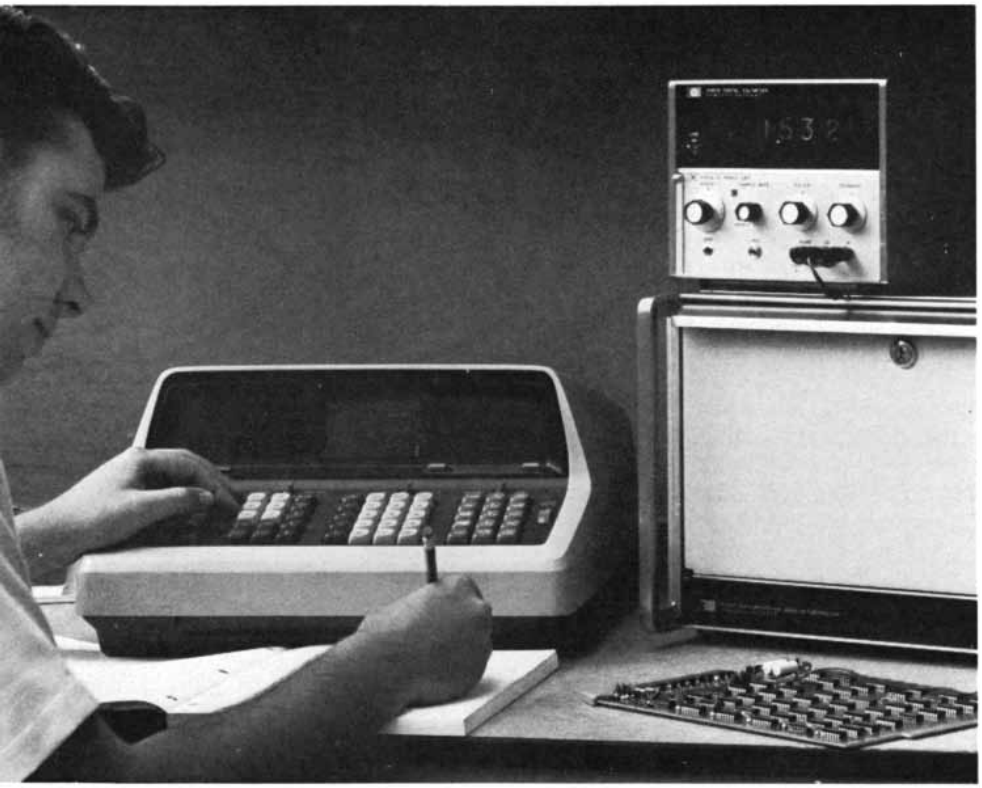
Considering man's limited resources in the Stone Age, one might readily assume that such marine products as the shell beads and bracelets unearthed at Neolithic sites near the Black Sea coast in the Balkans would be made from Black Sea shells. Isotope analysis by two British prehistorians has now shown that this is not so; ornaments from three such sites, some of them at least 6,000 years old, were made instead of shells from the considerably more distant Aegean Sea.

What enabled Nicholas Shackleton of the University of Cambridge and Colin Renfrew of the University of Sheffield to reach this surprising conclusion is the fact that not all bodies of water contain two isotopes of oxygen, O-16 and O-18, in the same proportion. Water molecules incorporating the heavier isotope have a slightly lower rate of evaporation, so that the water vapor returned to the atmosphere is depleted in O-18. In seas such as the Mediterranean (which includes the Aegean) the high rate of evaporation makes the ratio between the two isotopes slightly positive with respect to O-18; expressed as a deviation from an arbitrary standard, it is +1.1 to +1.3 parts per 1,000. In the Black Sea the opposite is true: the ratio ranges from −2.5 to −4.1 parts per 1,000. Marine organisms with a shell of course secrete the calcium carbonate of the shell in isotopic equilibrium with the water they inhabit, so that a *Spondylus* shell with a positive content of O-18, for example, cannot have come from the Black Sea, nor can one with a negative content have come from the Aegean.

Shackleton and Renfrew report in *Nature* that they analyzed samples of *Spondylus* ornaments from the Bulgarian Neolithic site of Tell Goljanio Delschevo near the Black Sea coast, from Gradeshnitsa in northwestern Bulgaria and from Vinča in Yugoslavia, and additional samples from a Greek site near the Aegean and contemporary *Spondylus* shells from the Black Sea. The samples from all four sites yielded O-18 ratios indicative of an Aegean origin.

The significance of the investigators' finding lies in the unusual pattern of Neolithic trade that it reveals. Unlike the quantity of the volcanic glass obsidian that was traded in the same period, the number of *Spondylus* shells found at the various sites does not diminish in proportion to the distance from the source of supply. Shackleton and Renfrew find a modern parallel in the ceremonial exchange of gifts among the Melanesians of the South Pacific, where the social significance of the gift outweighed its intrinsic value; this is the famous "kula" trade of the Trobriand Islanders observed during the 1920's by Bronislaw Malinowski. By a curious coincidence one common form of kula gift consisted of bracelets and beads made of *Spondylus* shells.

Some things are changing for the better.



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Let's assume that you now perform scientific and engineering computations on the HP 9100 Calculator, entering data off-line on its keyboard.

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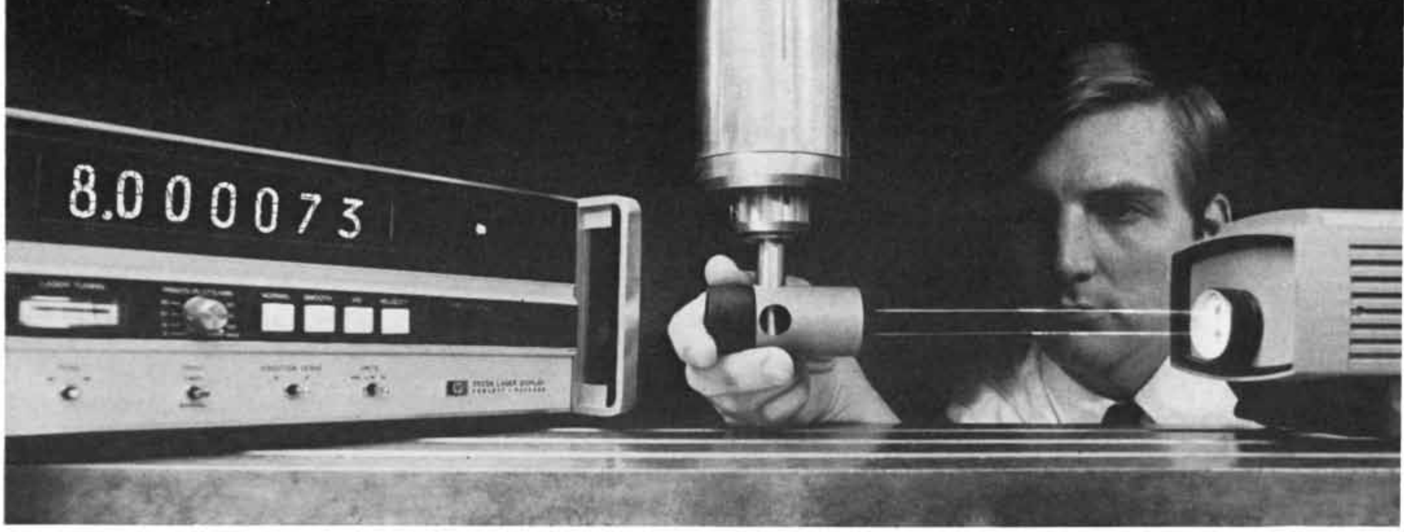
Math comes alive for grade school students

And they're learning it faster than ever before, according to Mr. William Rybensky, program director for computer-assisted instruction (CAI) at Ravenswood City School District, East Palo Alto, California. In his district, students are averaging 15 months of math progress in just 7 months. And at Willow School (where 400 children now regularly use the HP time-share system) some have finished 1½ years of math in less than three months!

And students really like working with our computer, because they receive immediate recognition for correct answers and avoid the embarrassment of making a mistake in front of the whole class. Teachers also appreciate the system. It gives them up-to-the-minute progress reports on every student and eliminates the need for checking answers. So the teacher has more time to coach slow learners and deal with the "why" questions.

For about 25 cents per student per day, any school district can enjoy the benefits of a Hewlett-Packard system, complete with software based on the Stanford Math Drill and Practice curriculum for grades 1 through 6. This $150,000 system is ready for delivery now, completely field-proven and fully supported.

If you'd like to find out how CAI from Hewlett-Packard can help your school district, just drop us a line.



For interferometers, two frequencies are better than one

All interferometers built since Michelson's original experiments in the 1890's use two light beams of the same frequency. They measure distance by counting the cycles of beam intensity in the reflected light caused by alternate constructive and destructive interference of the two beams, as the reflector is moved. Direction is measured by detecting the phase difference between two portions of the measuring beam. These two signals are used to drive a counter one way or the other, after dc amplification.

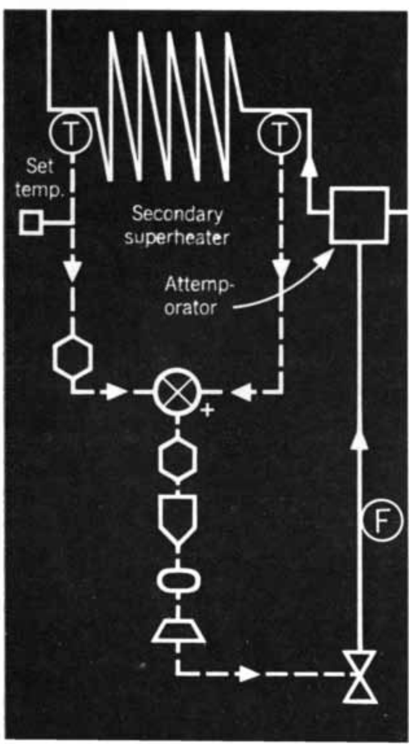
And there's the rub. Any variation in the intensity of the light source due to atmospheric disturbances or normal dc amplifier drift can cause erroneous readings or put the system out of commission.

A new interferometer completely avoids this problem by the simple expedient of operating entirely on ac. This was made possible by the development, in the HP Laboratories, of an entirely new laser which oscillates *on two frequencies simultaneously.* An axial magnetic field Zeeman splits its main spectral line into two frequencies, 1.8 MHz apart and of opposite circular polarization (thus easily distinguishable).

One of these frequencies (f_1) is isolated in a reference path. The other (f_2), isolated in a measuring path, is bounced off an external reflector and recombined with f_2 at the interferometer. If the external reflector remains stationary, the difference between the two is exactly 1.8 MHz. But when the reflector is moved, the measuring beam's frequency is Doppler-shifted at a rate of about 1 MHz for a 1 foot-per-second reflector velocity, and the difference between these two frequencies becomes $(f_1 \pm \Delta f - f_2)$.

Movement is determined by sensing differences between the Doppler signal and the constant reference signal $(f_1 - f_2)$ and counting the cycles on separate registers. A subtractor keeps a running count of the differences in quarter-wavelengths of light, while a built-in IC calculator converts wavelengths to units of length.

Besides a radical decrease in susceptibility to air turbulence, the HP Model 5525A Interferometer ($11,500) measures distance to 1 microinch resolution, requires no warmup and tunes itself automatically. These characteristics suggest great utility in metrology laboratories, for measurement from microinches to 200 feet, as well as machine tool use. The August 1970 issue of the HP Journal tells the whole story: write for your copy.



New tool for on-line system analysis

Very recently at a large power station in England, a system analysis of an attemperator or temperature control loop was completed on-line, without disturbing plant output in any way. As the control characteristic of the loop was displayed on a screen during the experiment, adjustments were made to optimize the control system and the results were displayed immediately.

The job of the control system engineer—to predict how the system will react to a given input pulse – has not always been so easy. If he tests the system with an impulse that is large enough to produce a measurable response, plant output is changed in a way that cannot be tolerated.

Some progress was made when control system analysts discovered the power of cross-correlation. With this mathematical technique, a test noise signal is applied to system input at such low levels that system output is not changed beyond normal background disturbances. Yet by cross-correlating the test noise with the system output over a relatively short period, the engineer is able to extract the impulse response of the system; background disturbances do not interfere because they are uncorrelated with the test noise.

At first, cross-correlation did not help because it could only be accomplished after the fact, through off-line digital computation. What made the difference in the English experiment was the availability of two new HP instruments: a Model 3721A on-line correlator that's about as easy to use as an oscilloscope, and a Model 3722A precision noise generator that synthesizes repeatable pseudo-random noise, ideally suited to system analysis. The correlator costs $8325 and the noise generator $2650. On request, we'll be glad to send you a packet of information on these two instruments, correlation and the on-line experiment.

If you're involved in the techniques of digital analysis or correlation, we can offer a new product-oriented handbook, "Discrete Signal Analysis," which will help. For this 96-page booklet or any of the other material mentioned, write to: Hewlett-Packard, 1502 Page Mill Road, Palo Alto, California 94304; Europe: 1217 Meyrin-Geneva, Switzerland.

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The Prospects of Fusion Power

Recent advances in the performance of several experimental plasma containers have brought the fusion-power option very close to the "break even" level of scientific feasibility

by William C. Gough and Bernard J. Eastlund

The achievement of a practical fusion-power reactor would have a profound impact on almost every aspect of human society. In the past few years considerable progress has been made toward that goal. Perhaps the most revealing indication of the significance of this progress is the extent to which the emphasis in recent discussions and meetings involving workers in the field has tended to shift from the question of purely scientific feasibility to a consideration of the technological, economic and social aspects of the power-generation problem. The purpose of this article is to examine the probable effects of the recent advances on the immediate and long-term prospects of the fusion-power program, with particular reference to mankind's future energy needs.

The Role of Energy

The role of energy in determining the economic well-being of a society is often inadequately understood. In terms of *total* energy the main energy source for any society is the sun, which through the cycle of photosynthesis produces the food that is the basic fuel for sustaining the population of that society. The efficiency with which the sun's energy can be put to use, however, is determined by a feedback loop in which auxiliary energy sources form a critical link [*see illustration on page 52*]. The auxiliary energy (derived mainly from fossil fuels, water power and nuclear-fission fuels) "opens the gate" to the efficient use of the sun's energy by helping to produce fertilizers, pesticides, improved seeds, farm machinery and so on. The result is that the food yield (in terms of energy content) produced per unit area of land in a year goes up by orders of magnitude. This auxiliary energy input, when it is transformed into food energy, enables large populations to live in cities and develop new ways to multiply the efficiency of the feedback loop. If a society is to raise its standard of living by increasing the efficiency of its agricultural feedback loop, clearly it must expand its auxiliary energy sources.

The dilemma here is that the economically less developed countries of the world cannot *all* industrialize on the model of the more developed countries, for the simple reason that the latter countries, which contain only a small fraction of the world's population, currently maintain their high standard of living by consuming a disproportionately large share of the world's available supply of auxiliary energy. Just as there is a direct, almost linear, relation between a nation's use of auxiliary energy and its standard of living, so also there is a similar relation between energy consumption and the amount of raw material the nation uses and the amount of waste material it produces. Thus the more developed countries consume a correspondingly oversized share of the world's reserves of material resources and also account for most of the world's environmental pollution.

In order to achieve a more equitable and stable balance between the standards of living in the more developed countries and those in the less developed countries, only two alternatives exist. The more developed countries could reduce their consumption of auxiliary energy (thereby lowering their standard of living as well) or they could contribute to the development of new, vastly greater sources of auxiliary energy in order to help meet the rising demands for a better standard of living on the part of the rapidly growing populations of the less developed countries.

When one projects the world's long-term energy requirements against this background, another important factor must be taken into account. There are finite limits to the world's reserves of material resources and to the ability of the earth's ecological system to absorb pollutants safely. As a consequence future societies will be forced to develop "looped," or "circular," materials economies to replace their present, inherently wasteful "linear" materials economies [*see bottom illustration on page 61*]. In such a "stationary state" system, limits on the materials inventory, and hence on the total wealth of the society, would be set by nature. Within these limits, however, the standard of living of the population would be higher if the rate of flow of materials were lower. This maximizing of the life expectancy of the materials inventory could be accomplished in two ways: increasing the durability of individual commodities and developing the technological means to recycle the limited supply of material resources.

The conclusion appears radical. Future societies must *minimize* their physical flow of production and consumption. Since a society's gross national product for the most part measures the flow of physical things, it too would be reduced.

But all nations now try to *maximize* their gross national product, and hence their rate of flow of materials! The explanation of this paradox is that in the existing linear economies the inputs for increasing production must come from the environment, which leads to depletion, while an almost equal amount of materials in the form of waste must be returned to the environment, which leads to pollution. This primary cause of pollution is augmented by the pollution that is produced by the energy sources used to drive the system.

In order to make the transition to a stationary-state world economy, the wealthier nations will have to develop the technology—and the concomitant auxiliary energy sources—necessary to operate a closed materials economy. This capability could then be transferred to the poorer nations so that they could develop to the level of the wealthier nations without exhausting the world's supply of resources or destroying the environment. Thus some of the causes of international conflict would be removed, thereby reducing the danger of nuclear war.

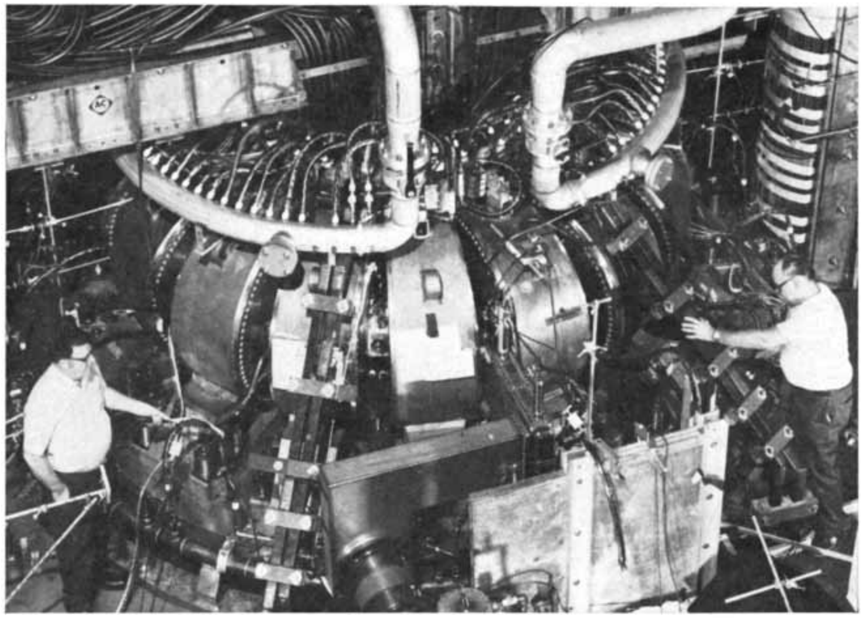
Of course any effort to bring about a rapid change from linear economies to looped economies will encounter the massive economic, social and political forces that sustain the present system. The question of how to distribute the stock of wealth, including leisure, within a stationary-state economy will remain. In summary, the world's requirements for energy are intimately related to the issues of population expansion, economic development, materials depletion, pollution, war and the organization of human societies.

The Energy Options

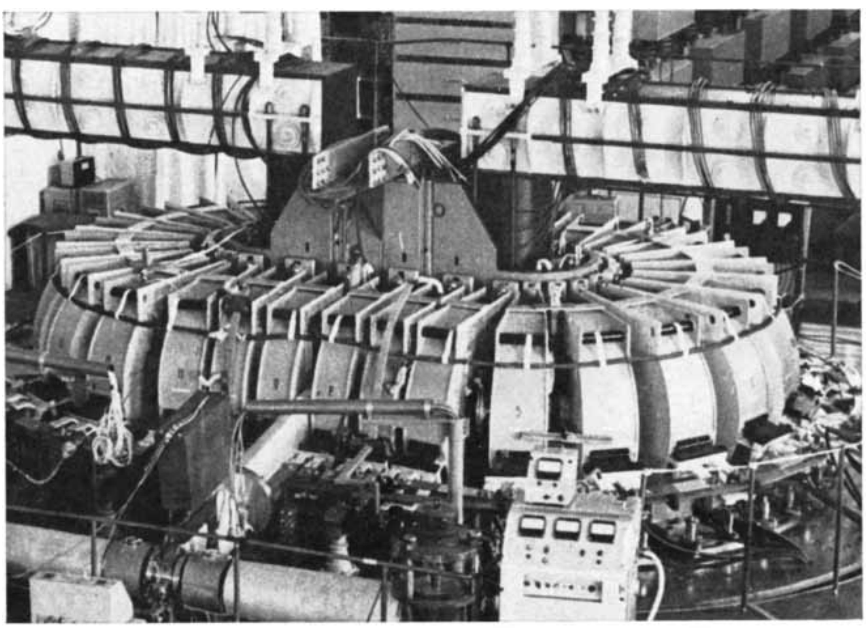
What are the available energy options for the future? To begin with there are the known finite and irreplaceable energy sources: the fossil fuels and the better-grade, or easily fissionable, nuclear fuels such as uranium 235. Estimates of the life expectancy of these sources vary, but it is generally agreed that they are being used up at a rapid rate—a rate that will moreover be accelerated by increases in both population and living standards. In addition, environmental considerations could further restrict the use of these energy sources.

Certain other known energy sources, such as water power, tidal power, geothermal power and wind power are "infinite" in the sense of being continuously replenished. The total useful *amount* of energy available from these sources, however, is insufficient to meet the needs of the future.

Direct solar radiation, resulting from the fusion reactions that take place in the core of the sun, is an abundant as well as effectively "infinite" energy source. The immediate practical obstacle to the direct use of the sun's energy as an effective auxiliary energy source is the necessity of finding some way to economically concentrate the available low energy density of solar radiation. Controlled fusion is another potentially "infinite" energy source; its energy output arises from the reduction of the total mass of a nuclear system that accompanies the merger of two light



U.S. TOKAMAK, a toroidal plasma-confinement machine used in fusion research, was recently put into operation at the Plasma Physics Laboratory of Princeton University. Until about a year ago this machine, formerly known as the Model-C stellarator and now called the Model ST tokamak, had been the largest of the stellarator class of experimental plasma containers developed primarily at the Princeton laboratory. The decision to convert it to the closely related tokamak design followed the 1969 announcement by the Russian fusion-research group of some important new results obtained from their Model T-3 machine, the most advanced of the tokamak class of plasma containers developed mainly at the I. V. Kurchatov Institute of Atomic Energy near Moscow. In large part because of the cooperative nature of the world fusion-research program, this conversion was accomplished quickly and the Model ST has already produced results comparable to those obtained by the Russians. Several other tokamak-type machines are being built in this country.



RUSSIAN STELLARATOR is now the largest representative of this class of experimental plasma containers in the world. It is named the Uragan (or "hurricane") stellarator and is located at the Physico-Technical Institute of the Academy of Sciences of the Ukrainian S.S.R. at Kharkov. In both photographs on this page the large circular structures surrounding and almost completely obscuring the toroidal plasma chambers are the primary magnet coils. The main difference between the tokamak design and the stellarator design is that in a tokamak a secondary plasma-stabilizing magnetic field is generated by an electric current flowing axially through the plasma itself, whereas in a stellarator this secondary magnetic field is set up by external helical coils situated just inside the primary coils and hence not visible.

nuclei. The most likely fuel for a fusion-power energy source is deuterium, an abundant heavy isotope of hydrogen easily separated from seawater.

In addition to these two primary "infinite" energy sources, secondary "infinite" energy sources could be made by using neutrons to transmute less useful elements into other elements capable of being used effectively as fuels. Thus for fission systems the vast reserves of uranium 238 could be converted by neutron bombardment into easily fissionable plutonium 239; similarly, thorium 232 could be converted into uranium 233. For fusion systems lithium could be converted into tritium, another heavy isotope of hydrogen with a comparatively low resistance to entering a fusion reaction and a comparatively high energy output once it does.

The prime hope for extending the world's reserves of nuclear-fission fuels is the development of the neutron-rich fast breeder fission reactors [see "Fast Breeder Reactors," by Glenn T. Seaborg and Justin L. Bloom; SCIENTIFIC AMERICAN, November, 1970]. Another potential source of abundant, inexpensive neutrons is a fusion-fission hybrid system, an alternative that will be discussed further below.

Fusion Energy

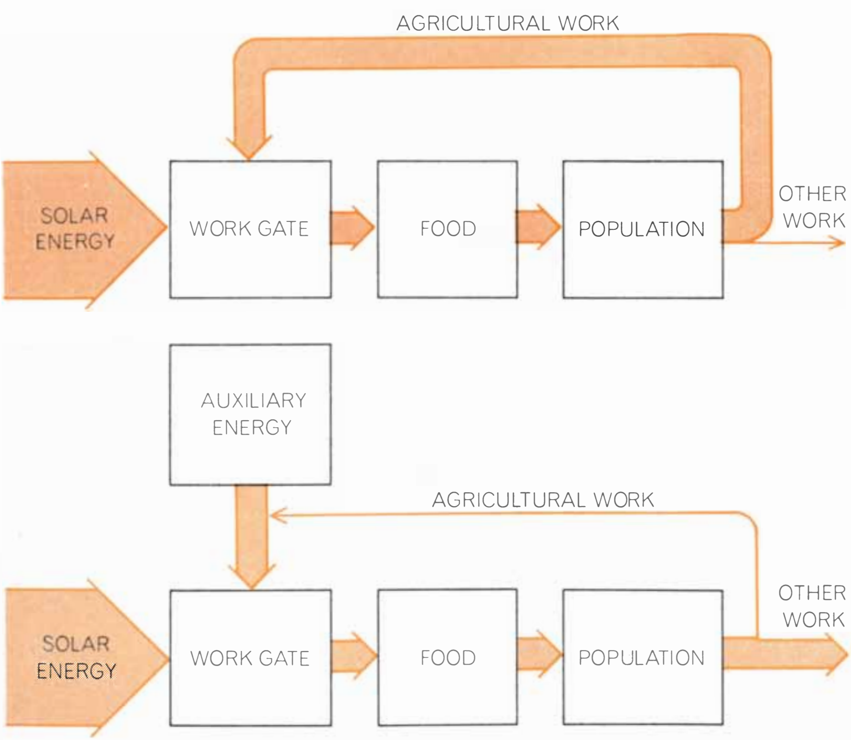
Nuclear fusion, the basic energy process of the stars, was first reproduced on the earth in 1932 in an experiment involving the collision of artificially accelerated deuterium nuclei. Although it was thereby shown that fusion energy could be released in this way, the use of particle accelerators to provide the nuclei with enough energy to overcome their Coulomb, or mutually repulsive, forces was never considered seriously as a practical method for power generation. The reason is that the large majority of the nuclei that collide in an accelerator scatter without reacting; thus it is impossible to produce more energy than was used to accelerate the nuclei in the first place.

The uncontrolled release of a massive amount of fusion energy was achieved in 1952 with the first thermonuclear test explosion. This test proved that fusion energy could be released on a large scale by raising the temperature of a high-density gas of charged particles (a plasma) to about 50 million degrees Celsius, thereby increasing the probability that fusion reactions will take place within the gas.

Coincident with the development of the hydrogen bomb, the search for a more controlled means of releasing fusion energy was begun independently in the U.S., Britain and the U.S.S.R. Essentially this search involves looking for a practical way to maintain a comparatively low-density plasma at a temperature high enough so that the output of fusion energy derived from the plasma is greater than the input of some other kind of energy supplied to the plasma. Since no solid material can exist at the temperature range required for a useful energy output (on the order of 100 million degrees C.) the principal emphasis from the beginning has been on the use of magnetic fields to confine the plasma.

The variety of magnetic "bottles" designed for this purpose over the years can be arranged in several broad categories in order of increasing plasma density [*see illustration on pages 56 and 57*]. First there are the basic plasma devices. These are low-density, low-temperature systems used primarily to study the fundamental properties of plasmas. Their configuration can be either linear (open) or toroidal (closed). Linear basic-plasma devices include simple glow-discharge systems (similar in operation to ordinary fluorescent lamps) and the more sophisticated "Q-machines" ("Q" for "quiescent") found in many university plasma-physics laboratories. Toroidal representatives of this class include the "multipole" devices, developed primarily at Gulf Energy & Environmental Systems, Inc. (formerly Gulf General Atomic Inc.) and the University of Wisconsin, and the spherator, developed at the Plasma Physics Laboratory of Princeton University.

Next there are the medium-density plasma containers; these are defined as systems in which the outward pressure of the plasma is much less than the inward pressure of the magnetic field. A typical configuration in this density range is the linear magnetic bottle, which is usually "stoppered" at the ends by magnetic "mirrors": regions of somewhat greater magnetic-field strength that reflect escaping particles back into the bottle. In addition extra current-carrying structures are often used to improve the stability of the plasma. These structures were originally proposed on theoretical grounds in 1955 by Harold Grad of New York University. They were first used successfully in an experimental test in 1962 by the Russian physicist M. S. Ioffe.



ROLE OF AUXILIARY ENERGY in determining the economic well-being of a society is illustrated by these two diagrams of agricultural feedback loops. In an economically less developed country (*top*) the bulk of the population must be devoted to the agricultural transformation of the sun's energy into food in order to support itself at a subsistence level. In an economically more developed industrial country (*bottom*) auxiliary energy sources "open the gate" to the more efficient utilization of the sun's energy, making it possible for the entire population to maintain a higher standard of living and freeing many people to live in cities and develop new ways to multiply the efficiency of the feedback loop.

		LIFE EXPECTANCY OF KNOWN RESERVES (YEARS)		LIFE EXPECTANCY OF POTENTIAL RESERVES (YEARS)		LIFE EXPECTANCY OF TOTAL RESERVES (YEARS)	
		AT .17Q	AT 2.8Q	AT .17Q	AT 2.8Q	AT .17Q	AT 2.8Q
FINITE ENERGY SOURCES	FOSSIL FUELS (COAL, OIL, GAS)	132	8	2,700	165	2,832	173
	MORE ACCESSIBLE FISSION FUELS (URANIUM AT $5 TO $30 PER POUND OF U_3O_8 BURNED AT 1.5 PERCENT EFFICIENCY)	66	4	66	4	132	8
	LESS ACCESSIBLE FISSION FUELS (URANIUM AT $30 TO $500 PER POUND OF U_3O_8 BURNED AT 1.5 PERCENT EFFICIENCY	43,000	2,600	129,000	7,800	172,000	10,400
"INFINITE" NATURAL ENERGY SOURCES	WATER POWER, TIDAL POWER, GEOTHERMAL POWER, WIND POWER	INSUFFICIENT		INSUFFICIENT		INSUFFICIENT	
	SOLAR RADIATION	10 BILLION	10 BILLION			10 BILLION	10 BILLION
	FUSION FUELS (DEUTERIUM FROM OCEAN)	45 BILLION	2.7 BILLION			45 BILLION	2.7 BILLION
"INFINITE" ARTIFICIAL ENERGY SOURCES (ELEMENTS TRANSMUTED FROM OTHER ELEMENTS BY NEUTRON BOMBARDMENT)	FISSION FUELS (PLUTONIUM 239 FROM URANIUM 238; URANIUM 233 FROM THORIUM 232)	8.8 MILLION	536,000	21 MILLION	1.3 MILLION	30 MILLION	1.8 MILLION
	FUSION FUELS (TRITIUM FROM LITHIUM) a) ON LAND b) IN OCEAN	48,000 120 MILLION	2,900 7.3 MILLION	UNKNOWN	UNKNOWN	48,000+ 120 MILLION	2,900+ 7.3 MILLION

WORLD ENERGY RESERVES are listed in this table in terms of their life expectancy estimated on the basis of two extreme assumptions, which were chosen so as to bracket a reasonable range of values. First, the assumption was made that the world population would remain constant at its 1968 level of 3.5 billion persons and that the energy-consumption rate of this population would remain constant at the estimated 1968 rate of .17 Q (Q is a unit of heat measurement equal to 10^{18} BTU, or British Thermal Units). Second, the assumption was made that the world population would eventually reach seven billion and that this population would consume energy at a per capita rate of 400 million BTU per year (about 20 percent higher than the present U.S. rate), giving a total world energy-consumption rate of 2.8 Q per year. (A commonly projected world energy-consumption rate for the year 2000 is one Q.) Current fission-converter reactors use only between 1 and 2 percent of the uranium's potential energy content, since the component of the ore that is burned as fuel is primarily high-grade, or easily fissionable, uranium 235. The world fission-fuel reserves were derived by multiplying the U.S. reserves times the ratio of world land area to the U.S. land area (approximately 16.2 to one). For fusion-converter reactors lithium-utilization studies show that natural lithium, a mixture of lithium 6 and lithium 7, would be superior to pure lithium 6 in a tritium-breeding reactor "blanket" and would yield an energy output of about 86.4 million BTU per gram. The figure for known world lithium reserves is based on a study carried out last year by James J. Norton of the U.S. Geological Survey. The potential reserves of lithium are unknown, since there has been no exploration program comparable to that undertaken for, say, uranium. Lithium, however, is between five and 15 times more abundant in the earth's crust than uranium. Finally, the life expectancy of the earth—and hence that of potentially useful solar radiation—is predicted to be at most 10 billion years.

The straight rods used by Ioffe in his experiment have come to be called Ioffe bars, but such stabilizing structures can assume various other shapes. For example, in one series of medium-density linear devices they resemble the seam of a baseball; accordingly these devices, developed at the Lawrence Radiation Laboratory of the University of California at Livermore, are named Baseball I and Baseball II.

Medium-density plasma containers with a toroidal geometry include the stellarators, originally developed at the Princeton Plasma Physics Laboratory, and the tokamaks, originally developed at the I. V. Kurchatov Institute of Atomic Energy near Moscow. The only essential difference between these two machines is that in a stellarator a secondary, plasma-stabilizing magnetic field is set up by external helical coils, whereas in a tokamak this field is generated by an electric current flowing through the plasma itself. The close similarity between these two designs was emphasized recently by the fact that the Princeton Model-C stellarator was rather quickly converted to a tokamak system following the recent announcement by the Russians of some important new results from their Tokamak-3 machine.

The astron concept, also developed at the Lawrence Radiation Laboratory at Livermore, is another example of a medium-density plasma container. In overall geometry it shares some characteristics of both the linear and the toroidal designs.

Higher-density plasma containers, defined as those in which the plasma pressure is comparable to the magnetic-field pressure, have also been built in both the linear and the toroidal forms. In one such class of devices, called the "theta pinch" machines, the electric current is in the theta, or azimuthal, direction (around the axis) and the resulting magnetic field is in the zeta, or axial, direction (along the axis). The Scylla and Scyllac machines at the Los Alamos Scientific Laboratory are respectively examples of a linear theta-pinch design and a toroidal theta-pinch design.

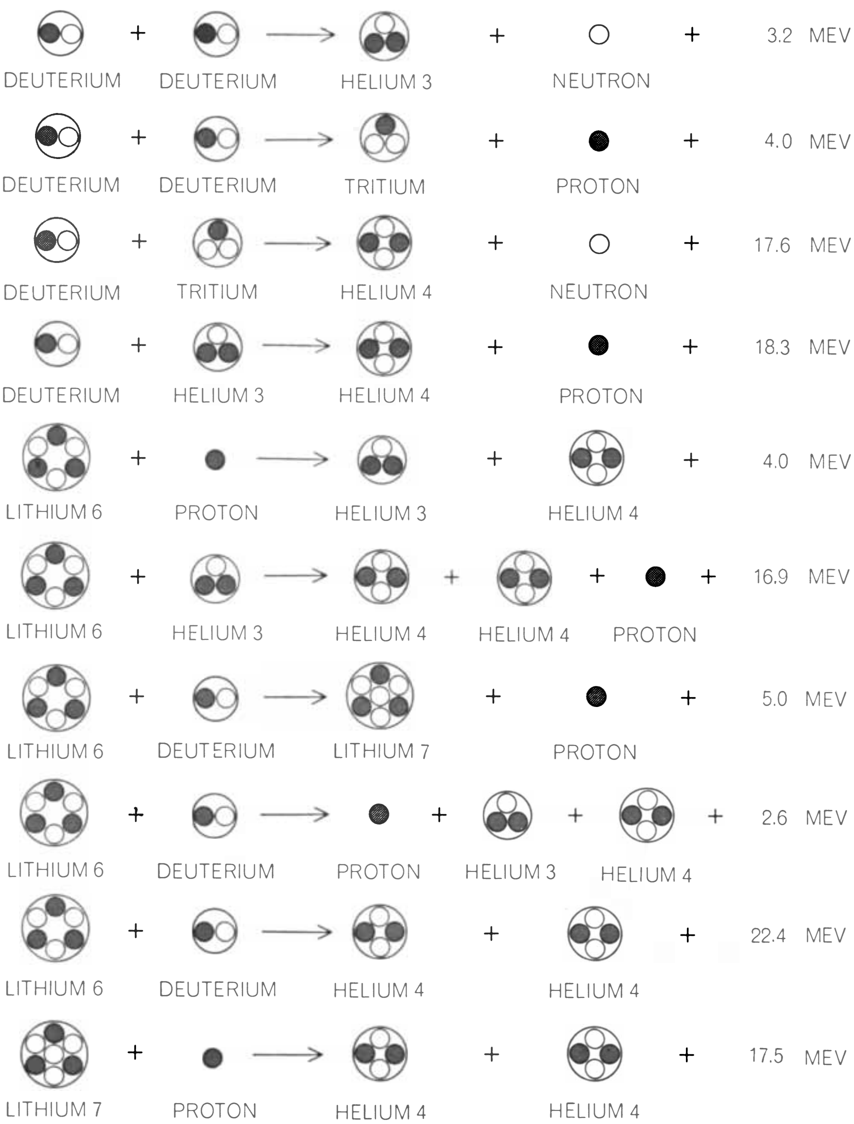
As the density of the plasma is increased further, one reaches a technological limit imposed by the inability of the materials used in the magnet coils to withstand the pressure of the magnetic field. Consequently very-high-density plasma systems are often fast-pulsed and obtain their principal confining forces from "self-generated" magnetic fields (fields set up by electric currents in the plasma itself), from electrostatic fields or from inertial pressures. In this very-high-density category are the "zeta pinch" machines, devices in which the electric current is in the zeta direction and the resulting magnetic field is in the theta direction. An example of this type of configuration is the Columba device at Los Alamos.

Other very-high-density, fast-pulsed systems include the "strong focus" designs, in which a stream of plasma in a cylindrical, coaxial pipe is heated rapidly by shock waves as it is brought to a sharp focus by self-generated magnetic forces, and laser designs, in which a pellet of fuel is ionized instantaneously by a pulse from a high-power laser, producing an "inertially confined" plasma. Still another confinement scheme that has been investigated in this general density range includes an electrostatic device in which the plasma is confined by inertial forces generated by concentric spherical electrodes.

The Fusion-Power Balance

What are the fundamental requirements for a meaningful release of fusion energy in a reactor? First, the plasma must be hot enough for the production of fusion energy to exceed the energy loss due to bremsstrahlung radiation (radiation resulting from near-collisions between electrons and nuclei in the plasma). The temperature at which this transition occurs is called the ignition temperature. For a fuel cycle based on fusion reactions between deuterium and tritium nuclei the ignition temperature is about 40 million degrees C. Second, the plasma must be confined long enough to release a significant net output of energy. Third, the energy must be recovered in a useful form.

In the first years of the controlled-fusion research program one of the major goals was to achieve the ignition temperature in a fairly dense laboratory plasma. Steady progress was made toward this goal, culminating in 1963, when the ignition temperature (for a deuterium-tritium fuel mixture) was reached in one of the Scylla devices at Los Alamos. This test, which was performed in a pure deuterium plasma to avoid the generation of excessive neutron flux, resulted in the release of fusion energy: about a thousandth of a joule per pulse, or 370 watts of fusion power during the three-microsecond duration of the pulse. If the test had been performed using a deuterium-tritium mixture, it would have released approximately a half-joule of fusion energy per pulse, or 180,000 watts of fusion power.

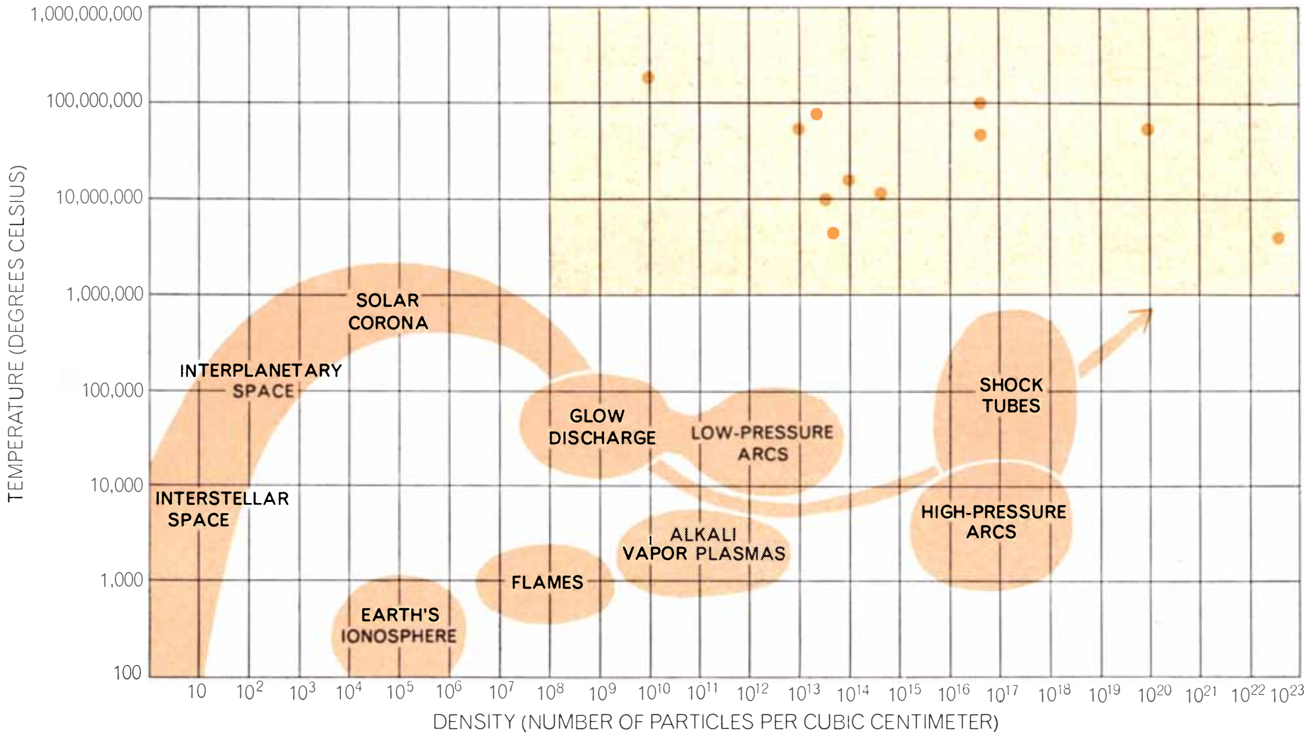


FUSION REACTIONS regarded as potentially useful in full-scale fusion reactors are represented in this partial list. The two possible deuterium-deuterium reactions occur with equal probability. The deuterium-tritium fuel cycle has been considered particularly attractive because this mixture has the lowest ignition temperature known (about 40 million degrees Celsius). Other fuel cycles, including many not shown in this list, have been attracting increased attention lately, since certain plasma-confinement schemes actually operate better at higher temperatures and offer the advantage of direct conversion to electricity. The energy released by each reaction is given at right in millions of electron volts (*MeV*).

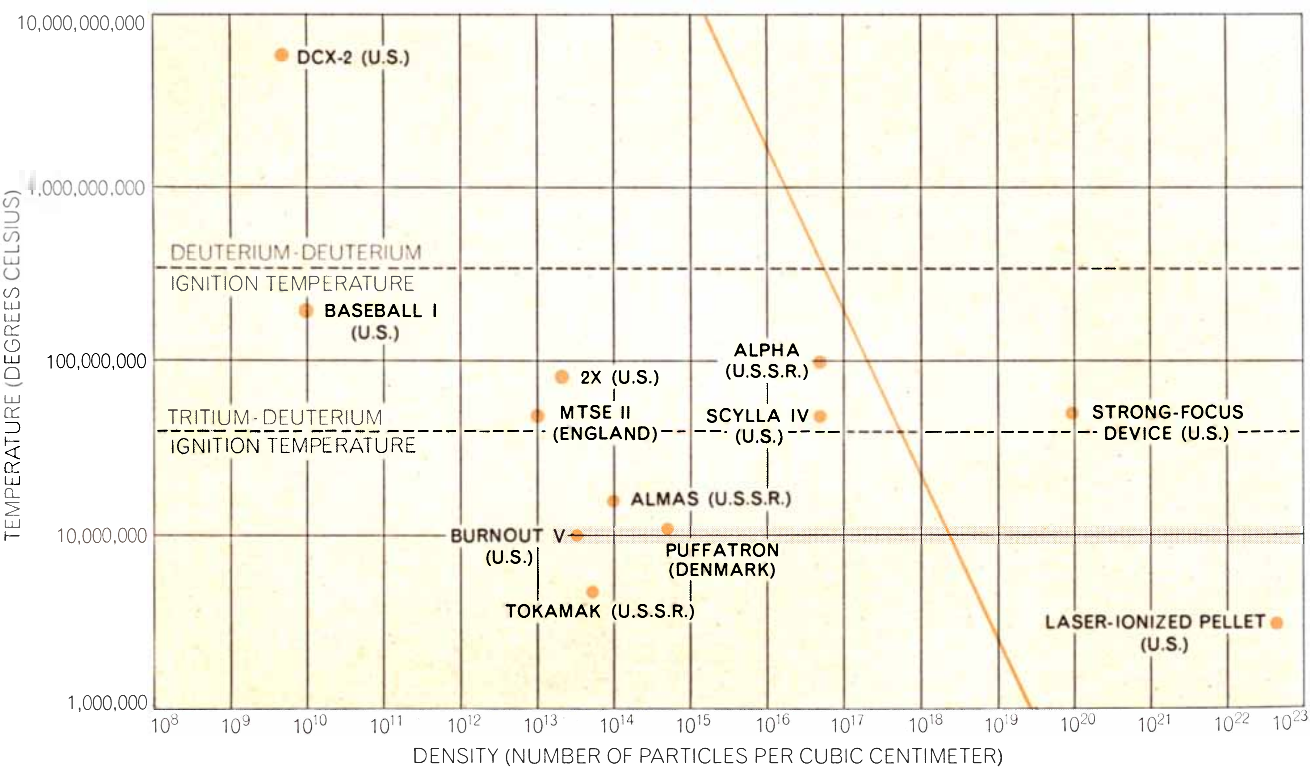
Today a large number of different devices have either achieved the deuterium-tritium ignition temperature or are very close to it [*see bottom illustration on opposite page*]. The main difficulties encountered in reaching this goal were comparatively straightforward energy-loss processes involving impurity atoms that entered the plasma from the walls of the container. A large research effort in the areas of vacuum and surface technology was a major factor in surmounting the ignition-temperature barrier.

The problem of confining a plasma long enough to release a significant net amount of energy has proved to be even more difficult than the problem of achieving the ignition temperature. Extremely rapid energy-loss processes—known collectively as "anomalous diffusion" processes—appeared to prevent the attainment of adequate confinement times. Plasma instabilities were the primary cause of this rapid plasma leakage [see "The Leakage Problem in Fusion Reactors," by Francis F. Chen; SCIENTIFIC AMERICAN, July, 1967]. Within the past few years, however, several large containment devices have reduced these instabilities to such a low amplitude that other more subtle effects, such as convective plasma losses and magnetic-field imperfections, can be studied. As a result it has been shown that there is no basic law of physics (such as an instability-initiated anomalous plasma loss) that prevents plasma confinement for times long enough to release significant net fusion energy. In fact, "classical," or ideal, plasma confinement has been achieved in several machines; this is the best confinement possible and yields a plasma-loss rate much lower than that required for a fusion reactor.

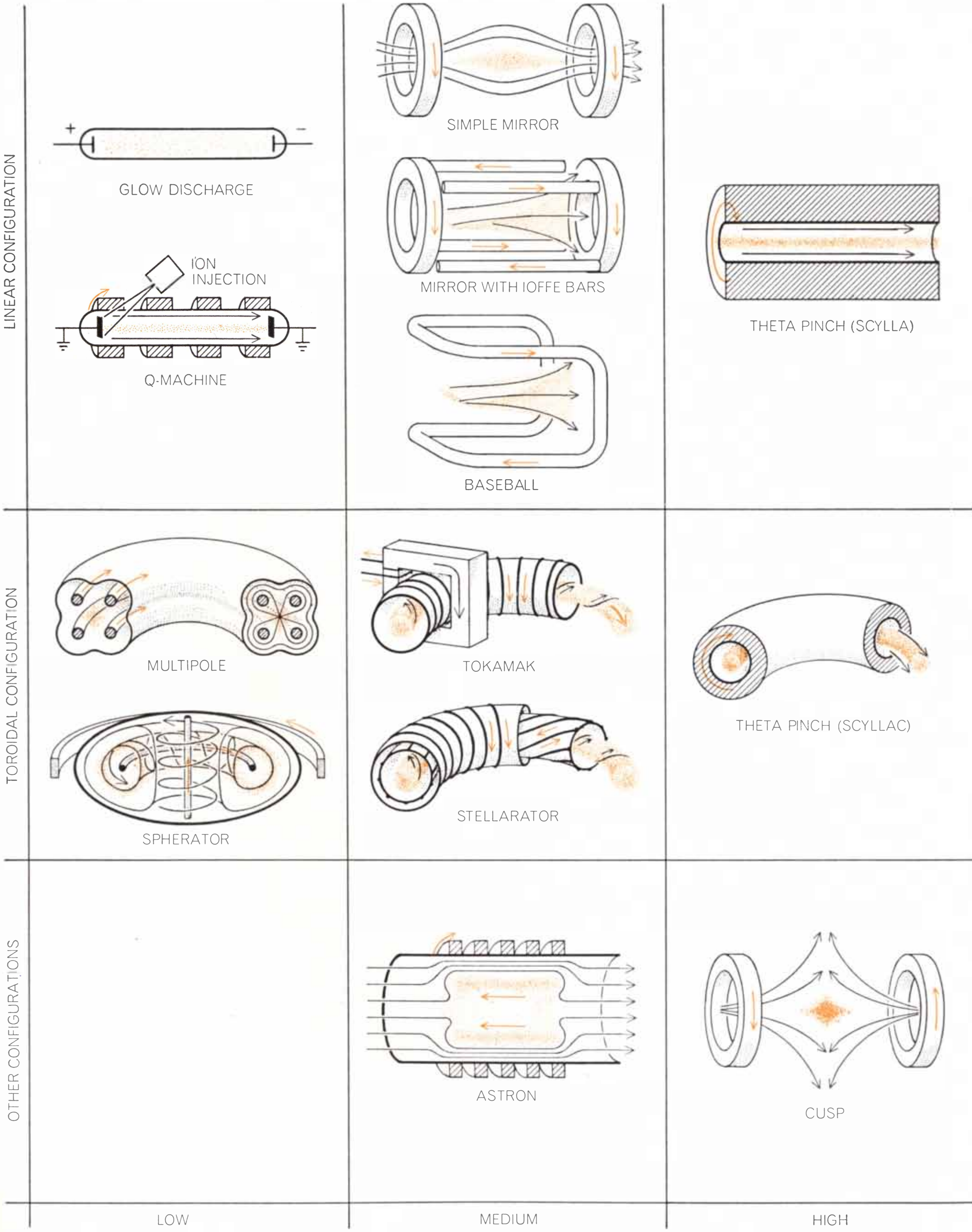
The twin achievements of ignition temperature and adequate confinement time, it should be noted, have taken place in quite different machines, each



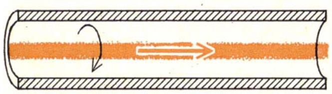
INDUSTRIALLY UNEXPLORED RANGE of plasma temperatures and densities has already been made available by the fusion-power research program. These experimental plasmas (*colored dots*), which range in temperature from 500,000 to a billion degrees C. and in density from 10^9 to 10^{22} ions per cubic centimeter, are compared here with various other industrial and natural plasmas.



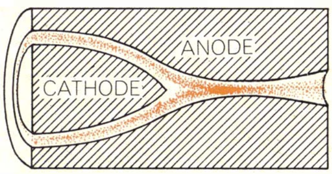
PLASMA EXPERIMENTS that have achieved temperatures near or above the fusion ignition temperatures of a deuterium-tritium fuel (*bottom horizontal line*) and a deuterium-deuterium fuel (*top horizontal line*) are identified by the name of the experimental device and the country in which the experiment took place in this enlargement of the upper right-hand section of the illustration at top. The diagonal colored line represents the limit beyond which the materials used to construct the magnet coils can no longer withstand the magnetic-field pressure required to confine the plasma (assumed to be 300,000 gauss in this case). Beyond this limit only fast-pulsed systems (in which the magnetic fields are generated by intense currents inside the plasma itself) or systems operating on entirely different principles (such as laser-produced, inertially confined plasmas) are possible. The record of six billion degrees C. was achieved with the aid of a high-energy ion-injection system associated with DCX-2 device at the Oak Ridge National Laboratory.



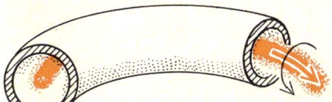
PRINCIPAL SCHEMES devised in the past 18 years to confine plasmas for fusion research are arranged in the illustration on these two pages in order of increasing plasma density (*left to right*) and overall geometry (*top to bottom*). Only a few examples are depicted in each category. In every case the plasma is in color, the colored arrows signify the direction of the electric current and the black arrows denote the direction of the resultant magnetic field. Various structural details have been omitted for clarity. For each example shown there are a large number of variations either already in existence or in the conceptual stage. Furthermore, the



ZETA PINCH



PLASMA FOCUS



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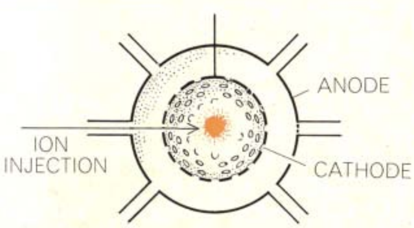
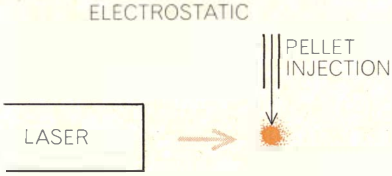


ELECTROSTATIC



LASER-IONIZED PELLET

VERY HIGH

fact that an example is given in one category does not necessarily mean that that configuration is not applicable to some other category; there are, for instance, toroidal Q-machines and medium-density cusp designs.

specially designed to maximize the conditions for reaching one goal or the other. How does one compare the performances of these machines in order to gauge how near one is to the combined conditions needed to operate a practical fusion-power reactor? The basic criterion for determining the length of time a plasma must be confined at a given density and temperature to produce a "break even" point in the power balance was laid down in 1957 by the British physicist J. D. Lawson. Combining data on the physics of fusion reactions with some estimates of the efficiency of energy recovery from a hypothetical fusion reactor, Lawson derived a factor, which he called R, that denoted the ratio of energy output to energy input needed to compensate for all possible plasma losses. Lawson's criterion is still in general use as a convenient yardstick for measuring the extent to which losses must be controlled in order to make possible the construction of a fusion reactor. Although more recent calculations consider many other physical constraints in order to arrive at the break-even power balance, these criteria still give values very close to those derived by Lawson.

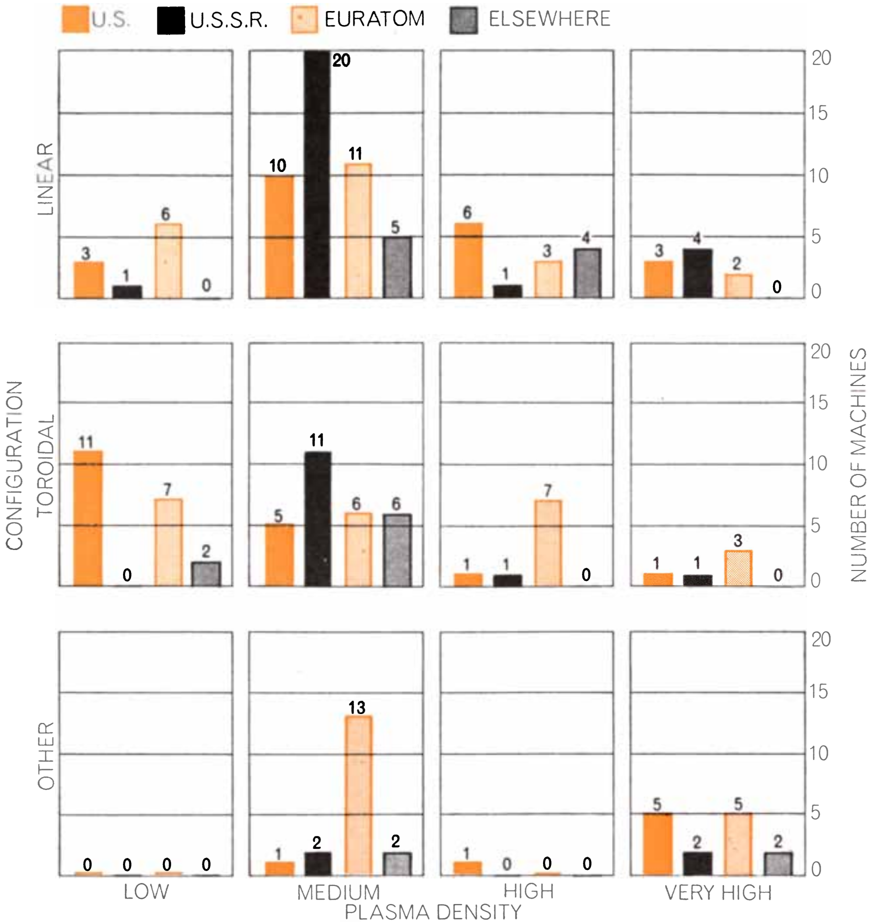
For a deuterium-tritium fuel mixture Lawson found that at temperatures higher than the ignition temperature the product of density and confinement time must be equal to 10^{14} seconds per cubic centimeter in order to achieve the break-even condition. This criterion defines a surface in three-dimensional space, the coordinates being the logarithmic values of density, temperature and confinement time [*see illustration on page 59*]. The goal of a break-even release of energy will have been achieved when the set of conditions for a given machine reaches this surface. It should be emphasized that the exact location and shape of the surface is a function of both the fuel cycle used and the recovery efficiency of the hypothetical reactor system. Fuels other than the deuterium-tritium mixture would increase the temperature needed to achieve a break-even power balance.

The extraordinary progress made recently by various groups in learning how to raise the combination of density, temperature and confinement time to a set of values approaching this break-even surface can be appreciated by referring to the illustration of the Lawson-criterion surface. The several plasma systems shown range in density from about 10^9 ions per cubic centimeter to 5×10^{22} ions per cubic centimeter. (Below a density of about 10^{11} ions per cubic centimeter the power density would be so low that it would require an impractically large reactor.) The particular density range chosen for investigation in each case is a function of the scientific preferences of the investigators concerning the best route to fusion power and the available technology (magnets, power supplies, lasers and so forth). Thus there are various trajectories to the break-even surface being followed through the three-dimensional "parameter space" of the illustration. Closing the gap between where each trajectory is now and the break-even surface depends in some cases (for example the tokamak devices) on obtaining a better understanding of the physical principles required to develop reliable scaling rules, whereas in other cases (such as the linear theta-pinch devices) all that may be required is an economic solution to the engineering problem of building a large enough system.

Fusion-Reactor Designs

How would a full-scale fusion reactor operate? In the first place fusion reactors, like fission reactors, could be run on a variety of fuels. The nature of the fuel used in the core of a fusion reactor would, however, have a decisive effect on the method used to recover the fusion energy and the uses to which the recovered energy might be put. Most research on reactor technology has centered on the use of a deuterium-tritium mixture as a fuel. The reason is that the mixture has the lowest ignition temperature, and hence the lowest rate of energy loss by radiation, of any possible fusion fuel. Nonetheless, other combinations of light nuclei have been considered for many years as potential fusion fuels. Prominent among these are reactions involving a deuterium nucleus and a helium-3 nucleus and reactions involving a single proton (a hydrogen nucleus) and a lithium-6 nucleus. Because containment based on the magnetic-mirror concept actually operates better at higher temperatures, a number of other fuels have been attracting increased attention [*see illustration on page 54*].

Depending on the fuel used, a fusion reactor could release its energy in several ways. For example, neutrons, which are produced at various rates by different fusion reactions, can cross magnetic fields and penetrate matter quite easily. A reactor based on, say, a deuterium-tritium fuel cycle would release approximately 80 percent of its energy in the form of highly energetic neutrons. Such a reactor could be made to produce electricity by absorbing the neutron energy in a liquid-lithium shield, circulating the



INVENTORY of the number of machines now operating throughout the world in each of the broad categories represented in the illustration on the preceding two pages is given in this table. The total number in each category is broken down into subtotals for the U.S., the U.S.S.R., the European Atomic Energy Community, or Euratom, countries (Belgium, France, Germany, Italy, Luxembourg and the Netherlands) and the rest of the world (principally Japan, Sweden and Australia). Britain, although not officially a member of Euratom, is included in the Euratom subtotal. The figures are drawn mainly from a recent survey compiled by Amasa S. Bishop and published by the International Atomic Energy Commission. The U.S. fusion-power program currently represents about a fifth of the world total.

liquid lithium to a heat exchanger and there heating water to produce steam and so drive a conventional steam-generator electric power plant [*see top illustration on page 60*].

This general approach could also lead to an attractive new technique for converting the world's reserves of uranium 238 and thorium 232 to suitable fuels for fission reactors—the fusion-fission hybrid system mentioned above. By employing the abundance of inexpensive, energetic neutrons produced by the deuterium-tritium fuel cycle to synthesize fissionable heavy nuclei, a fusion reactor could act as a new type of breeder reactor. This could have the effect of lowering the break-even surface defined by Lawson's criterion, bringing the fusion-breeding scheme actually closer to feasibility than the generation of electricity solely by fusion reactions. Cheap fuel might thus be made for existing fission reactors in systems that could be inherently safe. A "neutron-rich" economy created by fusion reactors would have other potential benefits. For example, it has been suggested that large quantities of neutrons could be useful for "burning" various fission products, thereby alleviating the problem of disposing of radioactive wastes.

Fuel cycles that release most of their energy in the form of charged particles offer still other avenues for the recovery of fusion energy. For example, Richard F. Post of the Lawrence Radiation Laboratory at Livermore has proposed a direct energy-conversion scheme in which the energetic charged particles produced in a fusion-reactor core are slowed directly by an electrostatic field set up by an array of large electrically charged plates [*see bottom illustration on page 60*]. By a judicious arrangement of the voltages applied to the plates such a system could theoretically be made to operate at a conversion efficiency of 90 percent.

J. Rand McNally, Jr., of the Oak Ridge National Laboratory has suggested that a long sequence of fusion reactions similar to those that power the stars could be reproduced in a fusion reactor. The data necessary to evaluate fuel cycles operating in this manner, however, do not exist at present.

The characteristics of a full-scale fusion reactor would depend not only on the fuel cycle but also on the particular plasma-confinement configuration and density range chosen. Thus it is probable that there eventually will exist a number of different forms of fusion reactor. For example, medium-density magnetic-mirror reactors and very-high-density laser-ignited reactors could be expected to operate at power levels as low as between five and 50 megawatts, which could make them potentially useful for fusion-propulsion schemes.

For central-station power generation the medium-density reactors would most likely operate on a deuterium-tritium fuel cycle in order to take advantage of the mixture's low ignition temperature. Because of the high neutron output associated with this fuel, a heat-cycle conversion system would be appropriate.

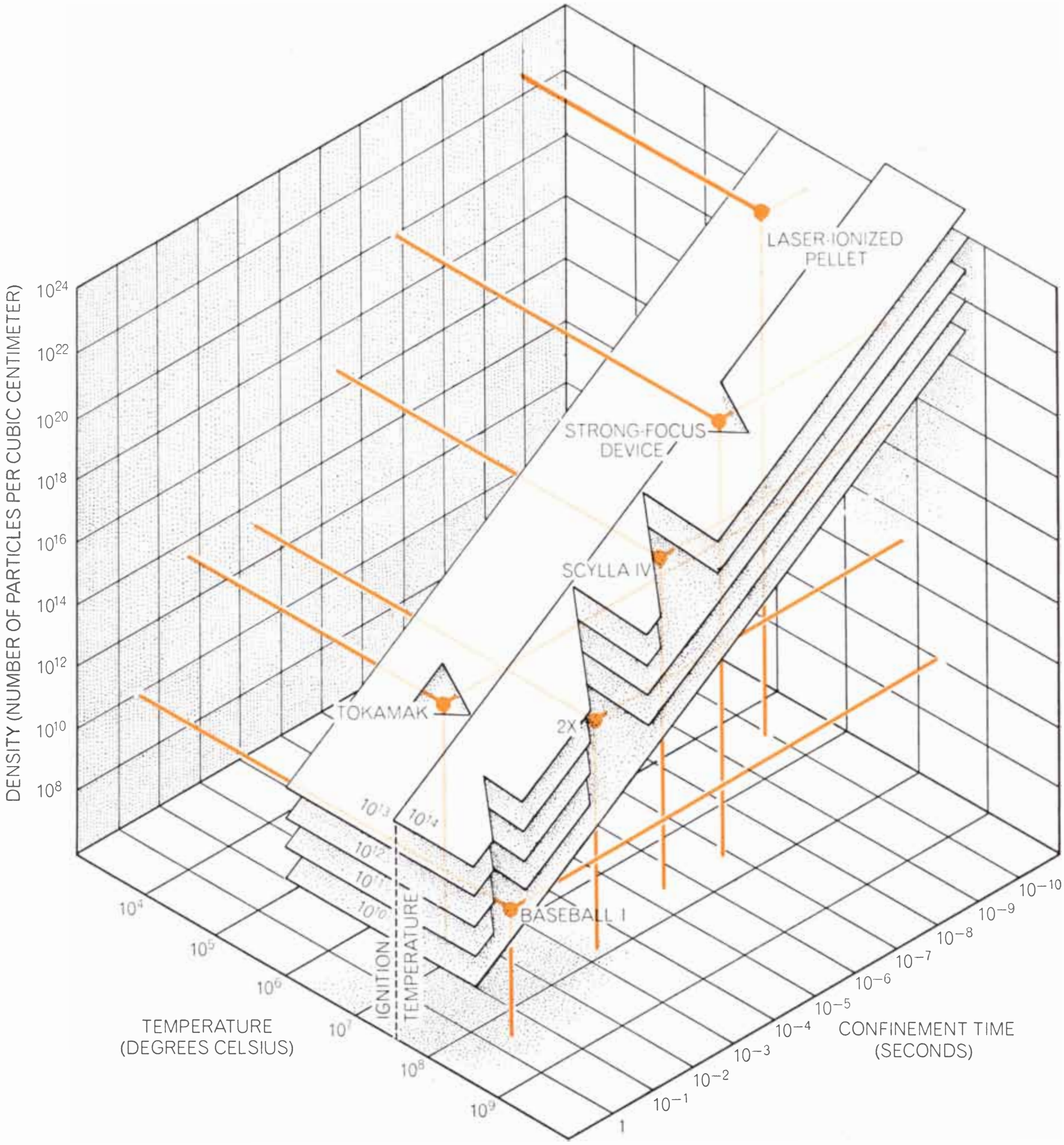
A reactor of this type would operate most efficiently with a power output in the billion-watt range. Before such a reactor can be built, it will be necessary to prove that the plasma will remain stable as present devices are scaled to reactor sizes and temperatures. Problems likely to be encountered in this effort involve the long-term equilibrium of the plasma, the interaction of the plasma with the walls of the container and the necessity of pumping large quantities of liquid lithium across the magnetic field.

Medium-density linear reactors would be better suited for fuel cycles that yield a major part of their energy output in the form of charged particles, since this approach would allow the direct recovery of the kinetic energy of these reaction products through schemes such as Post's. Such fuel cycles could be based on a deuterium-deuterium reaction, a deuterium-helium reaction or a proton-lithium reaction. A system operating on this principle could be made to produce direct-current electricity at a potential of about 400 kilovolts, which would be ideal for long-distance cryogenic (supercooled) power transmission.

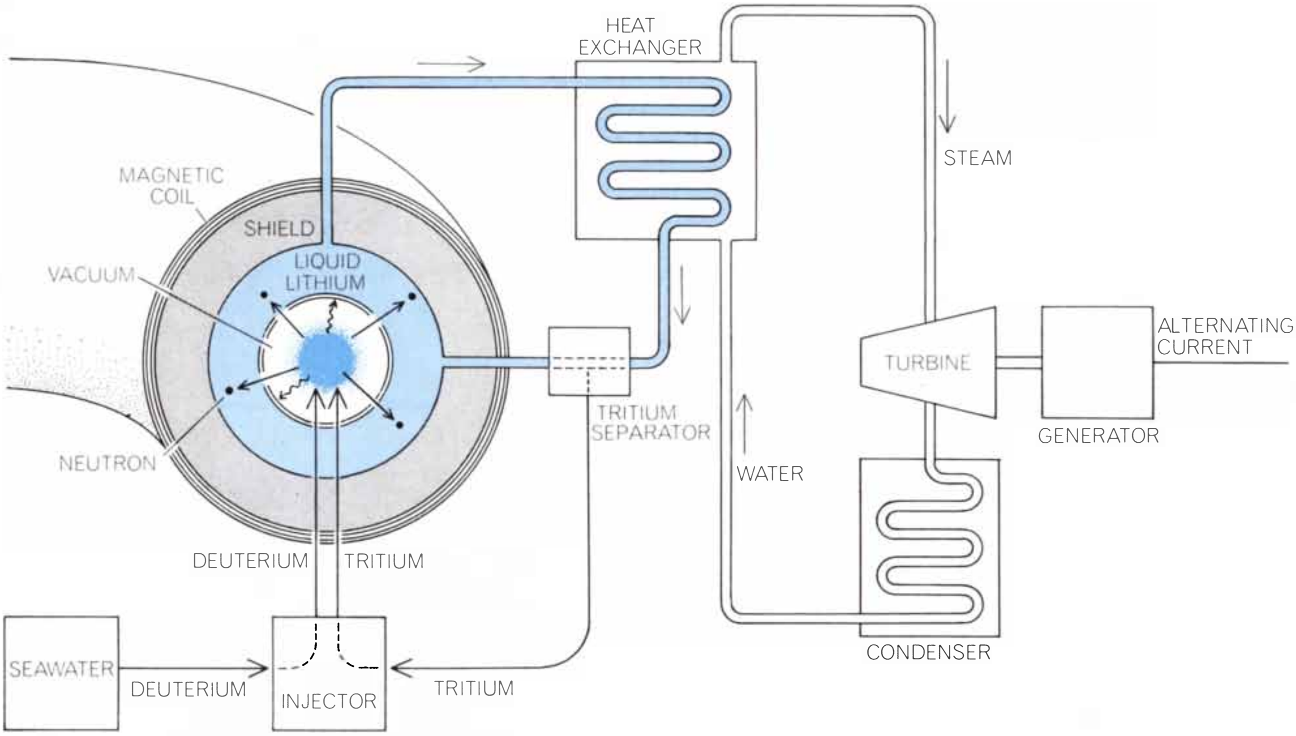
Although the break-even conditions would be lowered in this case (because of the high energy-conversion efficiency), it still remains to be shown that existing experiments can be scaled to large sizes and higher temperatures. Some major technological obstacles that need to be overcome include the construction of large atomic-beam injectors and extremely strong magnetic mirrors.

For reactors operating on the basis of any of the higher-density schemes, such as the theta-pinch machines or the fast-pulsed systems, major technological hurdles include the development of efficient energy-storage and energy-transfer techniques and problems related to heating techniques such as lasers.

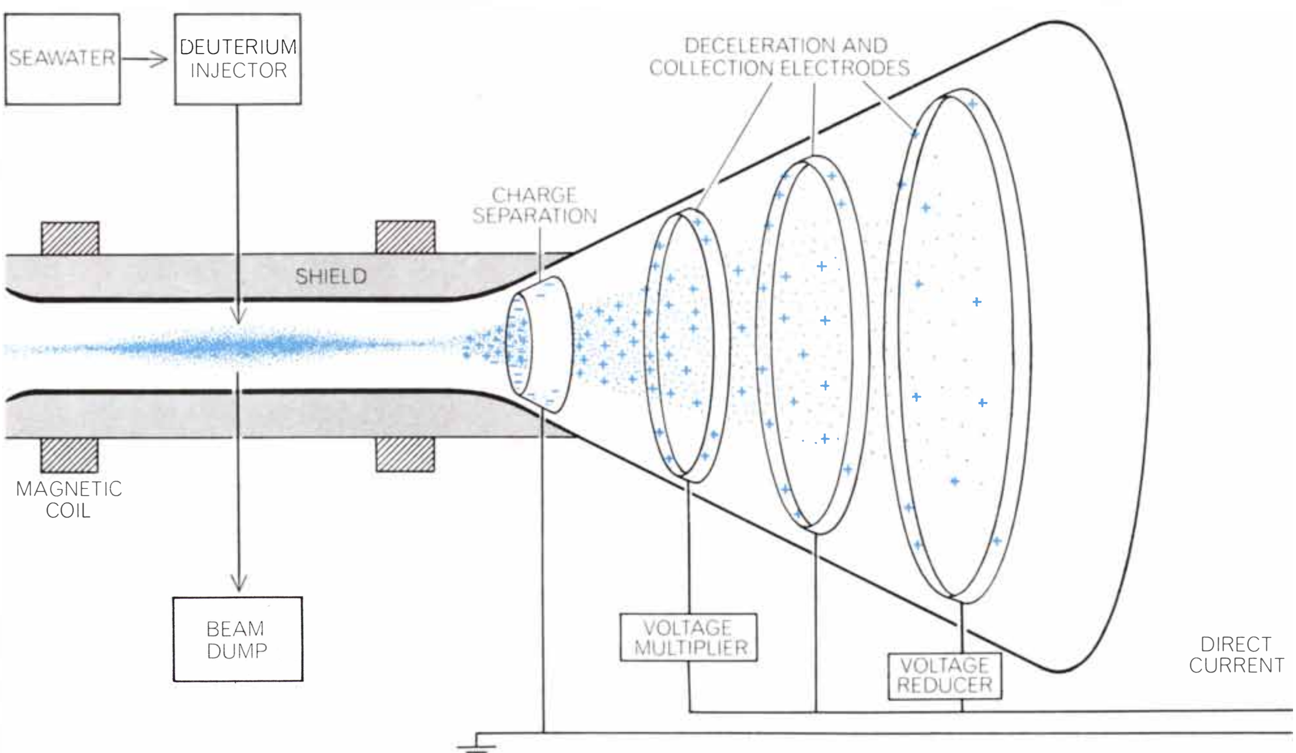
In addition to generating electric power and possibly serving in a propulsion system, fusion reactors are potentially useful for other applications. For example, fusion research has already made available plasmas that range in temperature from 500,000 to a billion degrees C. and in density from 10^9 to 10^{22} ions per cubic centimeter. Almost all industrial processes that use plasmas fall outside this range [*see top illustration on page 55*]. In order to suggest how this industrially unexplored range might be exploited, we recently put forward the concept of the "fusion torch." The gen-



BASIC CRITERION for determining the length of time a plasma must be confined at a given density and temperature to achieve a "break even" point in the fusion-power balance is represented in this three-dimensional graph. The graph is based on a method of analysis devised in 1957 by the British physicist J. D. Lawson. For a deuterium-tritium fuel mixture in the temperature range from 40 million degrees C. to 500 million degrees C., Lawson found that the product of density and confinement time must be close to 10^{14} seconds per cubic centimeter to achieve the break-even condition (based on an assumed energy-conversion efficiency of 33 percent). This criterion corresponds to the top layer in the stack of planes in the illustration. The lower planes, which correspond to successively smaller values of density times confinement time, are included in order to give some idea of the positions of the best confirmed results from several experimental devices with respect to the combination of parameters needed to operate a full-scale fusion reactor.



THERMAL ENERGY CONVERSION would be most effective in a fusion reactor based on a deuterium-tritium fuel cycle, since such a fuel would release approximately 80 percent of its energy in the form of highly energetic neutrons. The reactor could produce electricity by absorbing the neutron energy in a liquid-lithium shield, circulating the liquid lithium to a heat exchanger and there heating water to produce steam and thus drive a conventional steam-generator plant. The reactor core could be either linear or toroidal.



DIRECT ENERGY CONVERSION would be more suitable for fusion fuel cycles that release most of their energy in the form of charged particles. In this novel direct energy-conversion scheme, first proposed by Richard F. Post of the Lawrence Radiation Laboratory of the University of California at Livermore, the energetic charged particles (primarily electrons, protons and alpha particles) produced in the core of a linear fusion reactor would be released through diverging magnetic fields at the ends of the magnetic bottle, lowering the density of the plasma by a factor of as much as a million. A large electrically grounded collector plate would then be used to remove only the electrons. The positive reaction products (at energies in the vicinity of 400 kilovolts) would finally be collected on a series of high-voltage electrodes, resulting in a direct transfer of the kinetic energy of the particles to an external circuit.

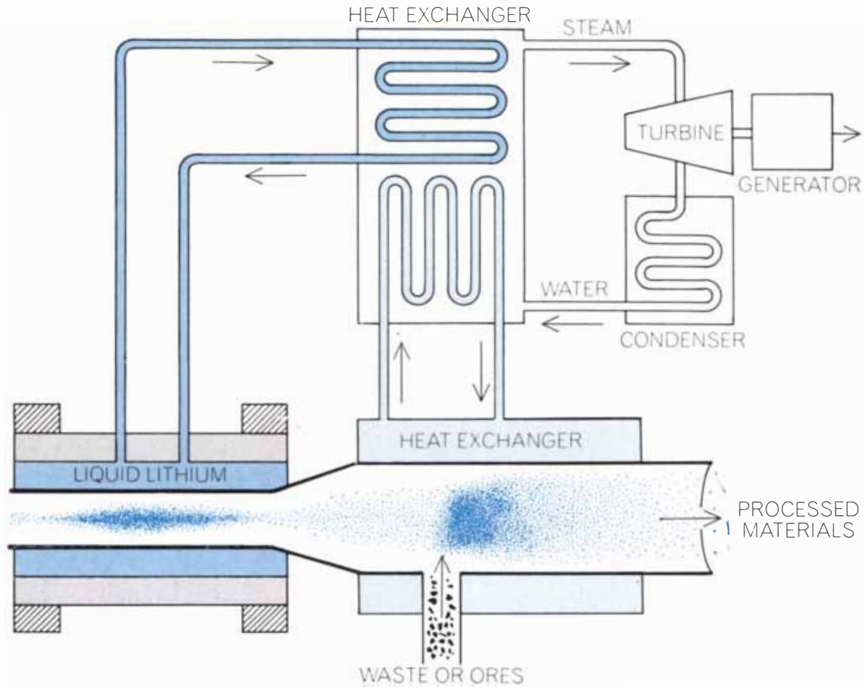
eral idea here is to use these ultrahigh-density plasmas, possibly directly from the exhaust of a fusion reactor, to vaporize, dissociate and ionize any solid or liquid material [*see top illustration at right*]. The potential uses of such a fusion-torch capability are intriguing. For one thing, an operational fusion torch in its ultimate form could be used to reduce all kinds of wastes to their constituent atoms for separation, thereby closing the materials loop and making technologically possible a stationary-state economy. On a shorter term the fusion torch offers the possibility of processing mineral ores or producing portable liquid fuels by means of a high-temperature plasma system.

The fusion-torch concept could also be useful in transforming the kinetic energy of a plasma into ultraviolet radiation or X rays by the injection of trace amounts of heavy atoms into the plasma. The large quantity of radiative energy generated in this way could then be used for various purposes, including bulk heating, the desalting of seawater, the production of hydrogen or new chemical-processing techniques. Because such new industrial processes would make use of energy in the form of plasmas rather than in the form of, say, chemical solvents, they would be far less likely to pollute the environment. Although the various fusion-torch possibilities are largely untested and many aspects may turn out to be impractical, the concept is intended to stimulate new ideas for the industrial use of the ultrahigh-temperature plasmas that have already been developed in the fusion program as well as those plasmas that would be produced in large quantities by future fusion reactors.

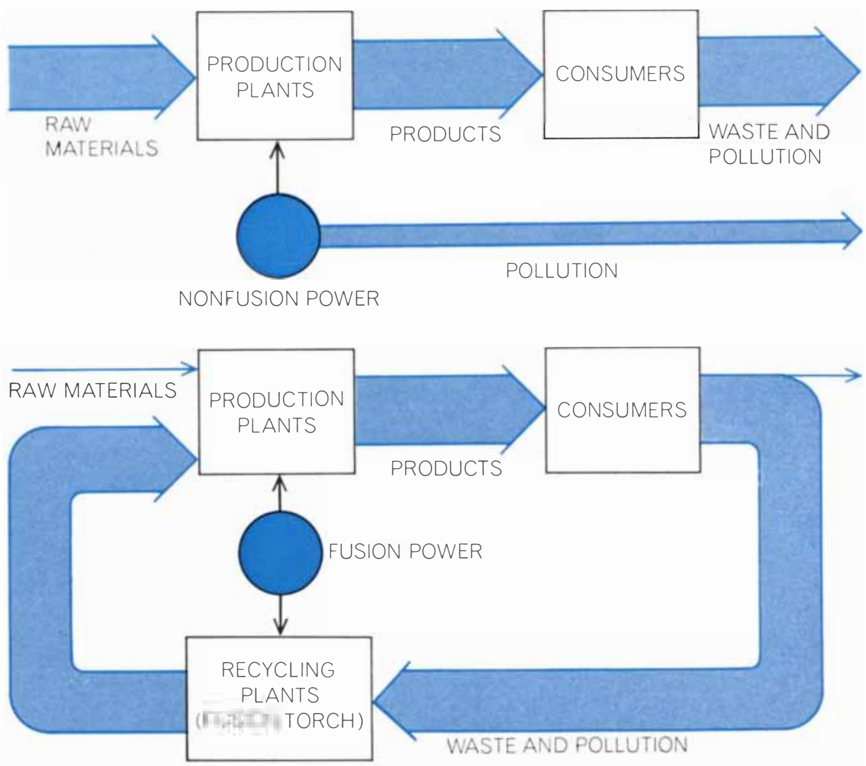
Environmental Considerations

The environmental advantages of fusion power can be broken down into two categories: those advantages that are inherent in all fusion systems and those that are dependent on particular fuel cycles and reactor designs. Among the inherent advantages, one of the most important is the fact that the use of fusion fuel requires no burning of the world's oxygen or hydrocarbon resources and hence releases no carbon dioxide or other combustion products to the atmosphere. This advantage is shared with nuclear-fission plants.

Another advantage of fusion power is that no radioactive wastes are produced as the result of the fuel cycles contemplated. The principal reaction products would be neutrons, nonradioactive heli-



POTENTIAL NONPOWER USE of fusion energy is represented by the concept of the "fusion torch," which was put forward recently by the authors as a suggestion intended to stimulate new ideas for the industrial exploitation of the ultrahigh-temperature plasmas already made available by the fusion-research program as well as those that would be produced by fusion reactors. The general idea is to use some of the energy from these plasmas to vaporize, dissociate and ionize any solid or liquid material. In its ultimate form the fusion torch could be used to reduce any kind of waste to its constituent atoms for separation.



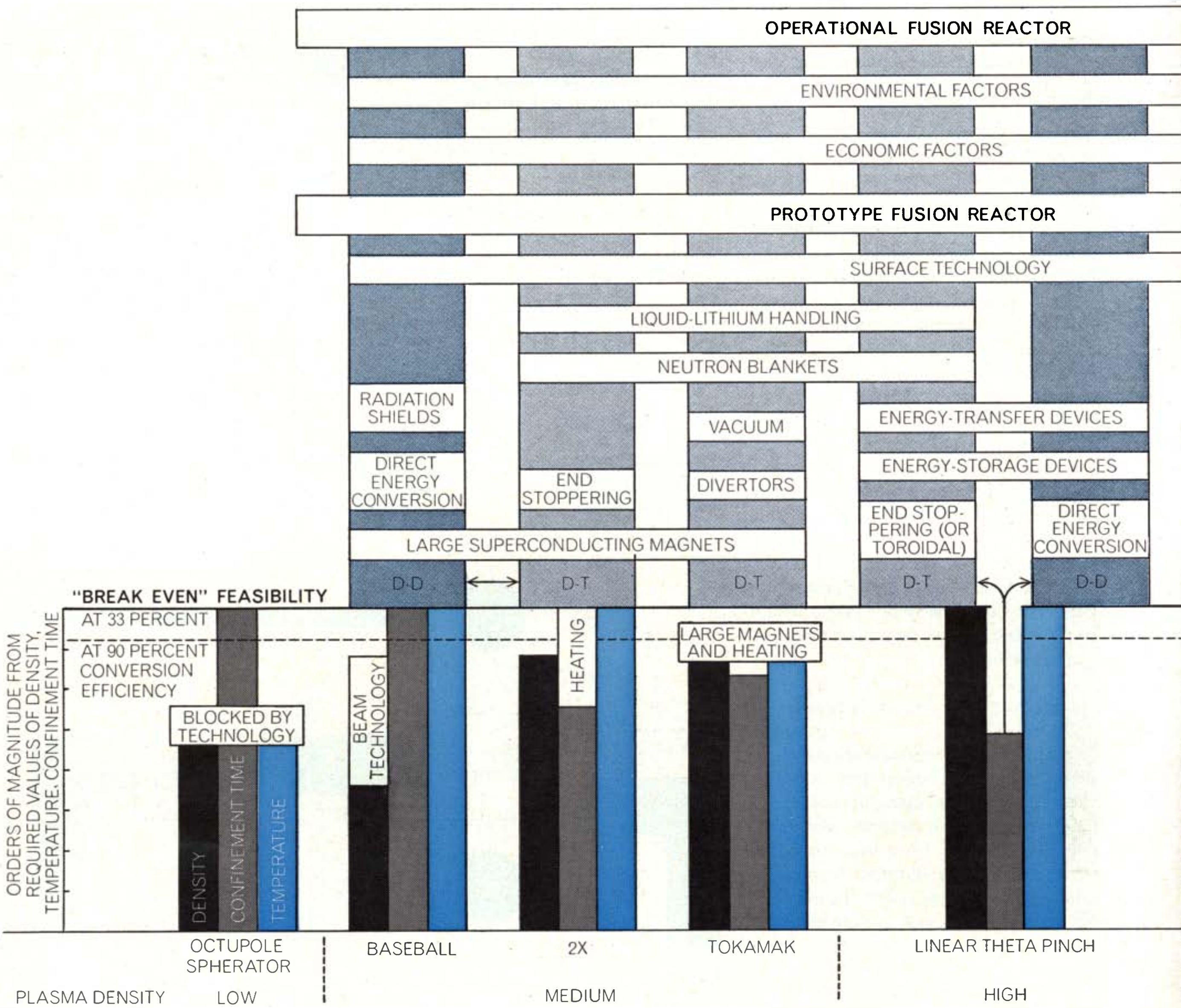
CLOSED MATERIALS ECONOMY could be achieved with the aid of the fusion-torch concept illustrated at the top of this page. In contrast to present systems, which are based on inherently wasteful linear materials economies (*top*), such a stationary-state system would be able to recycle the limited supply of material resources (*bottom*), thus alleviating most of the environmental pollution associated with present methods of energy utilization.

um and hydrogen nuclei, and radioactive tritium nuclei. It is true that tritium emits low-energy ionizing radiation in the form of beta particles (electrons), but since tritium is also a fusion fuel, it could be returned to the system to be burned. This situation is strongly contrasted with that in nuclear fission, which by its very nature must produce a multitude of highly radioactive waste elements.

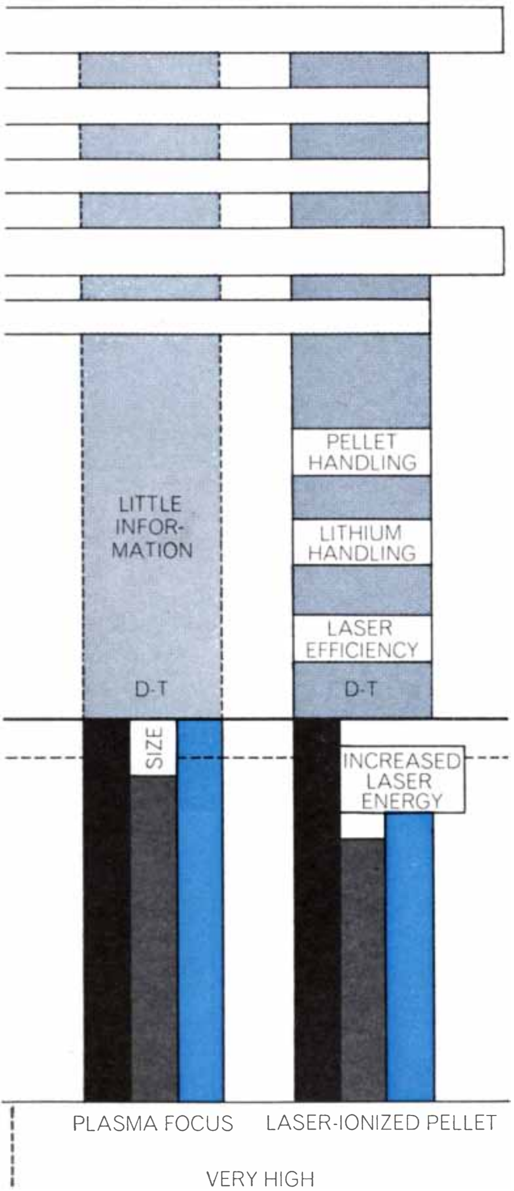
Fusion reactors are also inherently incapable of a "runaway" accident. There is no "critical mass" required for fusion. In fact, the fusioning plasma is so tenuous (even in the "high density" machines) that there is never enough fuel present at any one time to support a nuclear excursion. This situation is also in contrast to nuclear-fission reactors, which must contain a critical mass of fissionable material and hence an extremely large amount of potential nuclear energy.

Among the system-dependent environmental advantages of fusion power must be counted the fact that the only radioactive fusion fuel considered so far is tritium. The amount of tritium present in a fusion reactor can range from near zero for a proton-lithium fuel cycle to a maximum for a deuterium-tritium cycle, where a "blanket" for the production of tritium must be included. Tritium, however, is one of the least toxic of the radioactive isotopes, whereas the fission fuel plutonium is one of the most toxic radioactive materials known.

The most serious radiological prob-



REMAINING PROBLEMS that must be solved before the goal of useful, economic fusion power can be achieved are depicted schematically in this illustration. The major experimental routes to the goal are ordered according to plasma density. Various experimental devices are represented by bars indicating the best combination of plasma density, confinement time and temperature achieved by each device; the logarithmic scale at lower left gauges how far each of these essential parameters is from the values needed to attain break-even feasibility. Technological problems that must be solved in each case are labeled. The achievement of a prototype reactor will be a function not only of plasma technology but also of the fuel cycle and the method of energy conversion chosen. Thus medium-density magnetic-mirror devices could be built to operate with either a deuterium-tritium (*D-T*) fuel mixture or a deuterium-deuterium (*D-D*) fuel mixture; the arrows signify these alternatives. If a D-D cycle is chosen, then direct energy conversion is possible, and once the converters are developed very few obstacles would remain to delay the construction of a prototype reactor. If, on the other hand, a D-T cycle is chosen, then conventional thermal energy conversion would be needed, and the listed technological lems for fusion would exist in a reactor burning and producing tritium. A representative rate of tritium consumption for a 2,000-megawatt deuterium-tritium thermal plant would be about 260 grams per day. Tritium "holdup" in the blanket and other elements of the tritium loop would dictate the tritium inventory. Holdup is estimated to be about 1,000 grams in a 2,000-megawatt plant. If necessary, the doubling time of breeding tritium could be less than two months in order to meet the needs of an expanding economy. The amount of tritium produced by the plant is controllable, however, and need not exceed the fuel requirements of the plant.



hurdles would have to be overcome. Other systems operating on the D-T cycle would have to climb past similar hurdles. The high-density linear theta-pinch device could take either the thermal-conversion path or the direct-conversion path (*arrows*). The final step, from a prototype to an operational reactor, would proceed through a region in which economic and environmental considerations can be expected to be paramount.

Careful design to prevent the leakage of tritium fuel from a deuterium-tritium reactor is mandatory. Engineering studies that take into account economic considerations indicate that the leakage rate can be reduced to .0001 percent per day. The conclusion is that even for an all-deuterium-tritium fusion economy the genetic dose rate from worldwide tritium distribution would be negligible.

In fact, for a given total power output the tritium inventory for an all-deuterium-tritium fusion economy (including both the inventory within the plant and that dispersed in the biosphere) would be between one and 100 times what it would be for an all-fission economy. It is true that tritium would be produced in a deuterium-tritium fusion reactor at a rate of from 1,000 to 100,000 times faster than in various types of fission reactor. Since tritium is burned as a fuel, however, it has an effective half-life of only about three days rather than the normal 12 years.

A technology-dependent but possibly serious limitation on deuterium-tritium fusion plants could be the release of tritium to the local environment. The level would be quite low but the long-term consequences from tritium emission to the environment in the vicinity of a deuterium-tritium reactor needs to be explored. In general the biological-hazard potential of the tritium fuel inventory in a deuterium-tritium reactor is lower by a factor of about a million than that of the volatile isotope iodine 131 contained in a fission reactor. Of course there is no expectation in either case that such a release would occur.

The radioactivity induced in the surrounding structures by a fusion reactor is dependent on both the fuel cycle and the engineering design of the plant. This radioactivity could range from zero for a fuel cycle that produces no neutrons up to very high values for a deuterium-tritium cycle if the engineering design is such that the type and amount of structural materials could become highly activated under neutron bombardment. Cooling for "after heat" will be required for systems that have intense induced radioactivity. Even if the cooling system should fail, however, there could be no nuclear excursion that would disperse the radioactivity outside the plant.

Other system-dependent environmental advantages of fusion power include safety in the event of sabotage or natural disaster, reduced potential for the diversion of weapons-grade materials and low waste heat. In fact, the potential exists for fusion systems to essentially eliminate the problem of thermal pollution by going to charged-particle fuel cycles that result in direct energy conversion. Finally, there is the advantage of the materials-recycling potential of the fusion-torch concept.

The Timetable to Fusion Power

The construction and operation of a power-producing controlled-fusion reactor will be the end product of a chain of events that is already to a certain extent discernible. For controlled fusion, however, there can never be an instant equivalent to the one that demonstrated the "feasibility" of a fission-power reactor (the Stagg Field experiment of Enrico Fermi in 1942). To reach the plasma conditions required for a net release of fusion power it is necessary to first develop many new technologies. In this context the term "scientific feasibility" cannot be precisely defined. To some investigators it means simply the achievement of the basic plasma conditions necessary to reach the break-even surface in the illustration on page 59. To others it represents reaching the same surface—but with a system that can be enlarged to a full-scale, economic power plant. To a few it represents the attainment of a full understanding of all the phenomena involved.

Although these differing interpretations of what is needed to give confidence in our ability to construct a fusion reactor may be somewhat confusing, each interpretation nevertheless contains a modicum of truth. To depict the complexity of this drive toward the goal of fusion power we have prepared the highly schematic illustration on the opposite page. The goal is to achieve useful, economic fusion power. The major routes to the goal are ordered in the illustration according to plasma density. Various individual experiments have climbed past various obstacles to reach positions close to the break-even level. In fact, in some instances two of the three essential parameters (density, temperature and confinement time) have already been achieved. The ignition temperature has been achieved in a number of cases. The rest of the climb to the break-even level in some cases involves a better understanding of the physics of the plasma-confinement system, but in others it may involve only engineering problems. Indeed, the location of the break-even level is a function of the technology used. Direct energy conversion, for example, would lower this level.

The next portion of the climb, the

construction of a prototype reactor, will be a function of the route taken to scientific feasibility. For instance, if a deuterium-tritium mixture is the fuel, this would require the development of components such as lithium blankets, large superconducting magnets, radiation-resistant vacuum liners, fueling techniques and heat-transfer technology. If fuels that release most of their energy in the form of charged particles are considered, however, then in the case of mirror reactors direct-conversion equipment may be part of a device used to demonstrate break-even feasibility. The step from that device to a prototype reactor could then be very short because the conversion equipment would be already developed. Other devices would face similar problems of differing magnitude in prototype construction. The final step from a prototype to an operational reactor would proceed through a much more nebulous region in which economic and environmental considerations would influence the comparative desirability of different power plants.

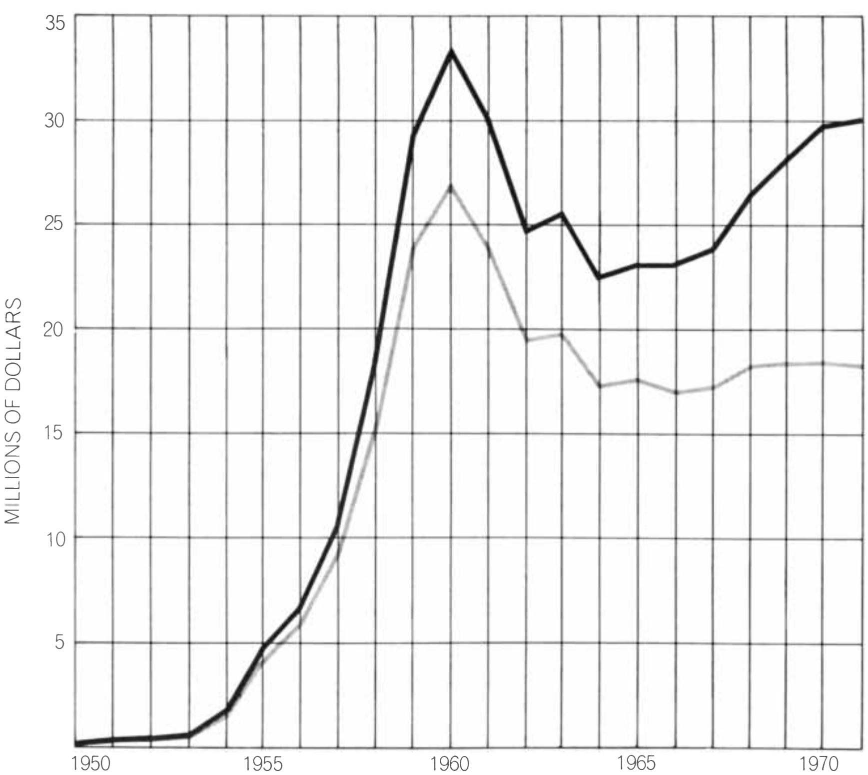
At present the main factor limiting the rate of progress toward fusion power is financial. The annual operating and equipment expenditures for the U.S. fusion program, when one uses the consumer price indexes to adjust these dollars for inflation, has remained fairly constant for the past eight years [*see illustration below*]. The total amount spent on the program since its inception is the cost equivalent of a single Apollo moon shot. The annual funding rate of about $30 million per year is the equivalent of 15 cents per person per year in the U.S.

The road to fusion power is a cumulative one in that successive advances can be built on earlier advances. At present the U.S. has a fairly broad program of investigations approaching the break-even surface for net energy release. It is essential that larger (and thus more expensive) devices be built if the goal of the break-even surface is to be reached. The surface should be broken through in a number of places so that the relative advantages of the possible routes beyond that surface to an eventual fusion-power reactor can be assessed.

Clearly the timetable to fusion power is difficult to predict. If the level of effort on fusion research remains constant or decreases slightly, the requirement for larger devices and advanced engineering will automatically cause a premature narrowing of the density range under investigation. This increases the risk of reaching the goal in a given time scale. To put it another way, it extends one's estimate of the probable time scale. If the level of fusion research expands sufficiently to maintain a fairly broad program across the entire density range, the probability of success increases and the probable time scale decreases. If fusion power is pursued as a "national objective," expanded programs could be carried out across the entire density range accompanied by parallel strong programs of research on the remaining engineering and materials problems to determine as quickly as possible the best routes to practical fusion-power systems. Therefore, depending on one's underlying assumptions on the level of effort and the difficulties ahead, the time it would take to produce a large prototype reactor could range from as much as 50 years to as little as 10 years.

There is at least one case in which the fusion break-even surface could be reached without making any new scientific advances and without developing any new technologies. This "brute force" approach, which might not be the optimum route to an eventual power reactor, would involve simply extending the length of the existing theta-pinch linear devices. It has been estimated that to reach the break-even surface by this method such a system would have to be about 2,000 feet long—less than a fifth of the length of the Stanford Linear Accelerator. This one fusion device, however, would cost an order of magnitude more than any experimental fusion device built to date. Even though a simple scaling of this type would introduce no new problems in plasma physics, one could not exclude the possibility of unexpected difficulties arising solely from the extended length of the system.

The length of such a device could be shortened by as much as 90 percent by installing magnetic mirrors at the ends, by increasing the diameter of the plasma or by making the system toroidal, but these steps would introduce new physical conditions. The system could also be shortened by the use of a direct energy-conversion approach, but this would introduce an unproved technology. At present a significant portion of the fusion-power program is concentrating on developing the new physics and technology that would reduce the cost of such break-even experiments. This continuing effort is sustained by the growing conviction that the eventual attainment of a practical fusion-power reactor is not blocked by the laws of nature.



FINANCIAL SUPPORT is currently the main factor limiting the rate of progress toward the goal of fusion power. The solid curve shows the annual operating and equipment expenditures for the U.S. fusion program. The gray curve shows these expenditures adjusted for inflation. The adjustment shows that fusion research has been funded by the Atomic Energy Commission at an essentially constant rate for the past eight years. Smaller research programs have been funded by both private industry and other Government agencies.

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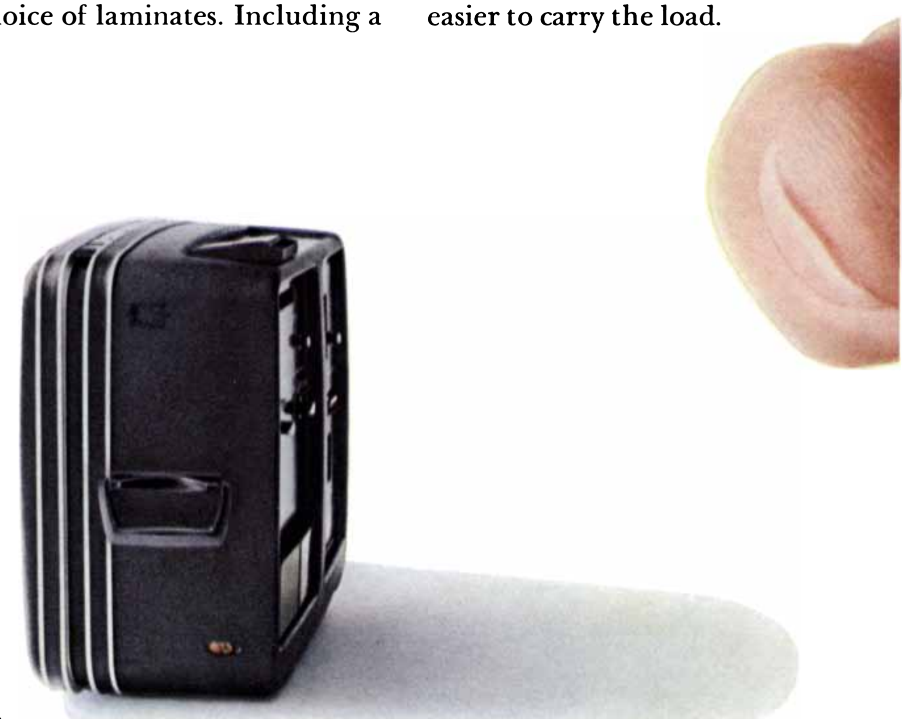

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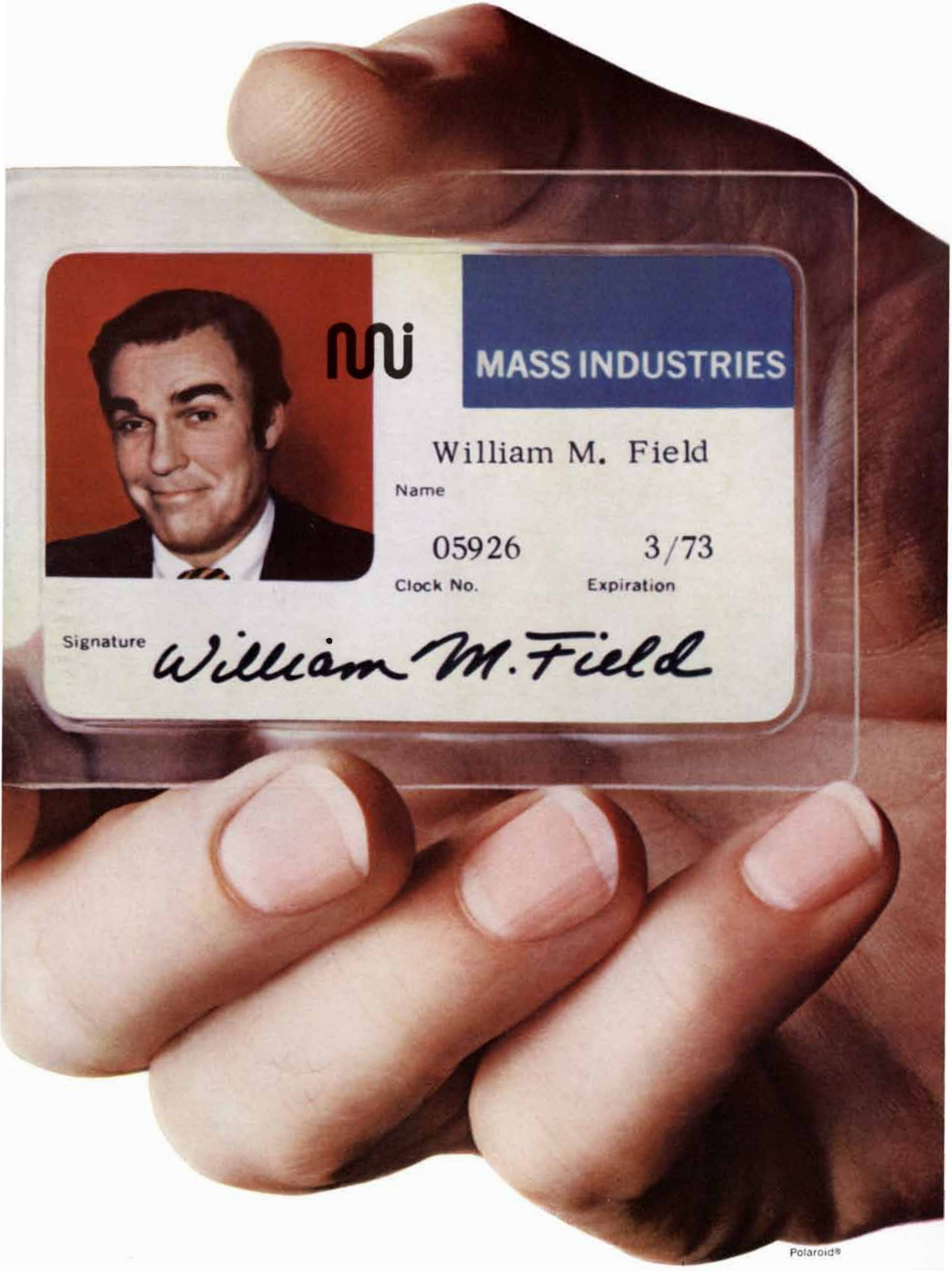

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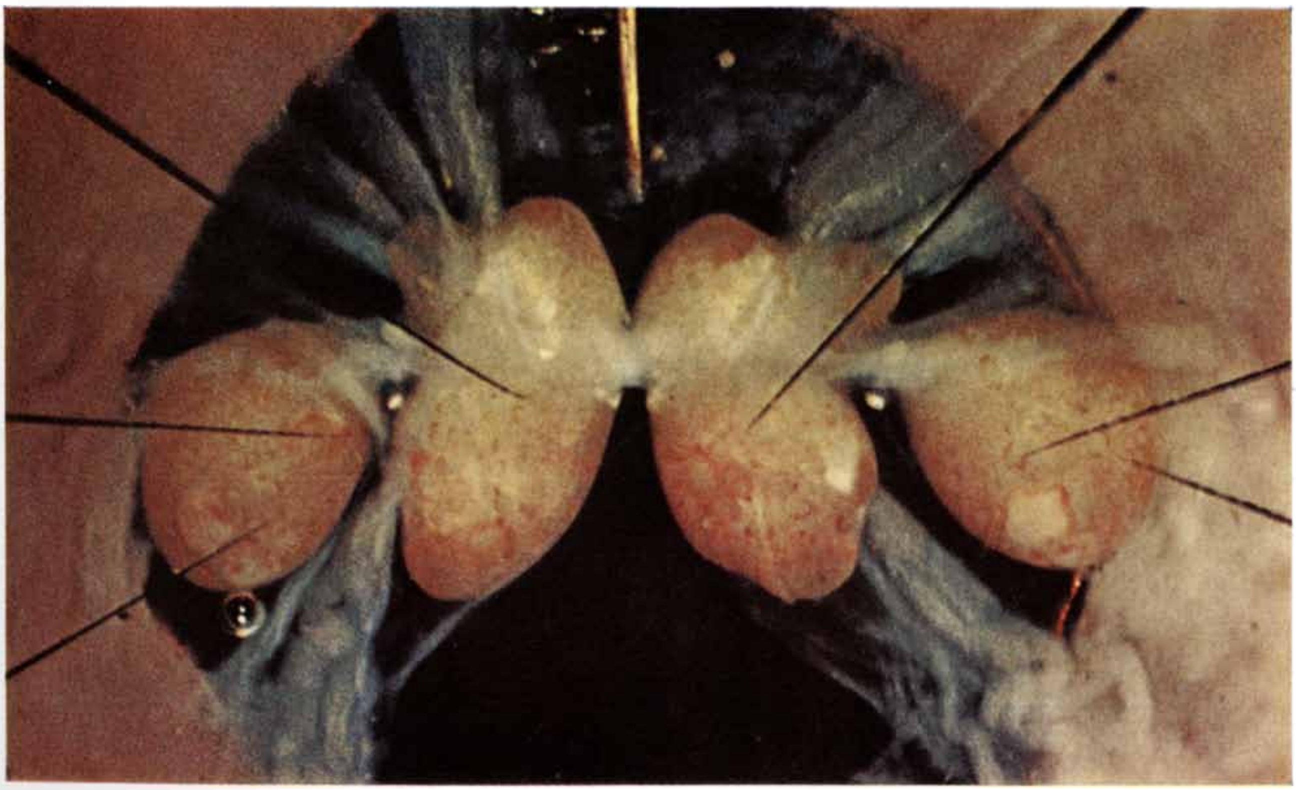
BRAIN OF THE MOLLUSK *TRITONIA*, a relative of the snails and slugs, can be mounted for experiments designed to ascertain the role of individual brain cells in controlling the animal's movements. Cells appear as small circles distributed over the brain's three pairs of lobes; many cells are naturally colored bright orange. This brain and the one below are about 1/4 inch across.



RECORDINGS ARE MADE of cellular activity in the brain of *Tritonia* by means of slender, tapered electrodes, which are the black needle-like objects in this photograph. Each electrode penetrates a single cell of the brain and records the electrical activity of the cell as the animal is stimulated to perform a series of movements that it normally executes to escape from predatory starfish.

Giant Brain Cells in Mollusks

Study of the neurons of a large mollusk with a stereotyped pattern of behavior yields a picture of what each cell does and how the cells interact to produce the behavior pattern

by A. O. D. Willows

The quest for detailed understanding of how the brain controls behavior can be pursued today at the primary level of the performance of individual brain cells. Although this kind of study is not yet feasible in mammals, with their enormously complex brains consisting of billions of minute cells, present techniques enable us to carry out such investigations in certain simple animals that have a brain consisting of a relatively small number of giant cells. In the University of Washington's Friday Harbor Laboratories, with a convenient mollusk as the subject, I have been investigating the control of instinctive behaviors, such as locomotion and escape, by specific cells whose function and location in the brain I have been able to determine. From these studies there is beginning to emerge a rather clear picture of each cell's responsibilities and how the cells collaborate to drive complex behavior.

Over the past 20 years investigators in laboratories in the U.S. and Europe have obtained considerable information about the nervous systems of simple animals such as snails, locusts, crabs and crayfish by probing their large nerve cells with microelectrodes [see "Small Systems of Nerve Cells," by Donald Kennedy; SCIENTIFIC AMERICAN, May, 1967]. Work on *Aplysia*, a sluglike mollusk sometimes called the sea hare, has been particularly fruitful. Intensive studies of its abdominal ganglion, an aggregate of neurons (nerve cells) located near the digestive organs, have disclosed many details of the cells' intrinsic properties, their geography and interactions and their activities in mediating reflex behavior [see "Nerve Cells and Behavior," by Eric R. Kandel; SCIENTIFIC AMERICAN, July, 1970].

Encouraged by the progress made in these various investigations, I decided in 1964 to undertake a study of cell systems within the brain itself, with a view to examining the control of an animal's complex, integrated behavior.

The first problem was to find a suitable animal. What was wanted was a subject with (1) large brain cells that could be identified individually, (2) a well-centralized nervous system concentrating most of the nerve cells in the brain and (3) a repertory of stereotyped behavioral activities (more elaborate than simple reflexes), the control of which could be demonstrated readily and unambiguously. I found that a near relative of *Aplysia* beautifully answered these requirements. This species, *Tritonia diomedia,* is a sluglike nudibranch (an animal whose branchia, or gills, are not encapsulated in a specialized cavity) that is sometimes more than a foot in length. Its brain cells range up to a millimeter in diameter, so that many of the individual cells can easily be resolved under a low-power dissecting microscope and some can be seen with the unaided eye. Moreover, the giant cells are identifiable by color; some are brightly colored with orange-yellow pigments and others are white in varying degrees of brightness.

Along with these favorable anatomical features *Tritonia* provides a form of behavior that is remarkably convenient for our research purpose. Like many other mollusks (notably clams, oysters and mussels) it is heavily preyed on, particularly by a voracious sun star (a multi-armed starfish) called *Pycnopodia,* and it has developed an instinctive escape reaction. In response to even the briefest touch by a predator such as the starfish, *Tritonia* instantly withdraws the touched area and then proceeds to extend its tail and oral veil into paddle-like structures and make swimming movements with its body. These movements, although clumsy and poorly directed, are vigorous enough to remove *Tritonia* from the clutches of the starfish. The burst of activity is thoroughly stereotyped. It includes a series of dorsal and ventral flexions of the body-wall muscles, lasts for about 30 seconds and is repeated in almost precisely the same pattern every time the stimulus occurs. Thus this behavior furnishes several essential features for our studies: the action involves a fairly elaborate system of muscles, continues long enough to be examined in detail and constitutes an invariable, integrated response to a specific stimulation of the nervous system.

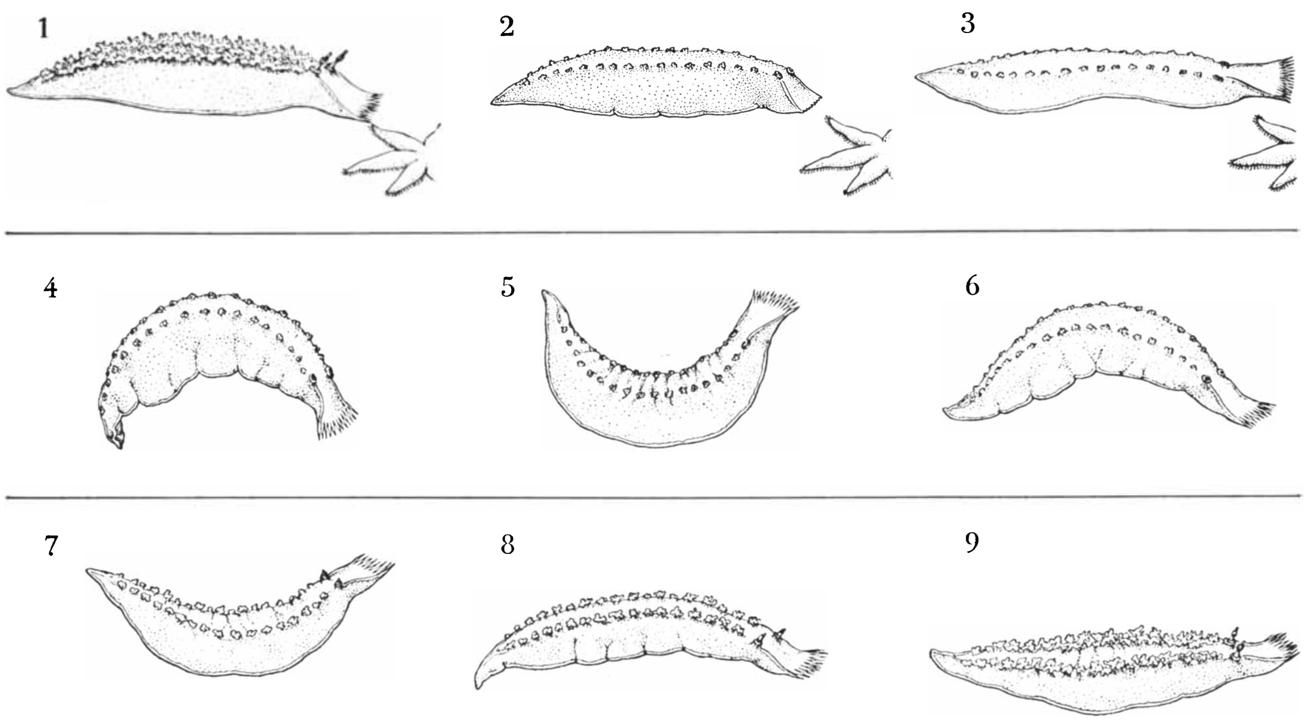
As preparation for the experimental investigations of the behavior I had to begin by identifying and mapping specific brain cells so that they could be recognized and examined routinely from animal to animal. With a low-power dissecting microscope I scanned the brains of many *Tritonia* individuals, noting the location, size and color of each prominent cell. On the basis of these criteria I was able to identify and give coded names to about 50 of the largest cells. For instance, one very large cell visible to the unaided eye could always be found on the surface of the right pleural ganglion, immediately to the left of a large nerve trunk; I labeled the cell RP-1. Other cells, occurring in pairs in the pedal ganglia on opposite sides of the brain, were identifiable by their size, color and symmetrical correspondence in position on the right and left sides. Still others were distinguishable mainly by their color; for example, some individual cells could be picked out because they were distinctly lighter in color than their neighbors.

After identifying the brain cells visually I set about the laborious business of tracking their communications, that is, determining from what region or regions of the body each cell received sensory messages and to what region, in turn, it sent messages. After inserting an extremely fine electrode (in the form of a glass micropipette) in the cell to record its electrical response to incoming impulses, I stimulated each of the more than 30 nerve trunks of the animal to determine which of the trunks would evoke a response in the cell. Since there were scores of identified brain cells to be tested in this way, and I repeated the test for each cell several times in different animals, the exploration entailed a very large number of trials—more than 20,000 measurements, in fact. Then, to determine where the cells sent their messages, I had to conduct the experiment in reverse, stimulating each cell and probing each nerve trunk in succession to detect whether or not it responded. (These experiments gave me an indication not only of the sources of the sensory messages to each cell but also of the paths the messages followed along the cell's axonal branches.) I then conducted a third set of experiments examining the communications between the cells in the brain itself, taking them pair by pair to see if stimulation of one cell affected the other and whether the effect was excitatory or inhibitory.

All in all, then, the three sets of measurements provided information about the input and the output of messages for each brain cell and about the individual cell-to-cell interactions of these neurons. I found that the activities, responses and interactions of the identified brain cells in different *Tritonia* individuals were highly predictable, indicating that the wiring of the nervous system in these animals varies little, if at all, from animal to animal. This suggests that there is a remarkably high level of precision in the development of connections in the nervous system. How the development is controlled is not yet understood.

Finally, in order to set up experiments to investigate the roles played by the various brain cells in driving and controlling *Tritonia's* behavior I had to find a way to immobilize the mollusk's brain (so that microelectrodes in the cells would remain in position) without restricting the animal's locomotion and escape movements. Fortunately *Tritonia's* near-neutral buoyancy in the water made possible a simple solution of the problem. I devised an arrangement whereby the animal, suspended at the surface of seawater in a tank, has freedom of body movement while a small platform inserted below the brain holds the brain still. The brain is opened by an incision made directly above it, and the cut is held open by means of fine hooks that are attached to threads wound on adjustable peg tighteners at the sides of the tank. A small, wax-covered stainless-steel platform, shaped to fit below the brain, is then thrust under it in the space between the main lateral nerve trunks, and with a mechanical manipulator the platform is raised slightly to lift the brain away from the mobile tissues below without stretching the nerve connections. To keep the brain immobile, a few small platinum pins are stuck through the connective tissue around the brain into the layer of tough wax covering the steel platform. Suspended in this way, *Tritonia* maintains its activity and responds to stimulation for many hours (in some cases for days). The experimental stimulations and measurements are made with microelectrodes inserted by means of micromanipulators into selected cells of the brain.

As I began these experiments, the first surprise I encountered was that the white cells in the brain apparently play no direct part in *Tritonia's* motor activi-



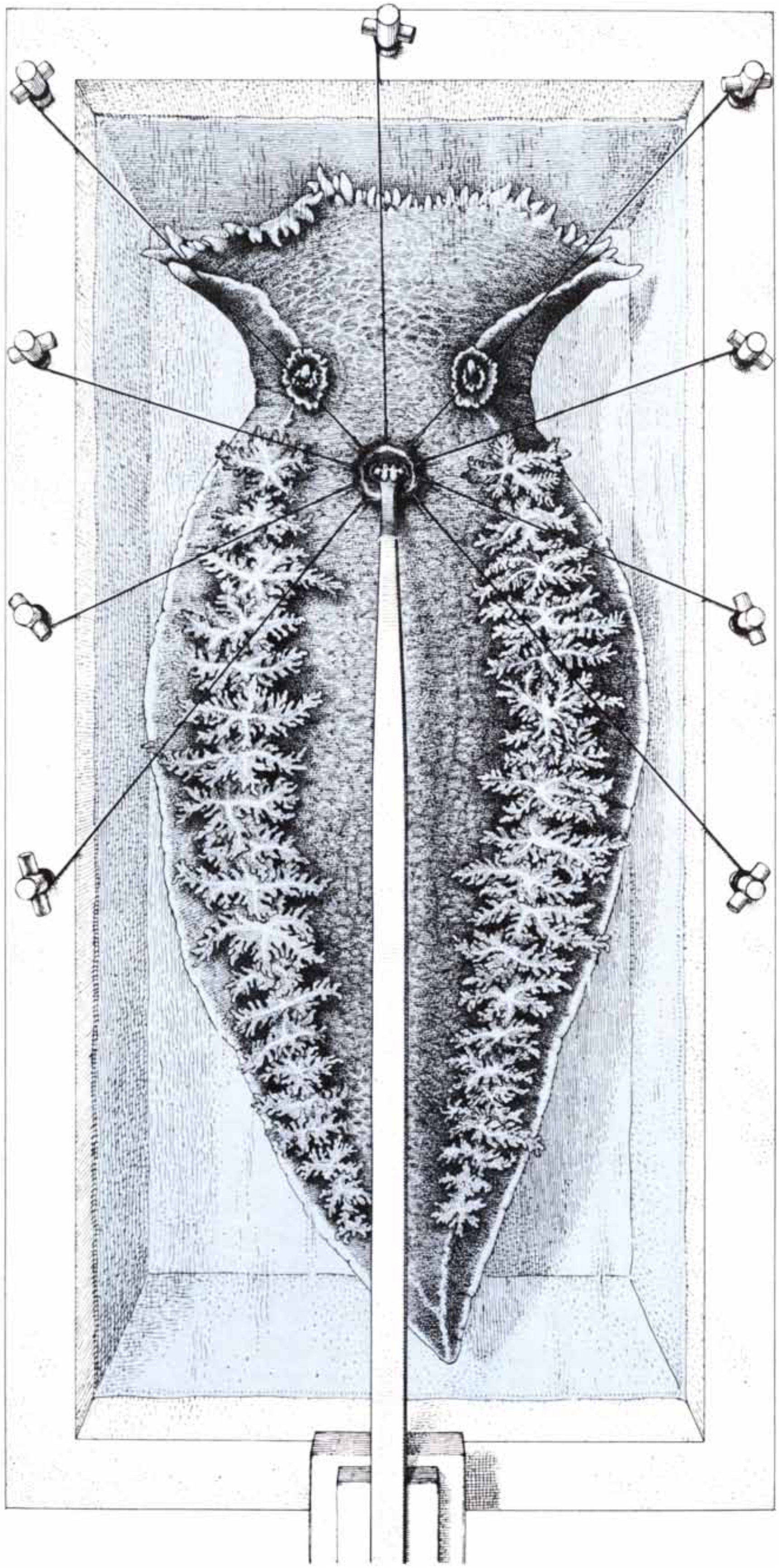
ESCAPE RESPONSE of *Tritonia* is the stereotyped behavior that the author investigated. When one of the animals, cruising normally (*1*), comes in contact with a starfish, it first pulls in extending parts of its body (*2*). Next there is an elongation and enlargement of head and tail regions into paddle-like structures (*3*). The animal then begins a series of ventral (*4*) and dorsal (*5*) flexions causing vigorous but poorly directed swimming movement. The response ends with a series of gradually weakening upward bends (*6–9*) with short intervals of relaxation between them. The escape behavior is initiated by chemicals exuded by the starfish.

ties. When I stimulated these very prominent whitish neurons, in no case was there an obvious motor response. Nor did the cells show any involvement, in the form of excitation of impulses, when the animal was induced to make vigorous movements by poking, pinching or contact with a starfish. I had to conclude that the white cells are probably not engaged in the brain circuitry that generates and controls movements. A clue to their possible function has been suggested by an investigation of the white brain cells in *Aplysia* by Felix Strumwasser and Lois Toevs of the California Institute of Technology. They injected the contents of whitish cells into normal *Aplysia* subjects and found that this caused the animals to lay eggs some time later. This finding and my own experiments lead me to suspect that the function of the white brain cells in *Tritonia* may be to secrete hormone-like substances that influence the long-term growth, development or general behavioral state of the animal.

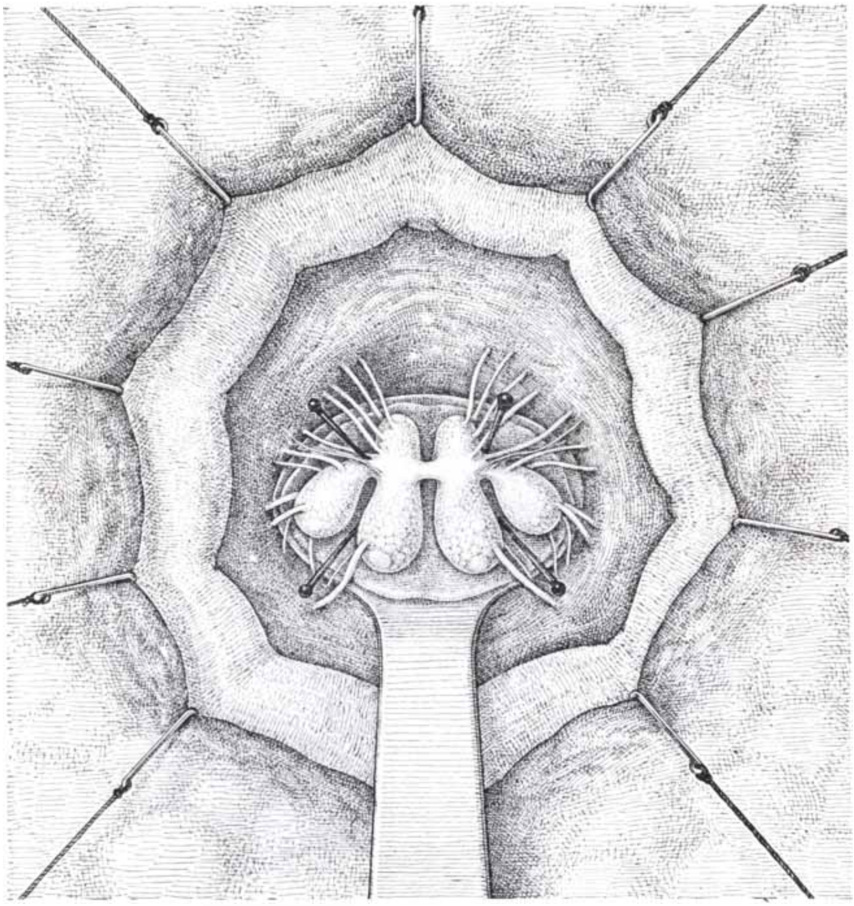
The orange-colored brain cells, on the other hand, told another story. They were quite definitely involved in motor activity. They also supplied answers (albeit of a mixed nature!) to a prime question: How specific, or how general, are the controls exercised by individual brain cells? Are recognizable movements of the entire animal driven by single cells, or do they depend on the combined action of networks of cells?

I found that when I stimulated an orange-colored cell with a current just sufficient to elicit impulses, the animal generally responded with activity by a well-defined, limited part of its musculature. For instance, stimulation of a certain prominent cell in the left pedal ganglion (labeled LPe-1) always caused contraction of a group of branchial tufts (gills) at the head end of the animal on the left side; stimulation of the corresponding cell on the right (RPe-1) produced contraction of the tufts on the right side. Similarly, the excitation of other individual pedal-ganglion cells elicited slight curling or turning movements by one side of the body. Single cells of the pleural ganglia turned out to exert somewhat more extensive control, producing bilateral responses; for instance, stimulation of either RP-1 or LP-1 caused the animal to draw in the branchial tufts on both sides of the body along its entire length.

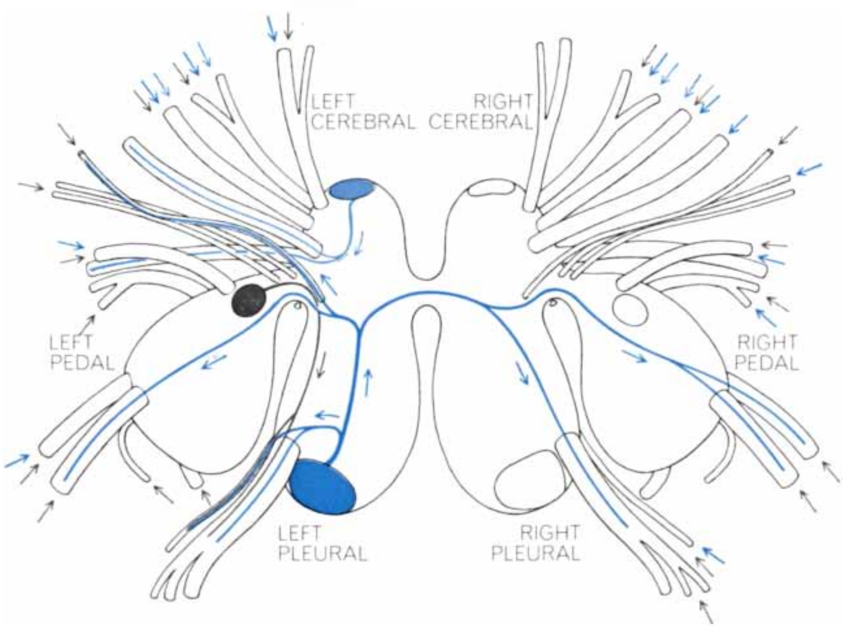
In all these cases there was no question that the individual cell was in the final pathway responsible for driving the response. As soon as the stimulation of



EXPERIMENTAL ARRANGEMENT entailed suspending *Tritonia* in shallow water and immobilizing its brain. The suspension apparatus consists of an array of threads attached to the animal by small hooks in the edge of an incision over the brain. The threads are adjusted by pegs around edge of the aquarium. Animal still can move with relative freedom.



SUSPENSION OF BRAIN was achieved by inserting a small, stainless-steel platform covered with wax under the brain and lifting it slightly so that it was removed from mobile tissues without stretching the nerve connections. With the brain pinned to the platform by pins put into the wax, microelectrodes can be inserted into individual cells of the brain.



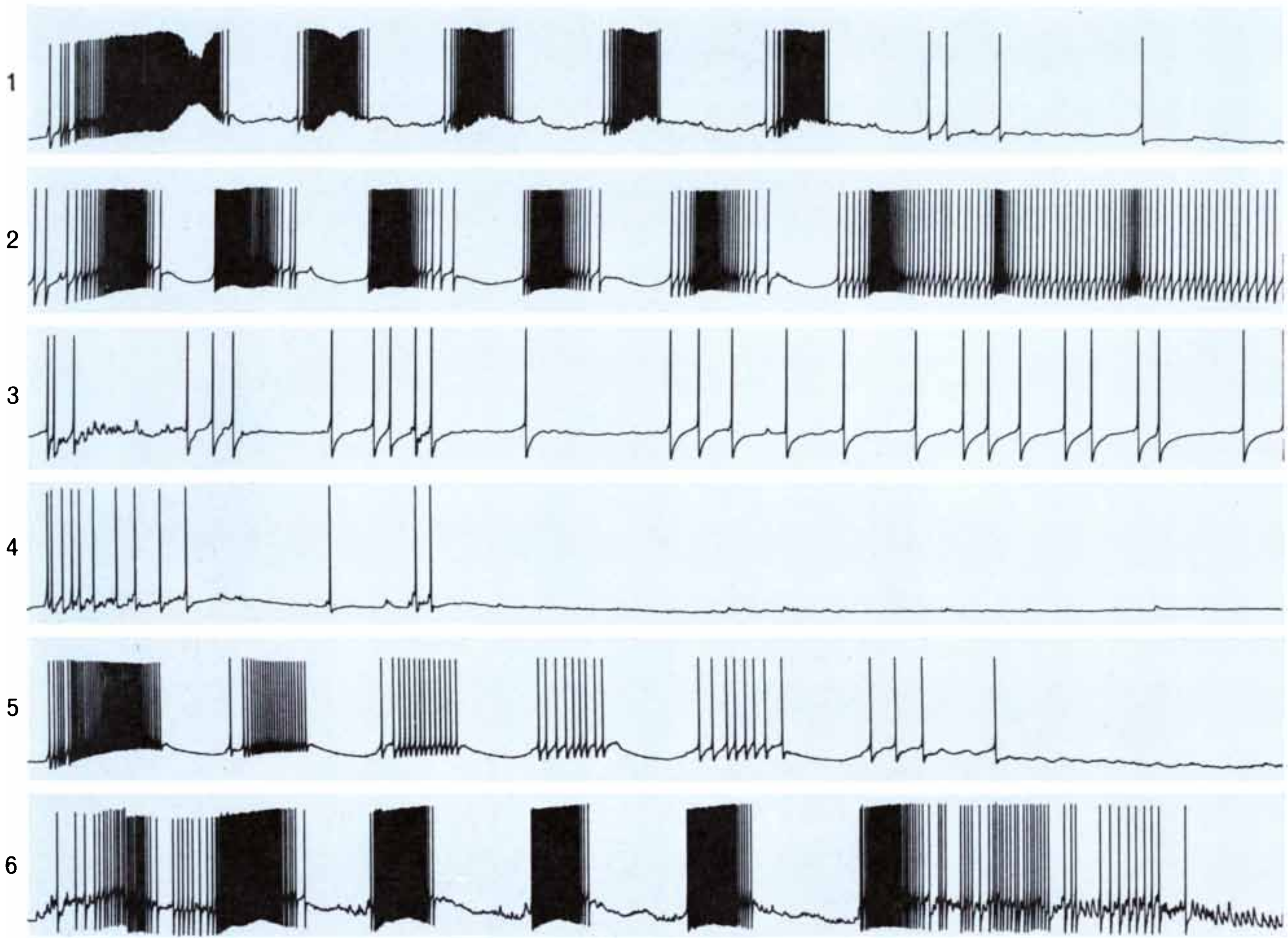
NEURAL CIRCUITRY of *Tritonia* was determined by stimulating individual brain cells and also the 30 nerve trunks and recording the resulting response. Here three individual cells are identified by shading arrangements that correlate with the inputs to and outputs from the cells along various nerve trunks. Circuitry proved to be the same in each animal.

the cell stopped, the muscular contractions ceased abruptly; when the current was stepped up, causing the cell to fire faster, the contractions speeded up. The responses in all cases were also remarkably consistent and predictable from animal to animal, confirming that *Tritonia*'s brain is structured according to a rigidly specified plan.

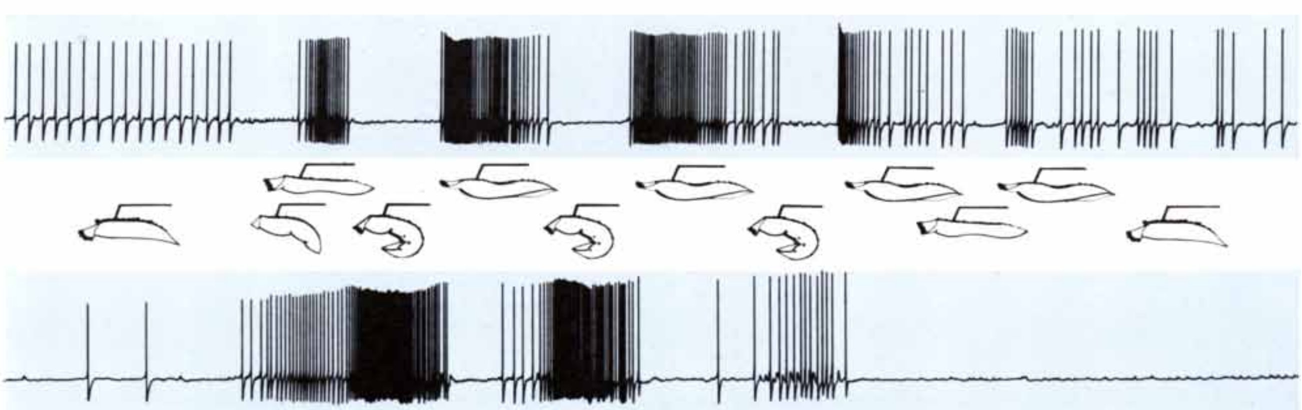
In the course of my exploration of the animal's brain cells with the stimulation experiments I came on a totally unexpected finding. Occasionally the excitation of a cell in a group near the central commissure joining the two halves of the brain elicited a complete playing out of the animal's normal swimming escape response in all its details: withdrawal, extension of the paddle-like organs and the series of body-bending movements. Most surprising, this behavior did not require continued stimulation during its duration: a brief stimulation of the cell (for less than a quarter of a second) was enough to set off the entire sequence of escape movements lasting for more than 30 seconds. Did the cell go on exciting itself during this period? The microelectrode's recording of its activity showed that it did not; frequently the cell ceased firing altogether within three seconds after the stimulation. The most likely explanation was that the cell triggered a series of firings by other neurons that drive the sequence of escape movements.

Looking further into the matter, I obtained several findings that support this idea and indicate how the coordinated firing by a group of neurons can come about. I found that when a number of cells in this sensitive region of *Tritonia*'s brain are stimulated simultaneously, the animal *always* executes the series of swimming movements (instead of only occasionally, as when just a single cell is excited). What makes it possible for a single cell to trigger firing by all these cells is the fact that many of the neurons in this region are interconnected by an unusual system of electrical junctions that allow impulses or prolonged fluctuations of polarity to pass from cell to cell. Hence the interconnected cells can fire impulses almost synchronously. Furthermore, the excitation can be fed back within the group, so that cells that have fired can be reexcited by neighbors they have excited. Accordingly a cascade of impulse bursts tends to develop, and such a cascade can account for the series of group firings by neurons that drives *Tritonia*'s swimming behavior.

The bursts occur only when the cells involved are primed to an excited state close to their threshold for firing, so that a few incoming impulses can trigger them. I found that the stimulus of touching *Tritonia* with a starfish brought the trigger neurons to the required state of excitation (that is, depolarization). This priming effect requires some form of stimulation of the body, such as the starfish's touch, exciting sensory channels that will deliver closely synchronized impulses in sufficient number to excite many trigger cells. In short, the brain of *Tritonia* "decides" whether or not to command swimming activity on the basis of the number of excitatory inputs impinging on the trigger neurons within a short period. After the trigger cells fire, ordering the animal to swim, there follow bursts of impulses in the various pedal-ganglia cells that drive the bending, curling, turning and flexing movements constituting the action of swim-



ACTIVITY of six cells in brain of *Tritonia* was recorded simultaneously for about 55 seconds as the animal was stimulated to swim. By correlating the cell impulses with observed movement of the body, one can determine the functional role of each cell. The top record (*channel 1*) represents a cell that drives the animal's downward flexion; channels *2* and *6* show cells that drive upward flexion on the right and left sides respectively; channels *3* and *4* show the activity of two cells that trigger the escape sequence, and channel *5* represents a cell that causes withdrawal of the gills on the left side of the body. Records also indicate interactions among cells.



SIMULTANEOUS RECORDINGS from two cells that drive flexions in the escape response of *Tritonia* are shown in correlation with the resulting movements. At top is record of a cell driving dorsal flexion; at bottom, record of a cell driving ventral flexion.

ming. Recordings made with electrodes during the swimming showed that these bursts in the pedal cells continue until swimming ceases.

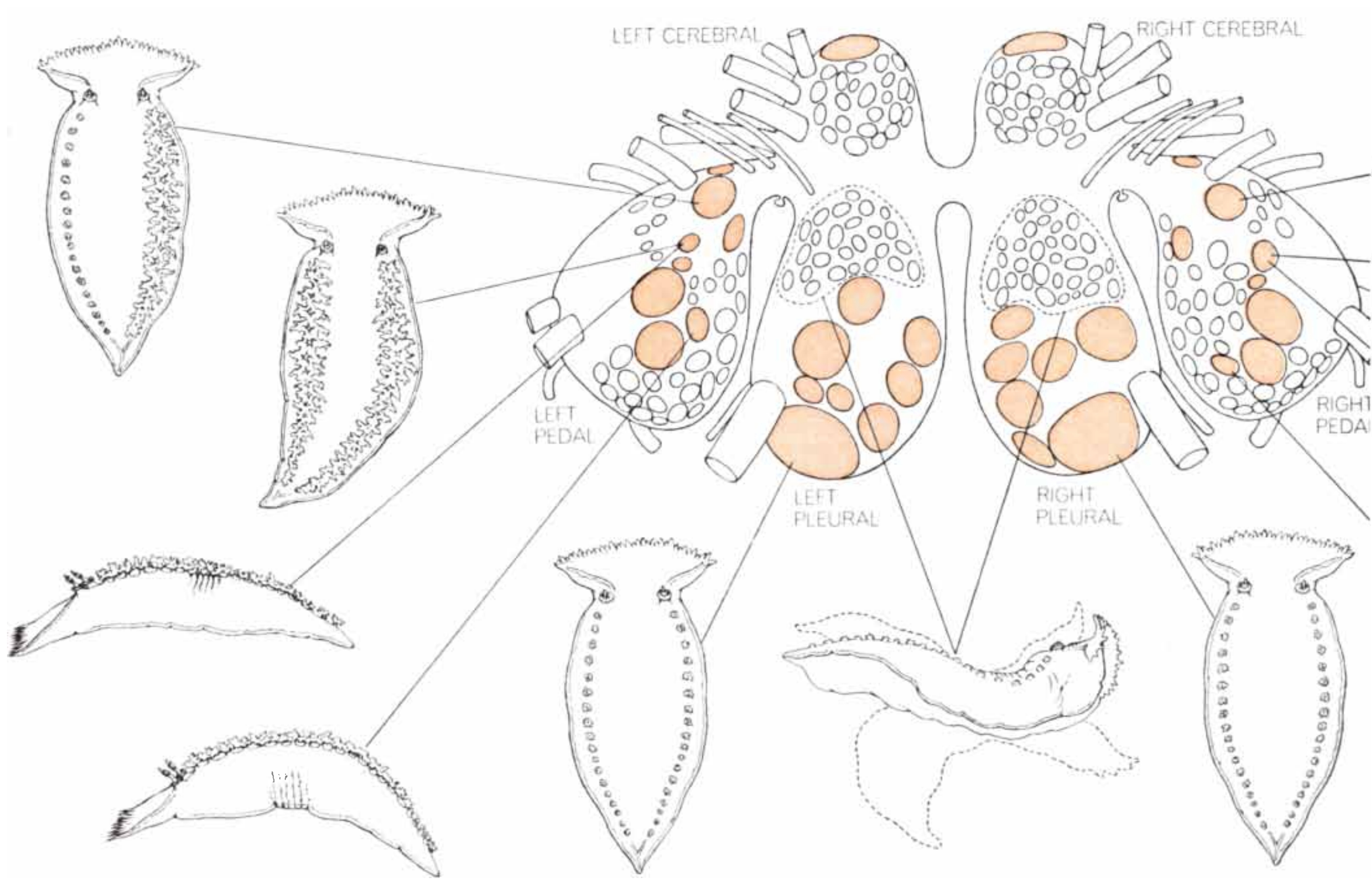
There are some long-standing questions regarding instinctive behavior of this kind. One that has been debated for nearly a century has to do with the overall performance of the activity. Does the brain drive the entire sequence of movements in accordance with a built-in general plan or does the behavior simply consist in a chain of reflexes, each one successively giving rise to the next? In the case of *Tritonia's* escape-swimming activity, for example, the latter theory would suggest that the animal's initial movement of withdrawal (after being touched by a starfish) may excite proprioceptors in the muscles to send impulses to brain cells that then direct elongation of the body, which in turn stimulates other brain cells to initiate swimming movements by other muscles, and so on. Thus the carrying out of the sequence would depend on actual movements of the muscles successively involved.

The reflex-chain hypothesis has recently lost support. Evidence has been accumulating that acts of locomotion such as flying, walking and swimming are driven by built-in circuits in the central nervous system, at least in simple animals [see "The Flight-Control System of the Locust," by Donald M. Wilson; SCIENTIFIC AMERICAN, May, 1968]. And this view is now emphatically confirmed by our work on *Tritonia.*

Derek Dorsett, working with me in our laboratory at Friday Harbor, made a significant discovery during a study of the animal's isolated brain. He found that a brief volley of shocks applied to certain peripheral nerve trunks of the brain often produced a series of from two to six bursts of impulses in certain cells of the pedal ganglia. These turned out to be very similar both in timing and in extent to the bursts generated in the same cells in intact animals during escape swimming. Further experiments on the isolated brain showed that many cells known to be involved in driving various muscle activities responded to electric shocks with series of impulse bursts. The patterns of bursts could also be produced in the pedal-ganglia cells by brief electrical stimulation of the trigger cells near the central commissure. To our great surprise the isolated brain appeared to be capable of playing back the complete escape-swimming sequence. Since the brain was divorced from any possible feedback from muscles or peripheral parts of the nervous system, the coordinated firing of its cells in the swimming pattern was obviously generated by circuitry within the brain itself.

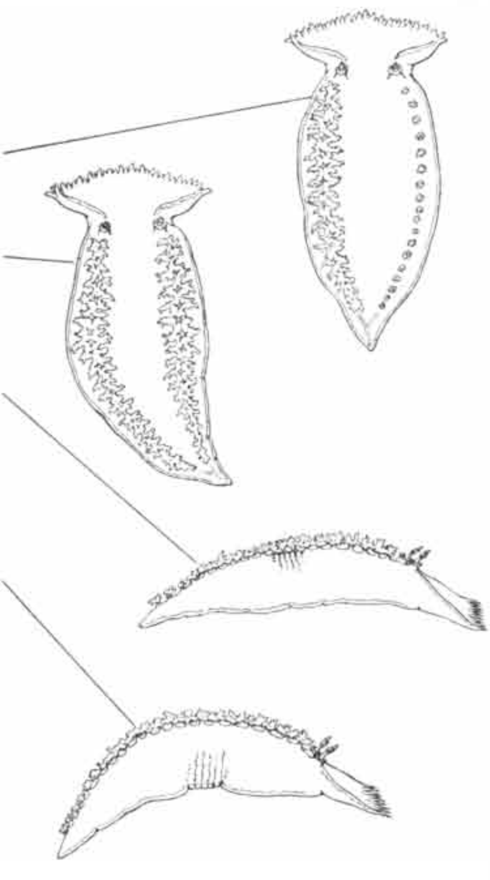
This does not necessarily mean that under normal circumstances the brain receives no sensory feedback from the activities of the animal's muscles or other peripheral organs. It is quite possible that there is some feedback, providing the brain with cues for modulating and coordinating subtle details of the escape behavior.

We cannot yet draw a complete diagram of the circuitry in the brain that drives *Tritonia's* escape swimming behavior. It is often difficult to confirm specific connections between cells, because most of the synaptic contacts (in *Tritonia* as well as in gastropod mollusks general-



KEY BRAIN CELLS and the body movements that result when they fire are identified. The bilateral symmetry evident in the distribution of cell pairs on opposite sides of the brain is also maintained at the functional level. Analogous muscular activities on the left and right sides of the body are controlled by the neurons of symmetrical pairs located respectively on the left and right pedal ly) are far from the cell bodies in which the electrodes are placed and transmission of impulses from one cell to another cannot always be observed directly. We can, however, detect interactions and infer connections between cells by various means, such as using electrodes to obtain simultaneous records of activity from several cells (as many as six) at once. These records show the phase relations of the several cells in guiding swimming activity and suggest patterns of connectivity.

There is reason to be confident that within a few years the cellular exploration of the nervous systems of *Tritonia* and other simple animals will provide a clear enough understanding of their nervous apparatus and mechanisms to describe these systems in the definitive terms usually reserved for man-made machines. These investigations should also help greatly in determining the general relations between the brain and behavior in the vast number of simple animal species comprising most of the animal kingdom—and ultimately in more complex animals.



ganglia. Neurons on pleural ganglia generally control bilateral responses; one neuronal group triggers the escape response.

THE FASTEST COMPUTER

ILLIAC IV is made up of 64 independent processing units that by operating simultaneously will be capable of solving complex problems in a fraction of the time needed by any other machine

by D. L. Slotnick

The computer ILLIAC IV, which is now nearing completion, is the fourth generation in a line of advanced machines that have been conceived and developed at the University of Illinois. ILLIAC I, a vacuum-tube machine completed in 1952, could perform 11,000 arithmetical operations per second. ILLIAC II, a transistor-and-diode computer completed in 1963, could perform 500,000 operations per second. ILLIAC III, which became operational in 1966, is a special-purpose computer designed for automatic scanning of large quantities of visual data. Since it processes nonarithmetical data it cannot be compared with the earlier ILLIAC's in terms of operational speed. ILLIAC IV, employing the latest semiconductor technology, is actually a battery of 64 "slave" computers, capable of executing between 100 million and 200 million instructions per second. Even that basic rate, although it is faster than that of any other computer yet built, does not express the true capacity of ILLIAC IV.

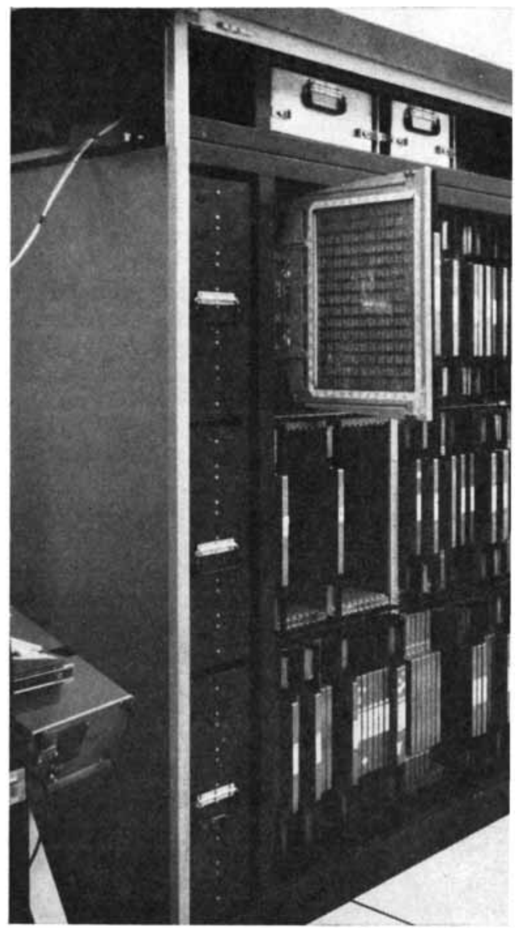
Unlike its three predecessors and all computers now on the market, which solve problems by a series of sequential steps, ILLIAC IV is designed to perform as many as 64 computations simultaneously. For such a computing structure to be utilized efficiently the problem must be amenable to parallel, rather than sequential, processing. In actuality problems of this kind constitute a considerable part of the total computational spectrum, ranging from payroll calculations to linear programming to models of the general circulation of the atmosphere for use in weather prediction. For example, a typical linear-programming problem that might occupy a large present-generation computer for six to eight hours should be solvable by ILLIAC IV in less than two minutes—a time reduction of at least 200 to one.

Subsystems for ILLIAC IV are being manufactured in a number of plants and are being shipped to the Burroughs Corporation in Paoli, Pa., for final assembly and testing. When the machine is finished a few months from now, it will be available over high-speed telephone lines to a variety of users, including the Center for Advanced Computation of the University of Illinois.

The ultimate limitation on the operating speed of a computer designed to operate sequentially [*see illustration on page 81*] is the speed with which a signal can be propagated through an electrical conductor. In practice this is somewhat less than the speed of light, which takes one nanosecond (10^{-9} second) to travel about one foot. Although integrated circuits containing transistors packed together with a density ranging from several hundred to several thousand per square inch have helped greatly to reduce the length of interconnections inside computers, designers have been increasingly aware that new kinds of logical organization are needed to penetrate the barrier set by the speed of light.

Over the past 10 years designers have introduced a number of variations on the strictly sequential mode of operation. One stratagem has been to overlap the operation of the central processing unit and the operation of input-output devices (such as magnetic-tape readers and printers). By means of a fine-grained separation of the computer's functional units a high degree of overlapping has been attained. Current efforts in "pipelining" the processing of "operands" will allow a further significant increase in speed.

Overlapping and pipelining, however, are both fundamentally limited in the advances in speed they can provide. The approach taken in ILLIAC IV surmounts fundamental limitations in ultimate computer speed by allowing—at least in principle—an unlimited number of computational events to take place simultaneously. The logical design of ILLIAC IV is patterned after that of the SOLOMON computers, prototypes of which were



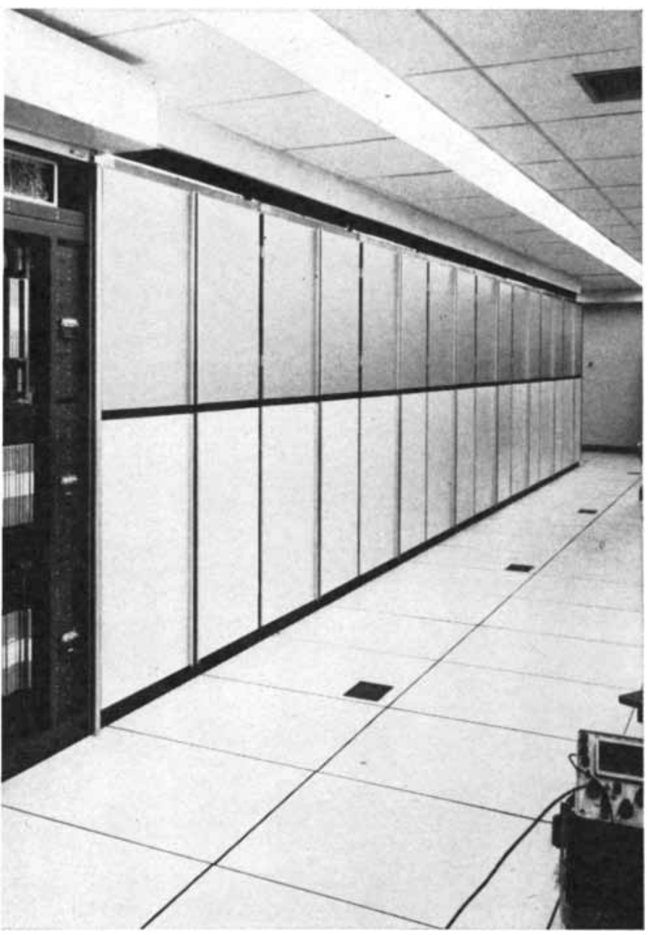
COMPUTER ILLIAC IV is nearing completion at the Great Valley Laboratories of the Burroughs Corporation in Paoli, Pa. Unlike conventional computers, which carry out logical and arithmetical operations in

built by the Westinghouse Electric Corporation in the early 1960's. In this design a single master control unit sends instructions to a sizable number of independent processing elements and transmits addresses to individual memory units associated with these processing elements ("processing-element memories"). Thus, while a single sequence of instructions (the program) still does the controlling, it controls a number of processing elements that execute the same instruction simultaneously on data that can be, and usually are, different in the memory of each processing element [*see top illustration on page 82*].

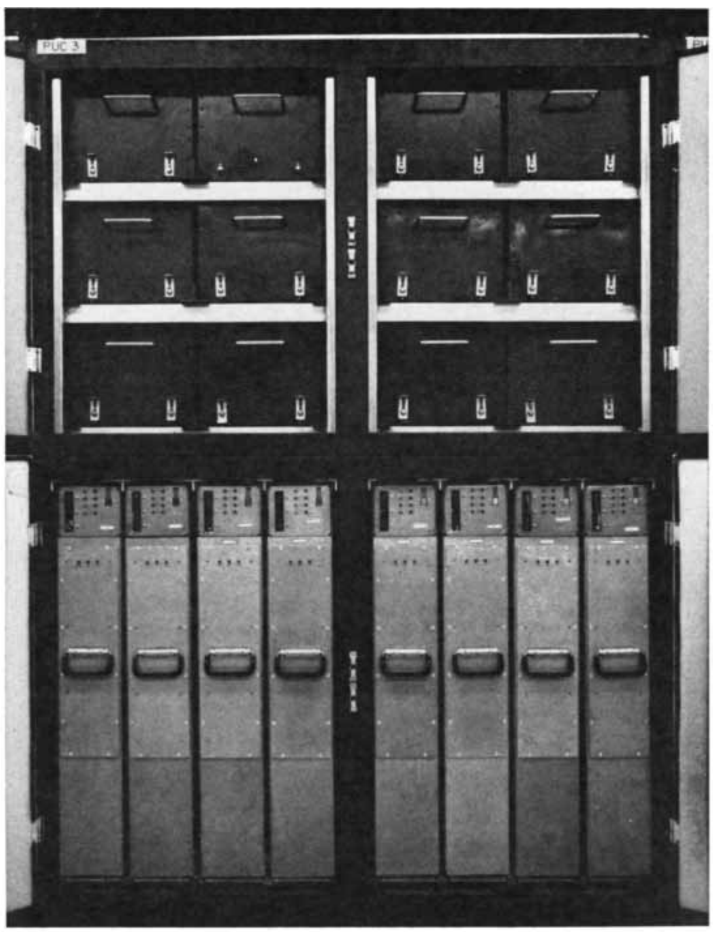
Each of the 64 processing elements of ILLIAC IV is a powerful computing unit in its own right. It can perform a wide range of arithmetical operations on numbers that are 64 binary digits (bits) long, where a digit is either 0 or 1, corresponding to the two "positions" of an electronic device with two stable states. These numbers can be in any one of six possible formats; the number can be processed as a single number 64 bits long with either a fixed or a "floating" point (corresponding to the decimal point in decimal notation), or the 64 bits can be broken up into smaller numbers of equal length. Each of the memory units has a capacity of 2,048 64-bit numbers. The time required to extract a number from memory (the access time) is 188 nanoseconds, but because additional logical circuitry is needed to resolve conflicts when two or more sections of ILLIAC IV call on memory simultaneously, the minimum time between successive operations of memory is increased to 350 nanoseconds.

Each processing element has more than 100,000 distinct electronic components assembled into some 12,000 switching circuits. A processing element together with its memory unit and associated logic is called a processing unit [*see illustrations on next two pages*]. In a system containing more than six million components one can expect a component or a connection to fail once every few hours. For this reason much attention has been devoted to testing and diagnostic procedures. Each of the 64 processing units will be subjected regularly to an extensive library of automatic tests. If a unit should fail one of these tests, it can be quickly unplugged and replaced by a spare, with only a brief loss of operating time. When the defective unit has been taken out of service, the precise cause of the failure will be determined by a separate diagnostic computer [*see top illustration on page 80*]. Once the fault has been found and repaired the unit will be returned to the inventory of spares.

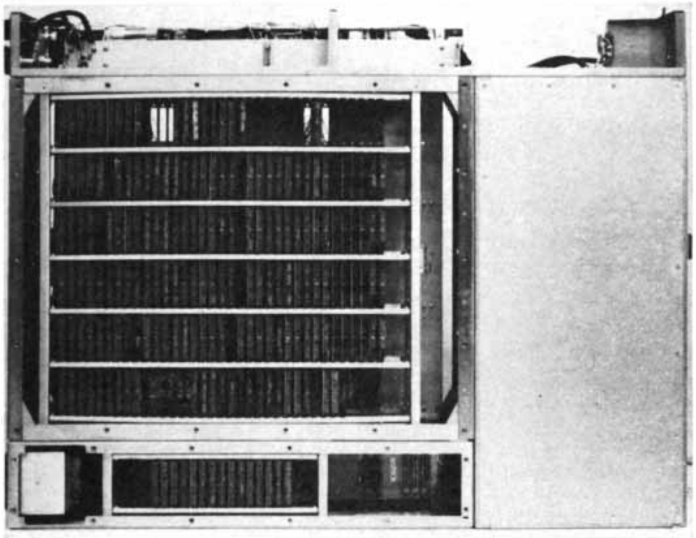
ILLIAC IV could not have been designed at all without much help from other computers. Two medium-sized Burroughs B 5500 computers worked almost full time for two years preparing the artwork for the system's printed circuit boards and developing diagnostic and testing programs for the system's logic and hardware. These formidable design, programming and operating efforts

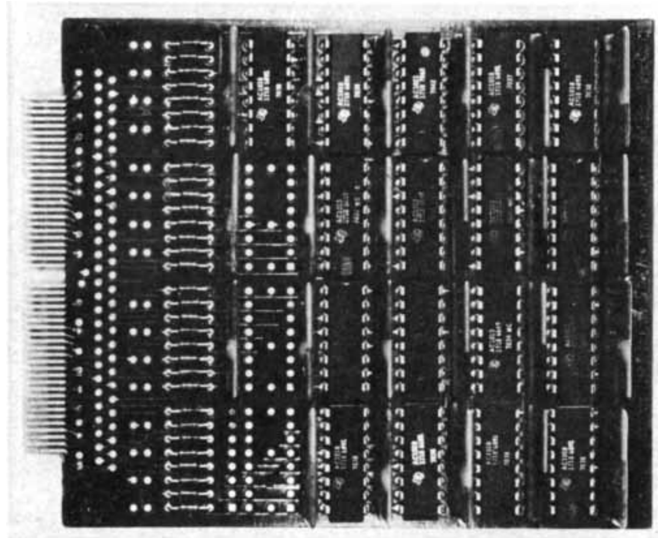


strict sequence, ILLIAC IV will solve complex problems in an all-at-once manner by coordinating the simultaneous operation of 64 "slave" computers, or independent processing units. ILLIAC IV was conceived and developed at the University of Illinois Center for Advanced Computation.



OPEN DOORS OF ILLIAC IV reveal vertical cases holding eight of the big machine's 64 independent but centrally controlled processing units. The 12 drawers at the top of the picture hold the power-supply modules associated with the eight processing units. A group of four processing units lies behind each of the 16 bottom doors in the photograph at the left.



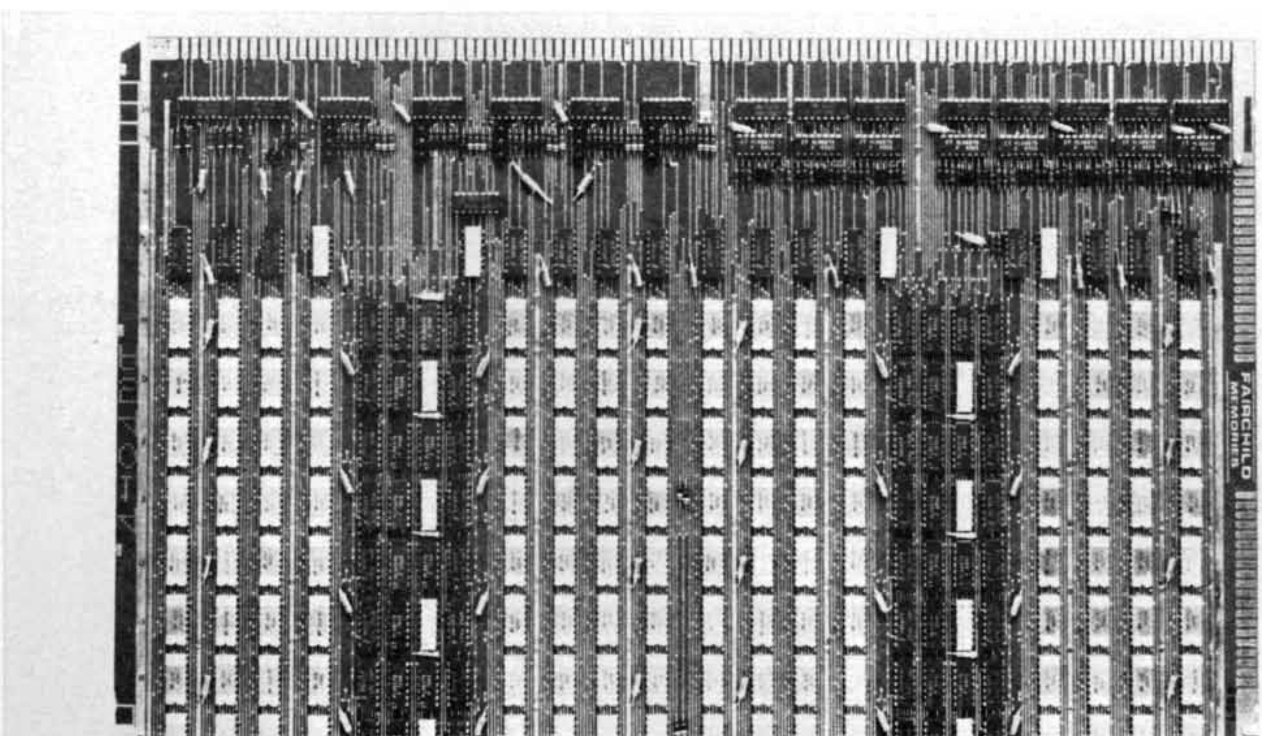


BACK-PLANE ASSEMBLY (*far left*) of one of ILLIAC IV's 64 processing elements contains up to 210 printed circuit boards arranged in six rows of 35 columns. Each circuit board (*second from left*) holds up to 20 "dual-in-line" packages (four rows by five columns) as well as some other electronic components such as resistors. Each dual-in-line package (*third from left*) contains 16 pins, which

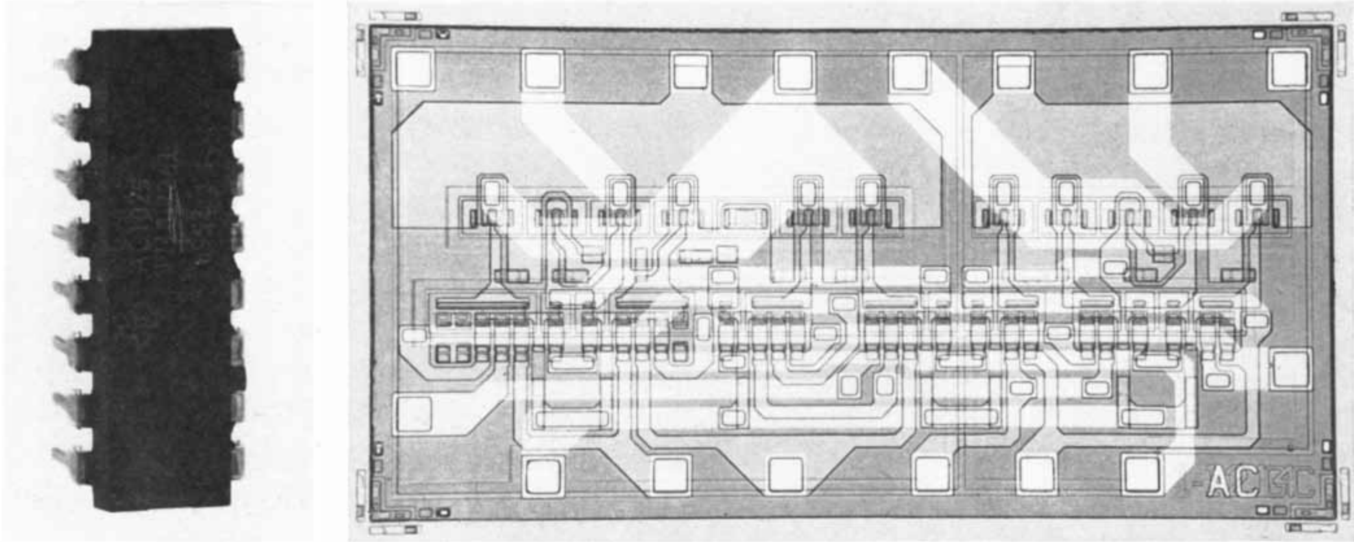
were under the direction of Arthur B. Carroll, who during this period was the project's deputy principal investigator.

In the course of a calculation it is frequently necessary to transfer data from one processing element to another; data paths are provided for this purpose [*see bottom illustration on page 83*]. In solving certain problems these data paths can be used to simulate directly the problem's geometric structure.

Although the 64 processing elements are under centralized control, only the simplest problems could be handled if the elements did not have some degree of individual control. Such control is provided by means of a "mode value," which can be set by each processing element and which depends on the different data values unique to each element. The program sets the mode value that identifies

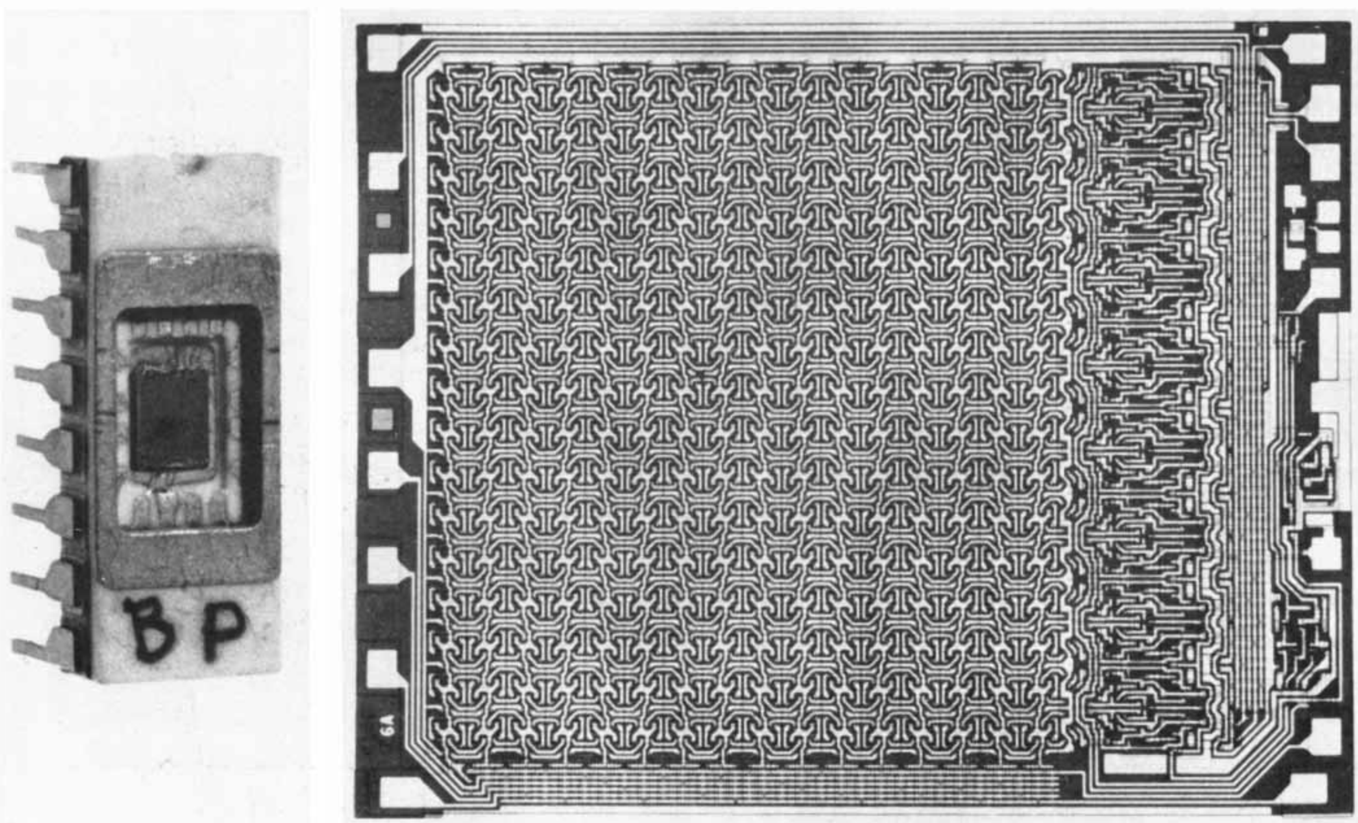


MEMORY ARRAY BOARD (*left*) is one of four that together constitute the high-speed, 131,072-bit memory associated with each of the 64 processing elements in ILLIAC IV. Each board holds up to 128 dual-in-line packages. Each package (*middle*) holds one chip and

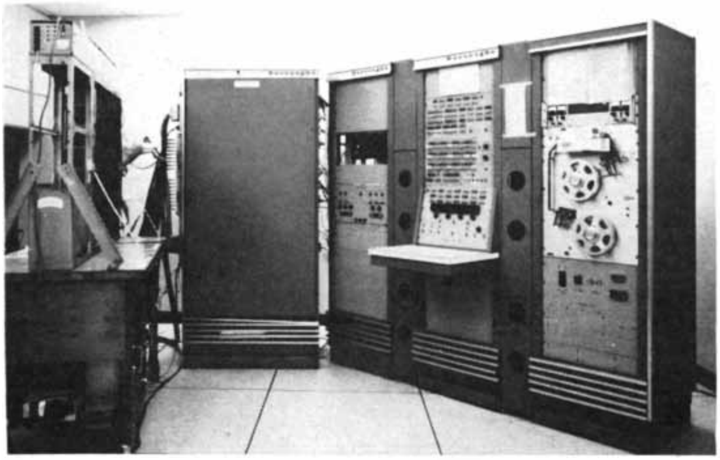


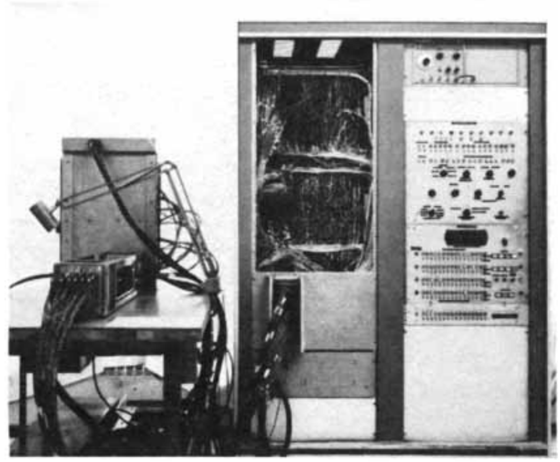
connect to an integrated circuit built up on a single chip of silicon measuring .095 by .05 inch. The integrated circuit, magnified 55 diameters at the far right, contains 34 transistors organized into seven "logic gates." The circuit chips are manufactured by Texas Instruments Incorporated. In all more than a quarter of a million chips will be used in ILLIAC IV's 64 processing elements.

those processing elements whose state (as defined by their mode value) enables them to respond to a given instruction or sequence of instructions. The elements not in this state are turned off. As a simple example, suppose at the start of a problem all mode values are set to 1, or "on." Now the program causes the control unit to "broadcast" to all 64 processing elements: Search your memory for *X* (some particular value). Each element carries out the search, and any element finding the value *X* sets its mode value to 0, or "off." The control unit may now issue a sequence of instructions to be performed only by those elements whose mode value is still 1, which allows them to keep operating. Similarly, the contents of two registers within a processing element can be compared, and the mode value can be set on the outcome of the

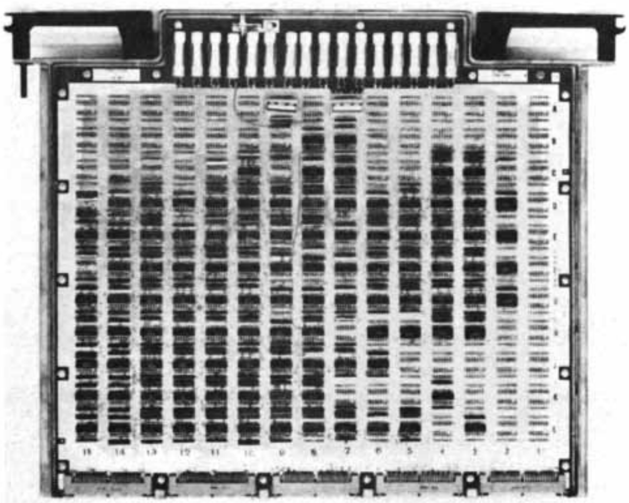


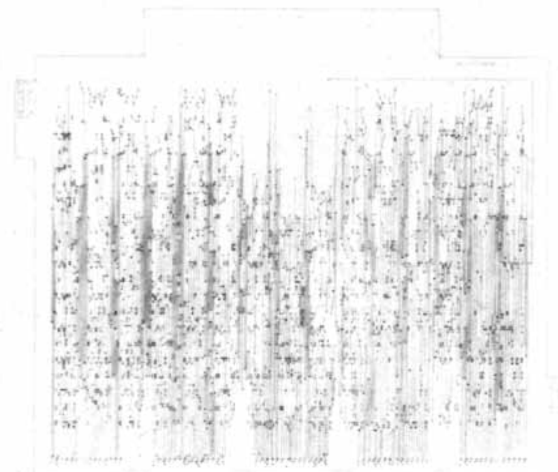
each chip contains integrated semiconductor circuits (*right*) with a storage capacity of 256 bits. The chips, each containing 2,485 transistors, resistors and diodes, were developed by the Semiconductor Division of Fairchild Camera and Instrument Corporation.

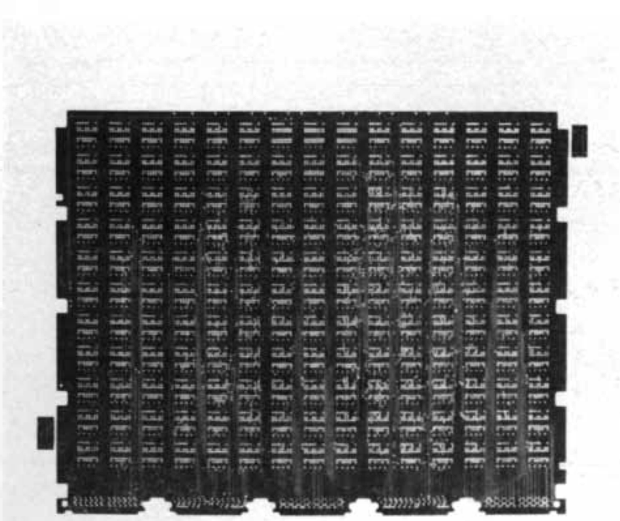


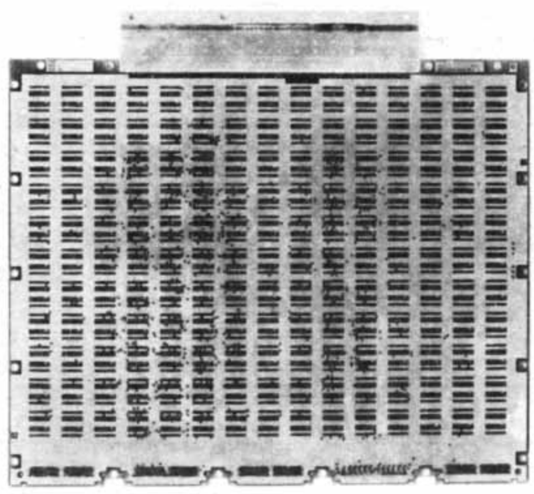


DIAGNOSTIC COMPUTERS, called exercisers, are housed in the cabinets at the right in each photograph. When one of ILLIAC IV's processors or memory units fails, it is immediately unplugged and replaced with a spare unit. The exact cause of the failure is then determined by a diagnostic computer. A defective processor has been unplugged and rolled over to the diagnostic computer in the photograph at the left; a defective memory unit is being examined by a different diagnostic computer in the photograph at the right.









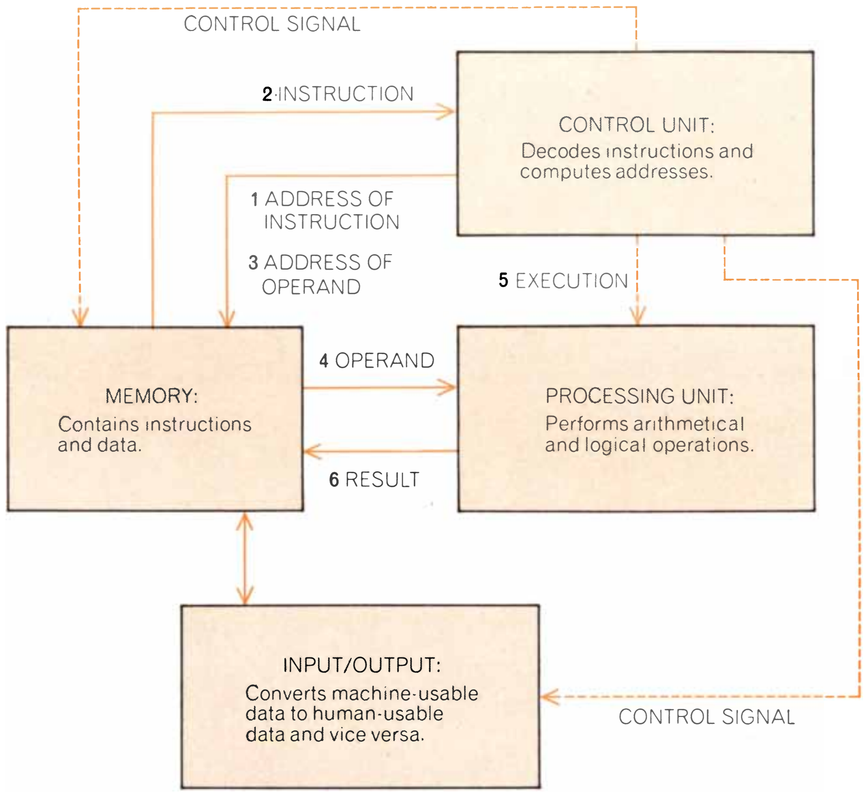
CONTROL-UNIT CARD (*top left*) is laminated from 12 separate layers that embody the complex wiring pattern for interconnecting several thousand electronic components. Three of the glass photographic positives of wiring patterns and etched copper wiring layers are shown in the other photographs. ILLIAC IV requires 64 control-unit cards, each of which can be removed for test or replacement.

comparison. Mode values are also used to determine when an iterative calculation should be terminated or when quantities have exceeded specified numerical limits. In short, mode values are the principal means for imposing a data-dependent, logical structure on a program.

In addition to the high-speed primary memories associated with each processing element, ILLIAC IV has two memories that are somewhat slower but have capacities that are considerably larger. The total capacity of the 64 primary memories is 64 × 2,048, or 131,072, numbers, each 64 bits in length. Thus the total high-speed storage is some 8.4 million bits. Most of the problems suitable for ILLIAC IV will require data capacities far exceeding this primary storage.

The additional data can be held either in a rotating-disk magnetic memory or in a new "archival" memory whose writing mechanism is a laser beam. The rotating-disk memory has a capacity of a billion bits, or about 120 times the capacity of the primary memory. The disk has 128 tracks, each with its own reading and recording head. The access time is determined by the time required for the disk to rotate into the position where the desired datum is under one of the fixed heads. Since the disk revolves once in 40 milliseconds, the average access time is 20 milliseconds, which is about 100,000 times slower than the access time of the primary memory. Once the disk is in position, however, data can be transferred to any of the 64 primary memories at the rate of half a billion bits per second, or roughly 100 times the rate at which data can be transmitted over a standard television channel. The archival memory, which has a capacity of a trillion bits, has a longer access time and a lower data-transfer rate [*see top illustration on page 83*].

These memory subsystems plus the more conventional peripheral equipment (punched cards, disk and tape units, printers, displays and so on) are under the direction of a medium-size general-purpose computer, the Burroughs B 6500 [*see bottom illustration on next page*]. This computer also bears the major responsibility for translating programs from the various programming languages available to the users into the detailed, hardware-determined language of the computer itself.



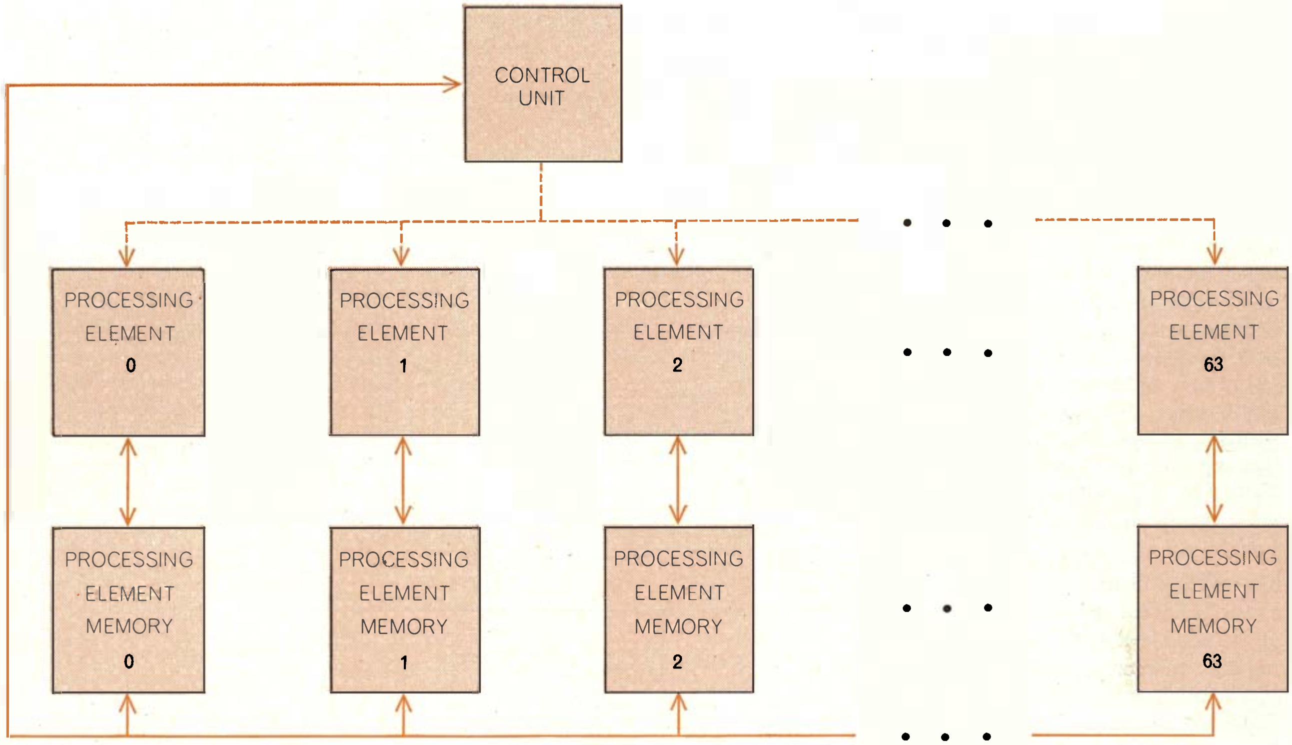
CONVENTIONAL COMPUTER is organized to carry out operations in sequence. A counter in the control unit determines the address of the next instruction in the sequence to be executed and transmits the address to the memory (*1*). The memory returns the instruction to the control unit (*2*). The instruction contains the address in the memory of the data (operand) on which an arithmetical or logical operation (also specified) is to be performed. This address is sent to the memory (*3*). The memory furnishes the selected operand to the processing unit (*4*). The control unit then transmits to the processor a sequence of electronic signals that contains the fine structure of the arithmetical or logical operation required by the program (*5*). The calculated result is then stored at a specified location in memory (*6*) for use in a subsequent operation or for conversion to printed form for the user of the machine. Advanced computers carry out this entire sequence in a few millionths of a second. Billions of repetitions may be needed to solve a complex problem.

Let us now examine how ILLIAC IV can be used to solve a simplified problem in mathematical physics. The problem belongs to the very large class of problems whose calculation can be performed in an "all at once" manner, using either ordinary or partial differential equations. The problem we shall trace requires the solution of Laplace's partial differential equation describing the distribution of temperature on the surface of a slab. Even the reader who is unfamiliar with such equations should be able to follow this example because the method for reaching a solution relies completely on the commonsense notion that the temperature at any point on the slab tends to become the average of the surrounding values.

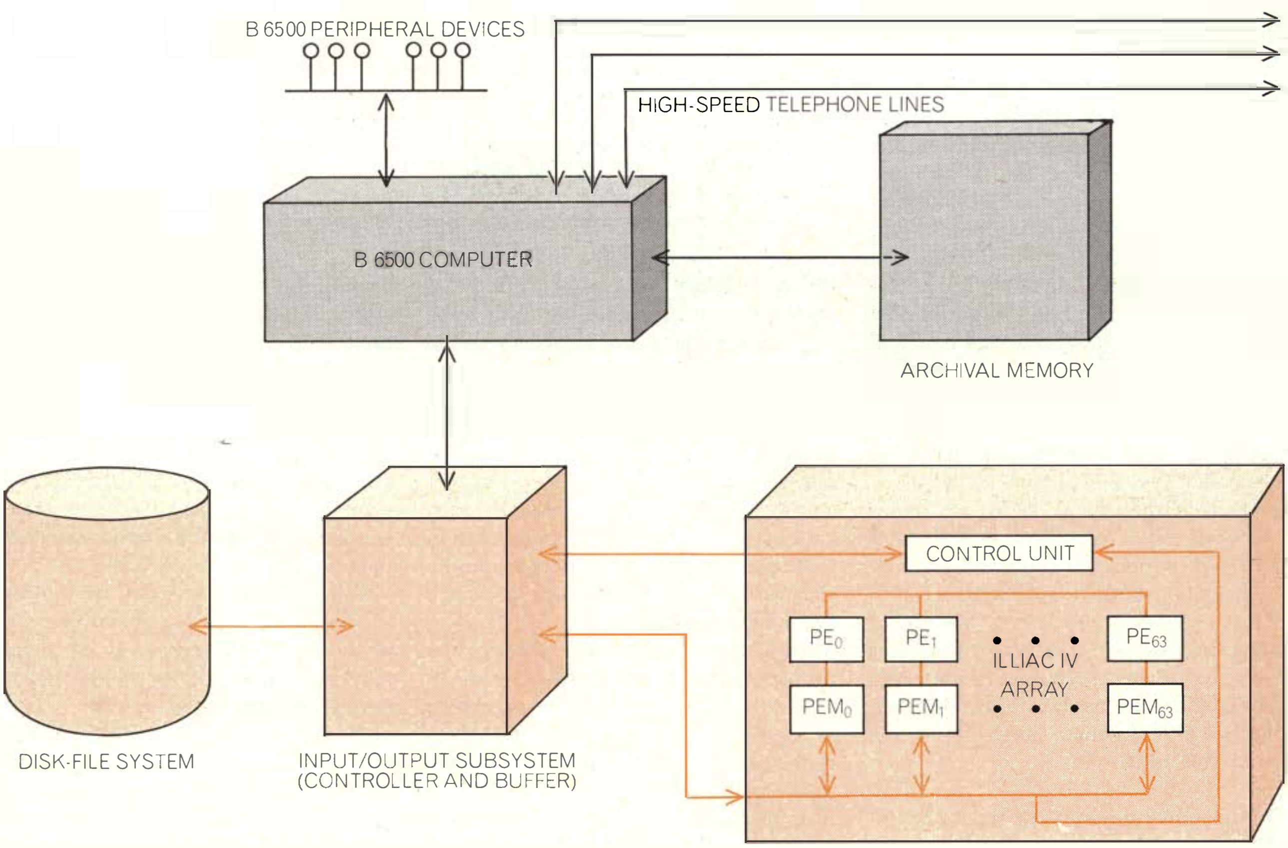
Laplace's equation for solving the problem is $\delta^2U/\delta x^2 + \delta^2U/\delta y^2 = 0$, where U corresponds to the temperature at a given position specified by the coordinates x and y on the surface of the slab. In this example we are asked to imagine that we are dealing with a rectangular slab of some material whose four edges are maintained at different temperatures. Eventually all the points on the surface of the slab will reach a steady-state temperature distribution reflecting the way heat flows from hotter edges to the cooler ones. The temperatures at the edges of the slab, which are held constant, are called the boundary conditions. If we use an x-y coordinate system to designate the location of any point on the surface of the slab, we can say that the temperature at any point is a function of x and y. In other words, every point x,y on the slab has associated with it a temperature $U(x,y)$.

When one uses a digital computer to solve this problem, one cannot, of course, obtain the temperature at an infinite number of points. The standard procedure is to digitize the variables x and y so that the slab is covered by a mesh, each square of the mesh being h units on a side. For the sake of simplicity we shall assume that our slab is a square and that it has been digitized into 64 x,y values or mesh points [*see illustration on pages 84 and 85*].

The method of solution can now be stated very simply: The temperature at



PARALLEL ORGANIZATION OF ILLIAC IV enables the control unit to orchestrate the operation of 64 processing elements, each with its own memory. There is a large class of mathematical problems that can be solved in an all-at-once manner by independent processors operating simultaneously, each about twice as fast as the single processor in an advanced sequential computer.



BLOCK DIAGRAM OF ILLIAC IV SYSTEM shows how the ILLIAC's control unit, together with its 64 processors and primary memory units, will be connected to ancillary pieces of equipment. A secondary memory is provided by a disk-file system with a capacity of a billion bits (binary digits). A tertiary memory is provided by a new "archival" memory system, which uses a laser beam for reading and writing. Accessed through a medium-size Burroughs B 6500 computer, it will have storage for a trillion bits.

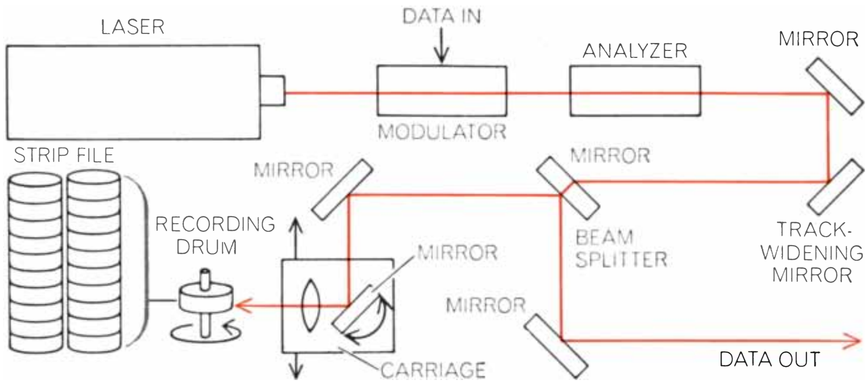
any interior mesh point is the average of the temperatures of the four closest mesh points. Thus the value of $U(x,y)$ equals the sum of four neighboring values of $U(x,y)$ divided by four. When this equation is made true for all points, there can be only one correct value for each point. This method is called "relaxation."

When the relaxation method is applied with a sequential, or conventional, computer, the usual procedure is to start at the top left of the slab and apply the basic equation at each interior point moving from left to right along each row of points and proceeding downward row by row. Since the 28 boundary points in our example are already specified, the equation would have to be applied 36 times (64 minus 28) to produce one relaxation of the relaxation method. As succeeding relaxations are performed on the set of mesh points the values of the temperatures converge to the exact solution. When values for two successive relaxations are very close to each other (within a specified error tolerance), one stops the process and says that the steady-state solution has been reached.

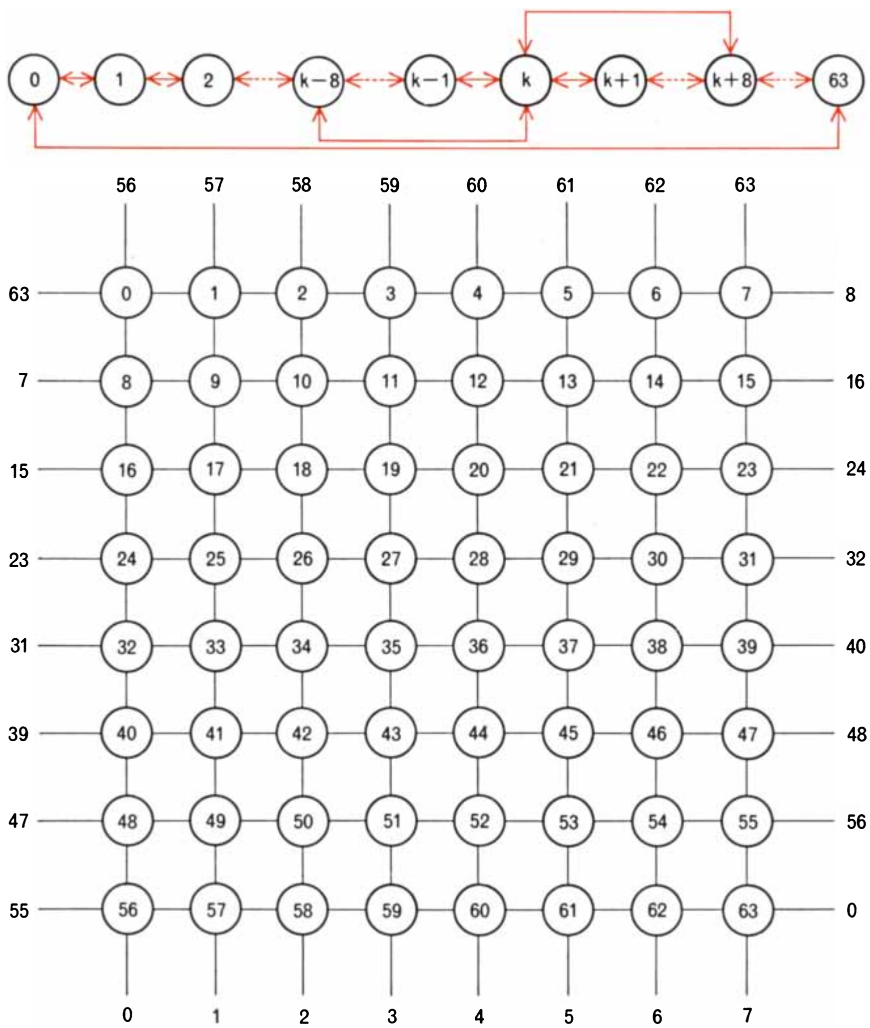
Let us now consider how this same problem could be solved by parallel processing on ILLIAC IV. If one stored each value of U in a separate processing element, all 36 inner values could be calculated simultaneously. A program could be written to compute new values for $U(x,y)$ not from top left to bottom right but all at once. When the first set of relaxation values for all 36 inner points has been obtained by simultaneous calculation, these values are available for the second relaxation.

Not only are the two algorithms, or mathematical routines, different for sequential and parallel computation but also the way the temperatures converge is different [*see illustration on pages 86 and 87*]. In the sequential method the temperatures at bottom right converge faster to the exact solution than those at top left. This happens because in sweeping from top left to bottom right the last computations in each relaxation sequence contain more new data than the computations made at the start of the sequence.

When the parallel algorithm is used, the values closest to the edges converge faster than those in the center of the mesh. The reason is that the outer values are closest to the boundary values, and at each iteration they have more new data available than the inner values. The convergence process can be likened to freezing. The sequential algorithm begins freezing at bottom right and proceeds to top left; the parallel algorithm begins



ARCHIVAL MEMORY is a new high-capacity secondary memory, developed by the Precision Instrument Company. The beam from an argon laser records binary data by burning microscopic holes in a thin film of metal coated on a strip of polyester sheet, which is carried by a rotating drum. Each data strip can store some 2.9 billion bits, the equivalent of 625 reels of standard magnetic tape in less than 1 percent of the volume. The "strip file" provides storage for 400 data strips containing more than a trillion bits. The time to locate data stored on any one of the 400 strips is about five seconds. Within the same strip data can be located in 200 milliseconds. The read-and-record rate is four million bits a second.



ARRAY OF 64 PROCESSING ELEMENTS in ILLIAC IV is connected in a pattern that can be regarded in either of two ways, which are topologically equivalent. The elements can be viewed as a linear string (*top*) with each processing element connected to its immediate neighbors and to neighbors spaced eight elements away. Equivalently, one can regard the processing elements as a square array (*bottom*) with each element connected to its four nearest neighbors. One can imagine the array rolled into a cylinder so that the processing elements in the top row connect directly to those in the bottom row. The last processing element in each row is connected to the first in the next row to produce a linear sequence.

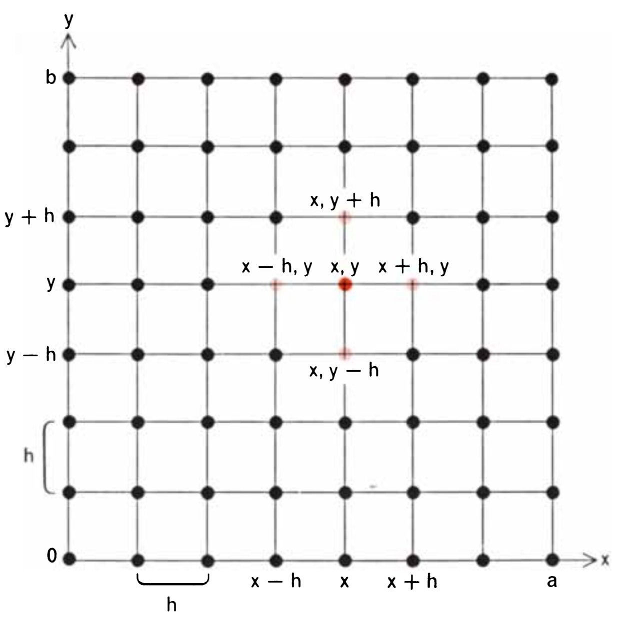
freezing around the edges and proceeds toward the center.

The time saved by using the parallel algorithm rather than the sequential one depends on the number of iterations needed to produce convergence. If both algorithms require the same number of iterations and both compute the same number of interior values, *P* (or 36 in the case of the example above), the parallel process is faster by a factor of *P*. Since the parallel process uses less new information for each iteration, however, it will normally take more parallel iterations to produce the same degree of accuracy as a sequential calculation. Inasmuch as ILLIAC IV has 64 "channels" available for processing iterations in parallel, it is up to 64 times faster than a sequential computer of comparable speed. This advantage in overall speed far outweighs the few extra iterations necessary to obtain a solution equal in accuracy to that produced by sequential processing.

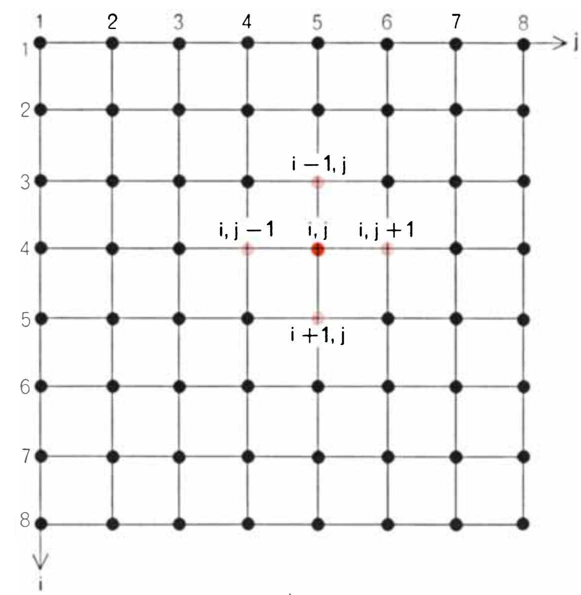
The reader may well ask at this point: "To what purpose can a computer of this large size be applied, and, indeed, is it necessary?" Or more pointedly he may ask: "Is it worth $30 million of public funds in these days of so many identified, competing needs?" Each of us must determine the answer for himself after examining the potential value of the machine. Let us, therefore, look at some of the applications.

Among the intended tasks for ILLIAC IV is linear programming, a mathematical technique for allocating the use of limited resources to maximize or minimize a specified objective. The resource limitations (constraints) are expressed as linear inequalities in which the variables are quantities of resources. The objective is specified as a linear function of these variables. Typical linear-programming problems presented to computers involve hundreds or even thousands of variables. Examples include routing deliveries to minimize distance traveled or to maximize deliveries per trip; blending, mixing, cutting or trimming raw materials to minimize waste or to maximize output value; selecting production methods that minimize cost or maximize output; scheduling production facilities to minimize delay or to maximize throughput. ILLIAC IV will be able to solve in reasonable time much bigger problems than have been attempted in the past. This capability flows from the use of parallel computation and the high data-transfer rate of the ILLIAC IV memory disk. The linear-programming problem mentioned above that ILLIAC IV should be able to solve in less than two minutes (but which would take six to eight hours on a present-generation computer) is one that has 4,000 constraints and 10,000 variables.

A problem of this order of difficulty is now under active study at the University of Illinois under the direction of Ian W. Marceau. It involves optimizing the output of the agricultural sector of the economy, ranging in size from a large region to an entire nation. The desired objectives will reflect national policy, and they will range from production of enough food to nourish a given population to producing export crops so that a developing country can obtain foreign-exchange credits. The resources to be managed include land, labor, machinery, fertilizers, pesticides, herbicides, storage facilities and capital. As Marceau has demonstrated, linear-program-



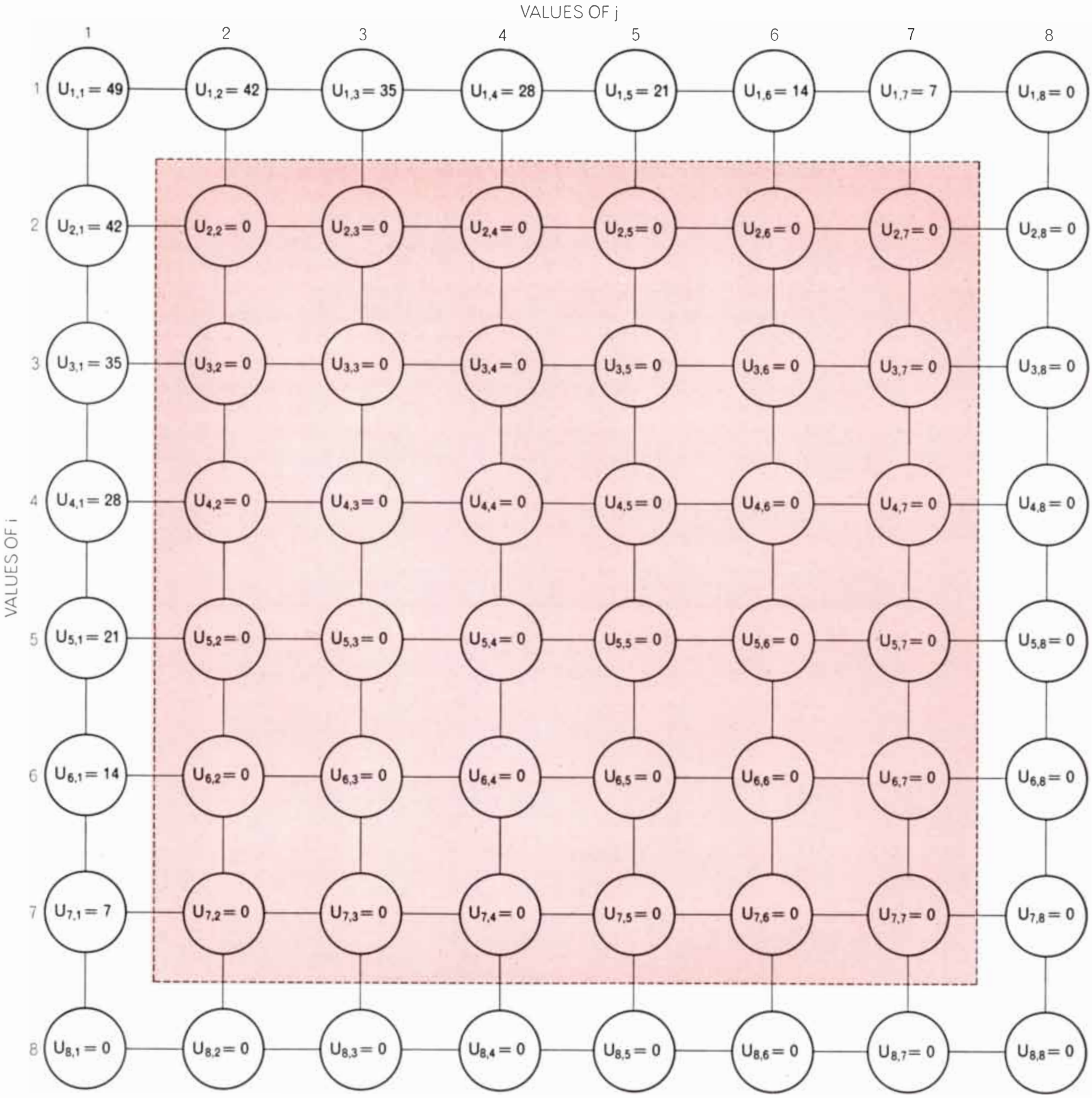
$$U(x, y) = \frac{U(x, y+h) + U(x+h, y) + U(x, y-h) + U(x-h, y)}{4}$$



$$U_{i,j} = \frac{U_{i-1,j} + U_{i,j+1} + U_{i+1,j} + U_{i,j-1}}{4}$$

PROBLEM OF FINDING TEMPERATURES ON A SLAB must be prepared for a computer by digitizing the slab into an array of points, with some arbitrary mesh spacing (*h*). The purpose of this illustration and those on the next three pages is to compare how such a problem would be solved by sequential methods with a standard computer and by parallel methods using ILLIAC IV. In this problem one imagines that the edges of a slab are arbitrarily held at certain fixed temperatures. The computer is asked to calculate the temperature at a network of interior points after the slab has reached equilibrium. Two methods of identifying the points in the network are depicted above. The more familiar method at the left expresses each point in terms of *x* and *y*. The temperature *U* at any point *x,y* is the average of the temperatures at the four nearest mesh points. The equation specifies these points in terms of *x* and *y* and the mesh spacing *h*. In programming a computer it is more convenient to use the integers *i* and *j* as positional indicators, in which case the temperature equation is rewritten as shown at the right. The temperatures at 28 points on the perimeter of the slab are the known quantities supplied to the computer (*see illustration on opposite page*). The temperatures at the 36 interior points are the unknowns. In this example all the points on the bottom of the slab and on the right edge are held at zero degrees. The values along the top and left edge vary according to position. These boundary temperatures do not change during the calculation. The ming models of a region or nation can also recognize constraints involving social costs, for example the harm done by the intensive application of nitrogenous fertilizers, the use of certain pesticides (such as DDT) or cultivation practices with long-term deleterious effects on the productivity of the land.

It must be pointed out that in order to apply linear programming to an entire economic sector one must incur considerable expense in gathering the data to be used in the model. Here too, however, the computer can help by making experimental trials and estimating the accuracy with which various input data need to be known in order to secure answers with a given level of precision. It is also possible to simulate alternative policies on the computer and estimate their effects on agricultural productivity. To test such



36 interior points are initially set to zero. When the problem is solved sequentially, the computer starts with the top left interior point $U_{2,2}$ and calculates its value using the numbers given above:

$$U_{2,2} = \frac{U_{1,2} + U_{2,3} + U_{3,2} + U_{2,1}}{4} = \frac{42 + 0 + 0 + 42}{4} = 21 .$$

The computer then calculates the value of $U_{2,3}$ using the *new* value of $U_{2,2}$ just obtained, which is 21, instead of the initial value, 0:

$$U_{2,3} = \frac{U_{1,3} + U_{2,4} + U_{3,3} + U_{2,2}}{4} = \frac{35 + 0 + 0 + 21}{4} = 14 .$$

The equation is similarly solved for the remaining 34 interior points, using at each step all the new values previously calculated. This sequence of 36 calculations is one "relaxation" of the relaxation method. If the problem were programmed for ILLIAC IV, on the other hand, each of the 36 interior points could be assigned to a separate processing element and 36 simultaneous solutions of the equation obtained. In this method the first relaxation consists of the 36 simultaneous solutions using *only* the numbers initially given. Thus the first solution of $U_{2,3}$ is $(35 + 0 + 0 + 0) \div 4 = 8.75$ rather than the value of 14 obtained in the sequential method. Succeeding simultaneous relaxations, however, can make use of values obtained previously. The way the two methods converge to yield the final answer is shown in the tables on the next page.

policies directly "in vivo" can be very costly. There is no reason why a computer program should not be the white rat or guinea pig for a proposed cure to a social problem.

Another application contemplated for ILLIAC IV is the establishment of natural-resource inventories to be used by municipal and regional planners. A Natural Resource Information System is now being developed at the University of Illinois in cooperation with the Northeast Illinois Natural Resource Service Center. The Ford Foundation has provided funds for the initial research and development program. The system will contain a wide range of information on the natural resources of a selected area: geology, hydrology, forestry and vegetation, climate, topography, soil characteristics and current land use. Marengo Township of McHenry County in Illinois has been selected for a pilot study.

The system is being designed so that it can easily be used by any decision-maker (including an individual taxpayer) regardless of his technical or administrative training. For example, an individual may want to know whether or not he can have a housing subdivision (or a tennis court or a fishpond) on his land. On the other hand, county administrators may be looking for the best site for a new hospital. The search for a hospital site could be reformulated into a series of commands that could be presented to the computer. For instance, search all tracts that lie between town *A* and town *B* and that are within two miles of route *C;* the area should be no smaller than five acres and no larger than 25 acres with the following characteristics: (1) one acre of soil capable of supporting a five-story hospital, with a gradient of less than 8 percent and not subject to flooding; (2) at least four acres (for a parking lot) that can be covered with asphalt without disturbing the underground water table; (3) trees at least 20 years old. If no tracts satisfied all these requirements, one or more of the less important conditions could be relaxed until a site was located.

The output of the information system is being designed to meet three levels of need. The simplest level will consist of a concise inventory listing. The next level will be an interpretation of the computer's search in prose that should be clear to an educated layman. The third level will be a highly technical description suitable for use by a specialist, such as a geologist or an ecologist. The objective of the information system is to shorten the planning process and to improve the quality of decisions. Although the system will use existing techniques of information retrieval, ILLIAC IV, with its speed and archival memory, will be able to analyze the stored information to a far greater depth than would be possible with any earlier computer.

Our unaugmented intellectual resources have not been capable of producing satisfactory solutions to the types of large-scale planning problems just described. It is in fact evident that we are currently faced with socially debilitating aftermaths of piecemeal planning—and nonplanning—in both of these areas. A rational 20th- (or 21st-) century society will not emerge solely on the basis of universal goodwill.

SEQUENTIAL METHOD — ONE RELAXATION

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	21.00	14.00	10.50	7.88	5.47	3.12	0
3	35	14.00	7.00	4.38	3.06	2.13	1.31	0
4	28	10.50	4.38	2.19	1.31	0.86	0.54	0
5	21	7.88	3.06	1.31	0.66	0.38	0.23	0
6	14	5.47	2.13	0.86	0.38	0.19	0.11	0
7	7	3.12	1.31	0.54	0.23	0.11	0.05	0
8	0	0	0	0	0	0	0	0

PARALLEL METHOD — ONE RELAXATION

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	21	8.75	7.00	5.25	3.50	1.75	0
3	35	8.75	0	0	0	0	0	0
4	28	7.00	0	0	0	0	0	0
5	21	5.25	0	0	0	0	0	0
6	14	3.50	0	0	0	0	0	0
7	7	1.75	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0

SEQUENTIAL METHOD — 10 RELAXATIONS

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	35.37	29.01	22.90	17.03	11.31	5.66	0
3	35	29.01	23.41	18.24	13.44	8.88	4.44	0
4	28	22.90	18.24	14.05	10.26	6.75	3.38	0
5	21	17.03	13.44	10.26	7.44	4.88	2.44	0
6	14	11.31	8.88	6.75	4.88	3.19	1.60	0
7	7	5.66	4.44	3.38	2.44	1.60	0.80	0
8	0	0	0	0	0	0	0	0

PARALLEL METHOD — 10 RELAXATIONS

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	34.27	27.05	20.53	14.81	9.60	4.74	0
3	35	27.05	19.87	14.08	9.48	5.90	2.83	0
4	28	20.53	14.08	9.06	5.62	3.22	1.49	0
5	21	14.81	9.48	5.62	3.09	1.61	0.69	0
6	14	9.60	5.90	3.22	1.61	0.73	0.28	0
7	7	4.74	2.83	1.49	0.69	0.28	0.10	0
8	0	0	0	0	0	0	0	0

SEQUENTIAL METHOD — 50 RELAXATIONS

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	36.00	30.00	24.00	18.00	12.00	6.00	0
3	35	30.00	25.00	20.00	15.00	10.00	5.00	0
4	28	24.00	20.00	16.00	12.00	8.00	4.00	0
5	21	18.00	15.00	12.00	9.00	6.00	3.00	0
6	14	12.00	10.00	8.00	6.00	4.00	2.00	0
7	7	6.00	5.00	4.00	3.00	2.00	1.00	0
8	0	0	0	0	0	0	0	0

PARALLEL METHOD — 50 RELAXATIONS

VALUES OF i \ VALUES OF j	1	2	3	4	5	6	7	8
1	49	42	35	28	21	14	7	0
2	42	35.98	29.96	23.96	17.96	11.96	5.98	0
3	35	29.96	24.94	19.92	14.92	9.94	4.96	0
4	28	23.96	19.92	15.90	11.90	7.92	3.96	0
5	21	17.96	14.92	11.90	8.90	5.92	2.96	0
6	14	11.96	9.94	7.92	5.92	3.94	1.96	0
7	7	5.98	4.96	3.96	2.96	1.96	0.98	0
8	0	0	0	0	0	0	0	0

DIFFERENT STAGES IN RELAXATION PROCESS are compared for sequential relaxations and parallel relaxations. The exact values are given in the array on the opposite page. The two methods for calculating the temperature of each of 36 interior points on a slab are described in the illustration on the preceding two pages. There one sees that a standard computer using sequential methods would obtain a value of 21 for point $U_{2,2}$ and 14 for $U_{2,3}$ in performing one relaxation. Here it is seen that after 10 relaxations by the sequential method the value of $U_{2,2}$ has climbed to 35.37 and the value of $U_{2,3}$ to 29.01. After 50 relaxations $U_{2,2}$ and $U_{2,3}$ have reached their exact values: 36 and 30. Using parallel relaxations ILLIAC IV would converge on the exact solution in a distinctly dif-

A quite different assignment for ILLIAC IV is numerical weather prediction, which early computer theorists such as John von Neumann regarded as one of the important motivations for their work. Numerical techniques developed over the past two decades are now in daily use and yield good results for periods of from 24 to 48 hours. These techniques involve the simulation of complex atmospheric processes by a mathematical model that combines extensive knowledge of the relevant physical processes with sophisticated mathematics and advanced computer technology.

The physical basis for all numerical simulations of the atmosphere is the conservation of mass, momentum and energy. These conservation principles are embodied in sets of differential equations (Laplace's equation is an example of a differential equation describing heat distribution on a slab), which cannot be solved without a computer. The physical scales of atmospheric phenomena that are simulated on the computer range from the microphysical processes of clouds to the continental motions of frontal systems. At the upper end of the physical scale there are general-circulation models that describe the atmosphere as a heat engine driven by the sun.

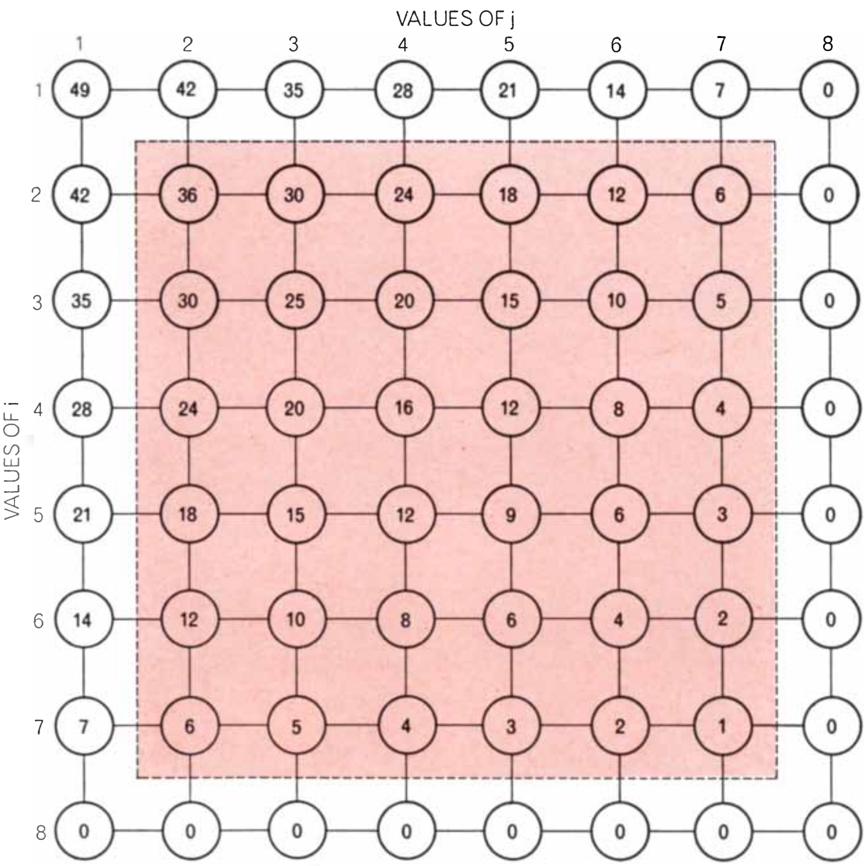
The complexity of these models is illustrated by the operational model of the atmosphere used by the National Weather Service in its daily forecasts. The atmosphere over the Northern Hemisphere is represented by six horizontal slices ranging from sea level to the stratosphere. Each slice contains 3,000 points at which initial values of wind velocity, temperature and pressure are inserted. The computer then applies the appropriate equations to predict what the velocity, temperature and pressure will be in the future at 10-minute intervals. A 24-hour forecast requires about an hour of computing time on a computer that can execute 300,000 instructions per second, or more than a billion instructions in all.

If the distance between the grid points were to be halved, the number of grid points would be quadrupled and the computer time needed for a 24-hour forecast would be increased eightfold. In other words, a third of a day would be consumed merely in making a 24-hour prediction. If the model yields significantly better short-range predictions than the 3,000-point model now in use, there is a good chance that numerical forecasts can be extended to five days with an accuracy comparable to that of the 48-hour forecasts now being generated.

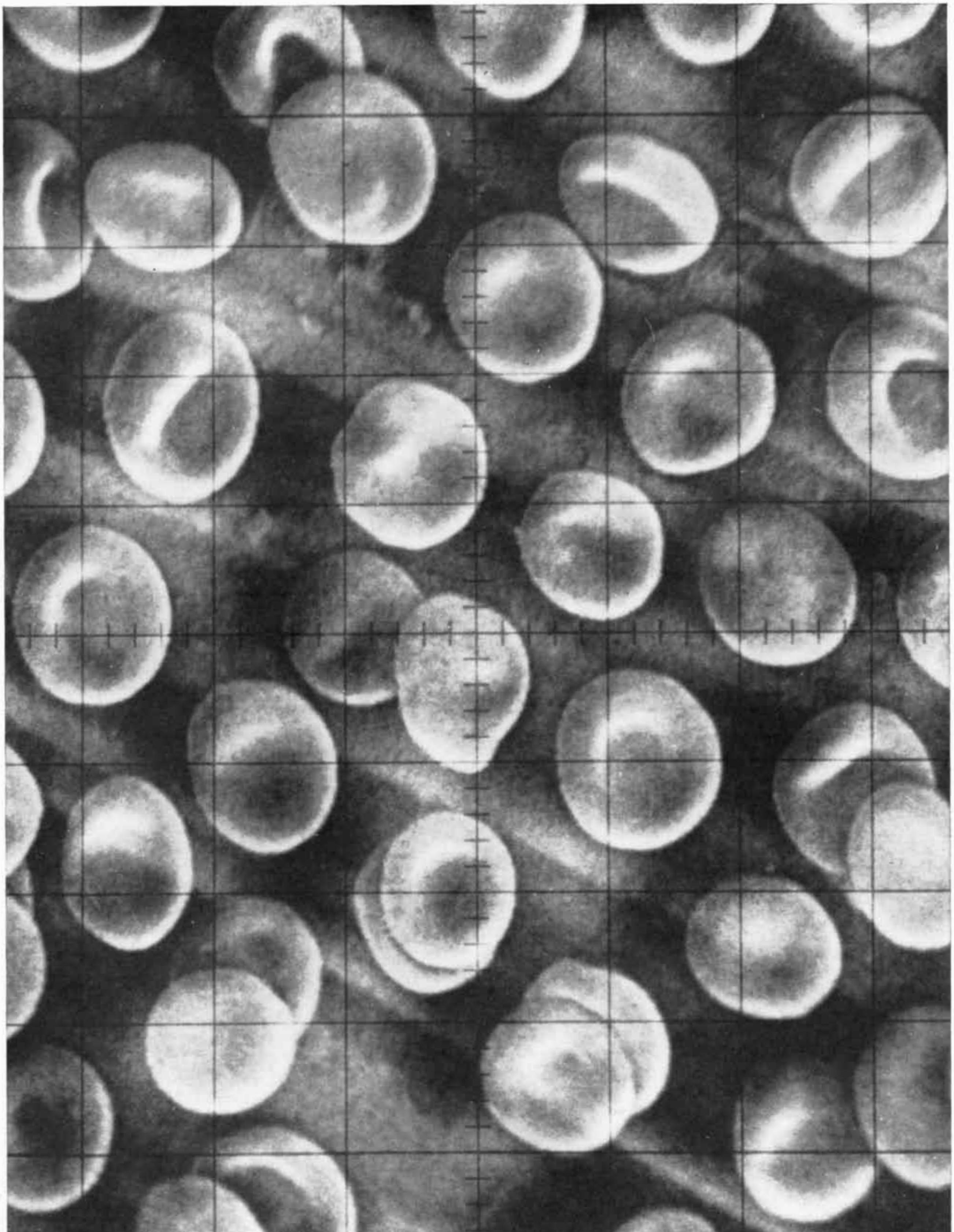
The actual computer techniques of weather forecasting can be advanced by testing them on ILLIAC IV. Until now investigators have been reluctant to experiment with a new predicting technique when it might involve many computer simulations, each of which could take up to 100 hours of computing time. When ILLIAC IV can reduce the running time from 100 hours to one hour, extensive experimentation will become feasible.

Mathematical models exist today for a large variety of physical systems and are in constant use as the basis for calculation aimed at prediction. Biological and biochemical systems have not been modeled with the same intensity of effort or success. There are a number of reasons for this. One can, for example, write a system of ordinary differential equations that might plausibly seem to describe the growth of a living cell. One can even measure initial concentrations with seemingly sufficient accuracy to do meaningful calculation. The number of equations in the system, however, corresponds to the number of genes in the chromosome, which is just too large a number to be handled in the cases of most interest. On the scale of real ecological systems, on the other hand, population models can be developed but measurements are extremely elusive. (How many alewives are in Lake Michigan?) Calculations would have to be performed with statistical variables to estimate a population range for each species of organism. This consumes computational capacity of a higher order of magnitude than deterministic calculation. Even the methodology of such calculation poses significant theoretical problems.

To summarize, I believe computers on the scale of ILLIAC IV will remove some of the very real barriers of capacity from certain calculations that have a direct bearing on our ability to produce a rational and enduring basis for life. Counterpoised is the computer's potential to play a significant role in the depersonalization and disordering of society. Scientists must not share the neutrality of the computer to the outcome.



ferent manner. After 10 relaxations it would obtain values of 34.27 and 27.05 for $U_{2,2}$ and $U_{2,3}$ respectively. The results after 50 relaxations, however, would be virtually the same. For this particular problem the parallel method requires a few more relaxations than the sequential method to achieve comparable results. ILLIAC IV, however, will be able to carry out 36 complete relaxations (and as many as 64 given a suitable problem) in the time that a comparably fast sequential computer would need to carry out one sequential relaxation.



NORMAL RED BLOOD CELLS have a biconcave shape. They can swell or shrink considerably if the outside solution is changed in such a way that osmotic pressure causes water to move into or out of the cells. Normally the cells are in osmotic balance with their environment. In this electron micrograph, made by Irene Piscopo of Philips Electronic Instruments, the enlargement is 4,570 diameters. The micrograph was made in connection with work being done in the laboratory of Patricia N. Farnsworth of Barnard College.

The State of Water in Red Cells

Water in these cells has long seemed to exhibit anomalous properties. Recent studies show that it is the same as other water; the apparent anomaly arises from the close association of hemoglobin molecules

by Arthur K. Solomon

Water is the primary stuff of blood. Indeed, most of the human body is water. A question that has remained open for some time is whether or not the intimate association between water and the electrically charged molecules in the living cell endows biological water with properties that set it apart from ordinary bulk water. The question has acquired added significance with the recent debate over the possibility of the existence of polywater, a dense form of water that is said to exist when water is held within an extremely narrow space, as in ultrafine glass capillaries [see "Superdense Water," by Boris V. Derjaguin; SCIENTIFIC AMERICAN, November, 1970].

Most of the water in a living cell is within tens of angstroms of a cell membrane, a similar structure or a large molecule (of protein or nucleic acid) with a strong electric charge. It is therefore certainly held within narrow bounds. For many years there has been a body of compelling evidence that the water in human red blood cells has anomalous properties. In our laboratory at the Harvard Medical School we have investigated this question and found that the answer lies not in anomalous water but rather in unexpected qualities arising from the close association of the hemoglobin molecules in the red blood cell. The finding has implications for the understanding of the physiology both of other types of cell and of certain subcellular organelles.

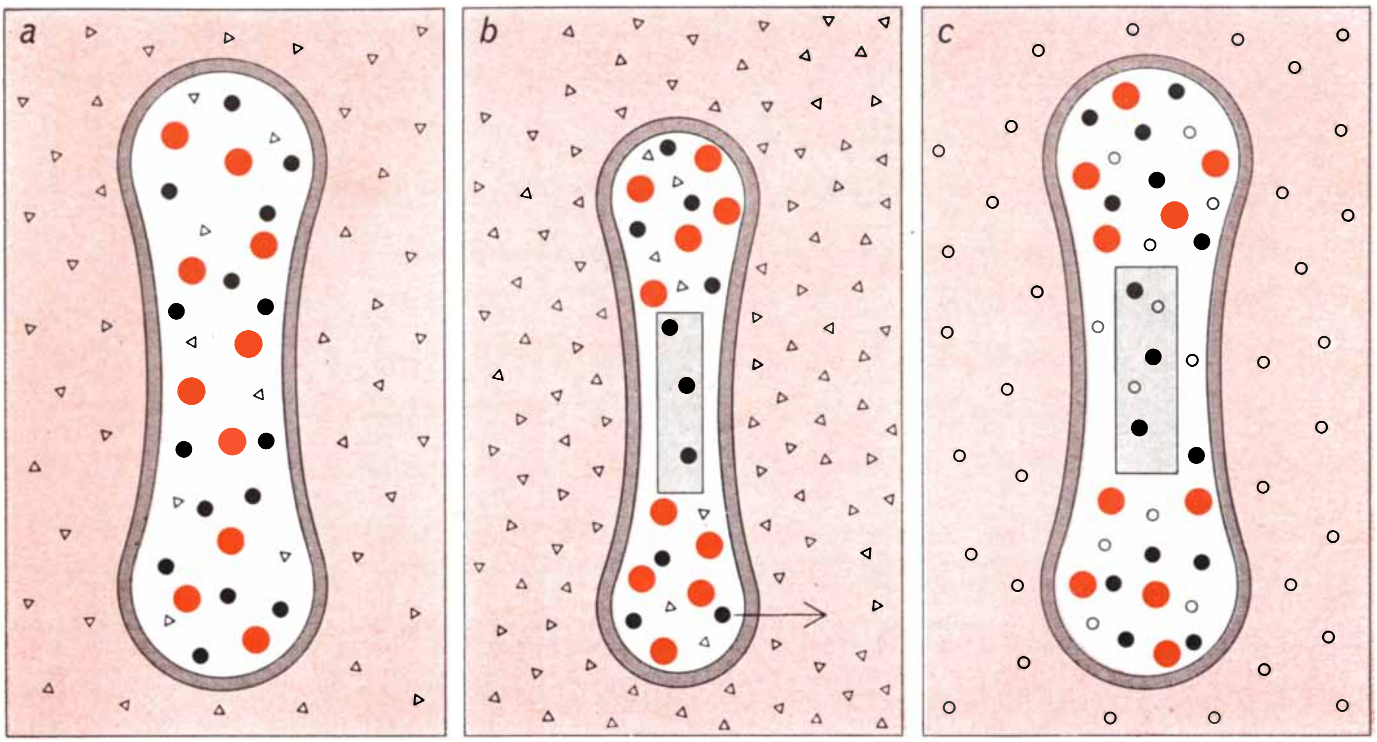
The properties of water in biological systems have engaged our attention primarily because of our interest in cell membranes. Water rapidly traverses the pores of cell membranes. The physical mechanisms that govern this movement are of interest not only in their own right but also because they illuminate the properties of the cell membrane and of the cell's contents.

The evidence for the apparent peculiarity of red cell water arose from classical studies of how cells shrink and swell in response to environmental stress. When red cells are placed in water, they swell until they burst, releasing their hemoglobin so that the entire solution quickly attains a uniform shade of red. The physical force that causes water to move into the cells, making them swell, is osmotic pressure: the pressure that arises as a result of the tendency of solutions separated by a porous membrane to equalize their concentrations. To put it another way, osmotic pressure is a thermodynamic measure of the activity of water and a reflection of the total concentration of solute, or dissolved substance, in the water. The Dutch physical chemist Jacobus van't Hoff showed long ago that the osmotic pressure of a solution is directly proportional to the total concentration of solute. (He was describing dilute solutions, which are the easiest to treat theoretically.)

When two solutions of different osmotic pressure are placed on opposite sides of a permeable membrane, both water and solutes move until the osmotic pressure on one side of the membrane equals the pressure on the other side. It is a law of fundamental importance that all physical systems left to themselves move toward equilibrium. In systems where only water can move, equilibrium means equality of water activity. With van't Hoff's law equality of water activity can be translated into equality of the concentration of a dissolved substance in dilute solutions on both sides of the membrane. In other words, if a solute (such as salt) cannot pass through the membrane, water will flow from the side of weaker salt solution into the side of stronger salt solution until the concentration of salt on the two sides is equal.

Although the membrane of the red cell lets water pass freely, it is impermeable to large molecules such as hemoglobin. Indeed, the red cell is specially adapted for carrying hemoglobin through the bloodstream by packaging hemoglobin at high concentration in each cell. The membrane is also highly impermeable to cations, or positively charged ions, such as sodium. It is precisely this resistance to the passage of cations that enables the cell to carry its large concentration of hemoglobin through the body without rupturing because of osmotic pressure. If the red cell were permeable to dissolved salts and not to hemoglobin, the resulting difference of osmotic pressure between the outside of the cell and the inside would be equivalent to a hydrostatic pressure of about 2.5 pounds per square inch. Water would thus move into the cell to dilute the hemoglobin, and the cell would eventually burst. Since the membrane is essentially impermeable to cations, however, the cell can effectively adjust its internal concentration of cations by pumping out any excess in order to maintain an osmotic balance and thereby compensate for its large load of hemoglobin. Water activity is therefore equal inside and outside the cell.

In contrast to the membrane's impermeability to cations is the freedom of movement it gives to anions, or negatively charged ions, such as chloride. Indeed, the membrane is about a million times more permeable to the chloride anion than to the cations potassium and sodium. Its permeability to anions does not affect the total internal concentration of solute, however, because of the action of another important physical principle: the requirement for electroneutrality. The number of positive



OSMOTIC CHANGES result from changes in the external environment of red blood cells. At *a* a cell is depicted in an isotonic solution, meaning one where the interior and exterior environments of the cell are in osmotic balance. If salt is added to the outside solution (*b*), water flows out of the cell to restore the osmotic balance and the cell shrinks. The apparent anomaly of red cell water in this situation is that 20 percent of it (*bar*) appears not to participate in the osmotic process and not to dissolve salt. At *c* a cell is shown in osmotic bal-

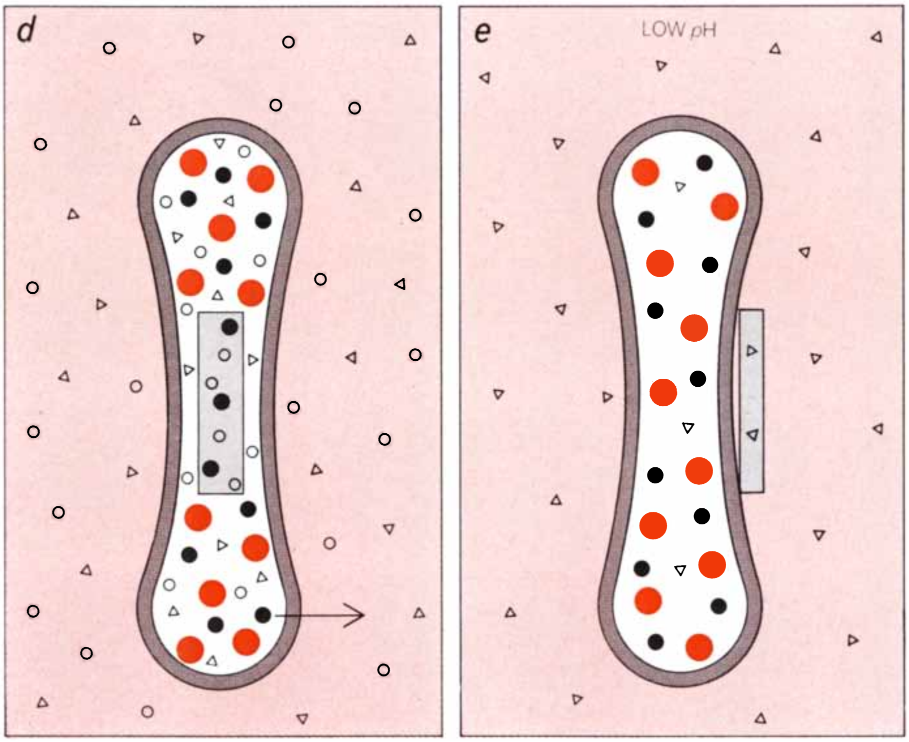
charges in the cell must exactly equal the number of negative charges. Although chloride is free to move, it can do so only in exchange for another anion. No net loss of anions from the cell is possible without an equal loss of cations, and the loss of cations is prevented by the cell membrane's properties of permeability.

The operation of these two principles—equality of water activity and electroneutrality—means that it is possible to adjust the water content of a red cell by adjusting the salt concentration of an external solution. If the salt concentration outside the cell is increased, water will rush out to equalize the solute concentration and the cell will shrink. If the external salt concentration is decreased, the cell will swell. The red cell is normally a biconcave disk, resembling a tennis ball that has been pushed in at two opposite poles until the poles almost touch. This shape allows for a considerable amount of swelling as the cell moves from biconcave disk to sphere; the increase in volume can be approximately twofold before the membrane breaks.

In a case where the external salt concentration is increased and water moves out of the cell to dilute the external solution, application of the van't Hoff law means that the decrease in cell water should be directly proportional to the increase in external osmotic pressure caused by the external salt. Here is where the apparent anomalous nature of cell water arises, because the proportionality is not as the van't Hoff law would have it. Instead it appears that only 80 percent of the cell water is needed to fit the osmotic equation. The other 20 percent, which is sometimes termed "nonosmotic water," seems to be in a kind of limbo. Although there is some disagreement over the exact figure, there has been widespread agreement that an appreciable fraction of the red cell's water exhibits apparently anomalous osmotic properties. This conclusion, of course, rests on the validity of the simple equation that relates the external osmotic pressure to the volume of water in which the solutes in the cell are dissolved.

A physical explanation was at hand that appeared suitable to account for the apparent anomaly of cell water. M. F. Perutz of the Laboratory of Molecular Biology at Cambridge in England found in his studies of the X-ray diffraction of hemoglobin molecules that when the molecules are crystallized from a concentrated salt solution, they form regular arrays with a 15-angstrom channel separating adjacent molecules [see "The Hemoglobin Molecule," by M. F. Perutz; SCIENTIFIC AMERICAN, November, 1964]. From measurements of density it was possible for Perutz to determine that the composition of the water in the channels differed from the composition of the water in the external solution. He calculated that the internal water behaved as though a layer one molecule thick surrounding the hemoglobin molecule were impervious to external salts, being in effect a kind of bound water that excluded ions. Perutz was working with horse hemoglobin; David L. Drabkin of the University of Pennsylvania School of Medicine obtained similar results with human hemoglobin and suggested that this impervious water layer was also found around each molecule of hemoglobin within the living red blood cell. The suggestion seemed plausible, since the amount of apparent nonosmotic water in the red cell was just about enough to provide a layer one molecule thick.

Before long, however, further evi-



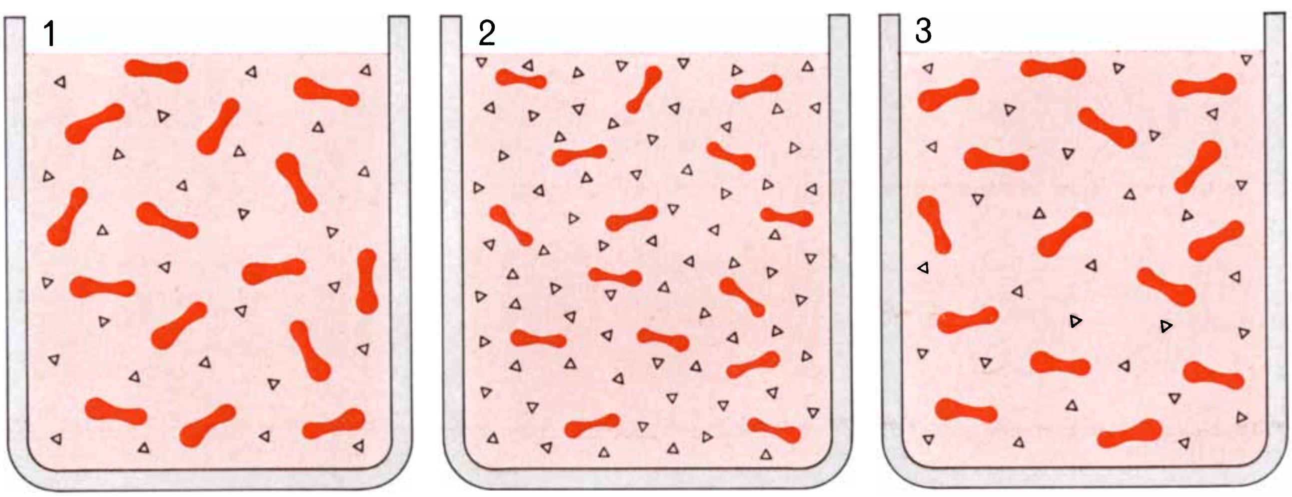
ance with glucose, which dissolves in all the cell water. If both salt and glucose are added to the outside solution (*d*), all the cell water dissolves glucose but 20 percent still appears unable to dissolve salt. If the *p*H of the external solution is lowered, however, salt dissolves in all the cell water (*e*). Indeed, according to the equation relating cell volume to external osmotic pressure, more water than the cell contains appears to be needed.

also able to dissolve in all the cell water. He subsequently joined our group, and we decided to take a further look at the properties of apparent anomalous water.

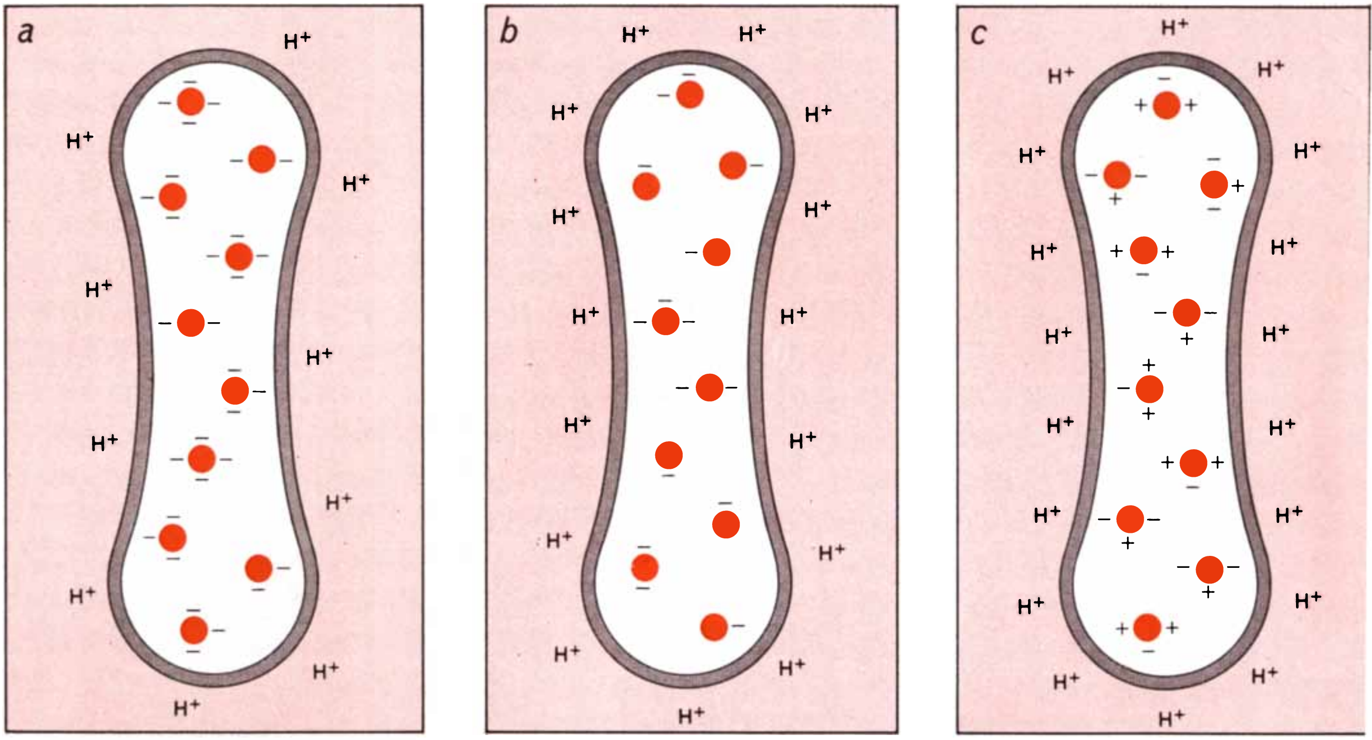
It had initially been fairly easy to accept the concept of a layer of water one molecule thick that would exclude all solutes because of its close association with hemoglobin. It was much more difficult, however, to imagine a kind of water that would rigidly exclude ions such as potassium while readily dissolving glucose and ethyl alcohol. We first had to rule out the possibility that this surprising discrepancy resulted from some apparently unimportant difference in technique between the two kinds of experiment. To do so we measured the distribution of glucose in exactly the same experiments wherein we had studied the swelling properties of red cells. The experiments confirmed the discrepancy: the osmotically effective cell water was still only 80 percent of the total cell water, but the glucose could dissolve in all the cell water [*see illustration on these two pages*].

There were only four logical possibilities to explore. The first was that some solute might unexpectedly leak out of the cell when it shrank, thereby upsetting the obligatory inverse relation between cell volume and external osmotic pressure. The second concerned the osmotic behavior of hemoglobin. It had long since been shown by the British biophysicist Gilbert S. Adair that the osmotic pressure of hemoglobin increases more rapidly than the concentration of hemoglobin. The osmotic coefficient,

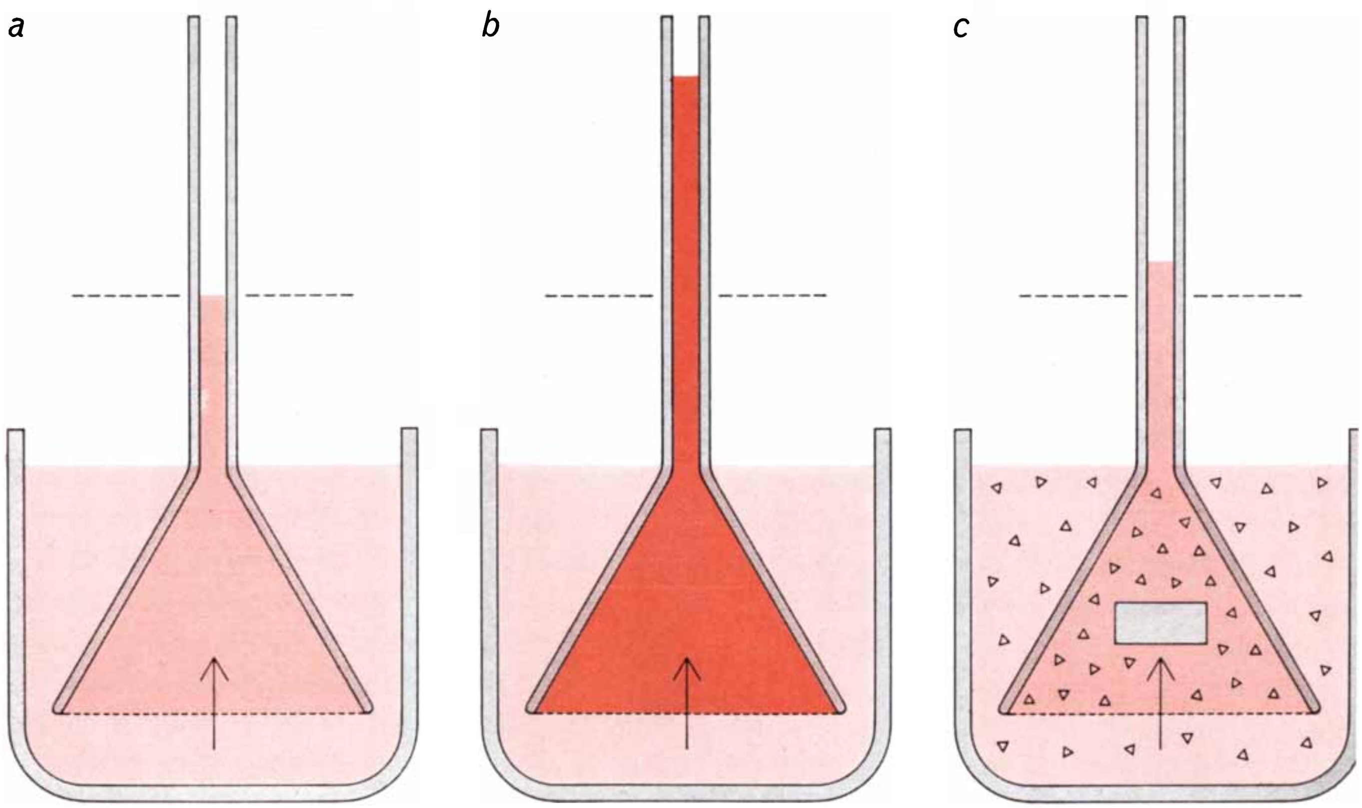
dence that was brought forward undermined our confidence in this explanation. In a series of experiments on the transport of glucose across red cell membranes D. M. Miller of the Canadian Department of Agriculture found that the concentration of glucose in the cell water reached a value equal to that in the external solution, in contrast to our evidence that the cellular concentration of ions was only 80 percent of the external concentration. In separate experiments C. M. Gary-Bobo of the Collège de France had found that ethyl alcohol was



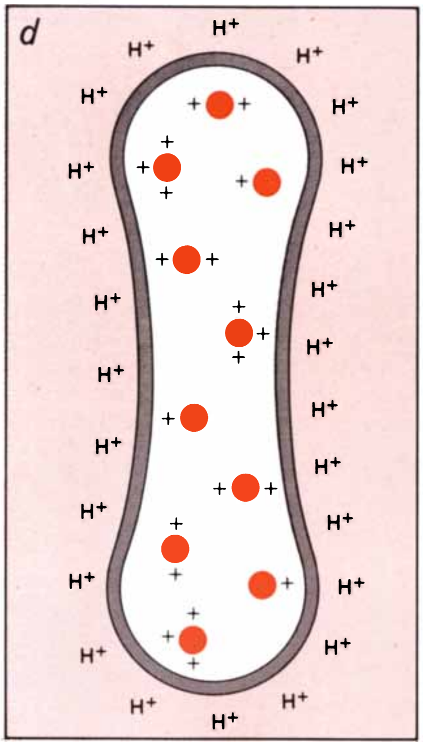
CHANGES OF VOLUME of red blood cells were studied in the author's laboratory to investigate the possibility of a leakage of solute, or dissolved substances, from the cells. After a batch of cells had been established in an isotonic external solution (*1*) the external concentration of salt was increased (*2*) and the cells shrank. When the salt concentration was restored to normal (*3*), the cells returned to normal size. The same results were achieved when the experiment was done in reverse, with the cells caused to swell rather than shrink. A net loss of solute would have meant that the cells would not return to their normal volume as they did at stage *3* in each set of experiments. A phenomenon that the experiments did not rule out, however, was a balanced leakage of solute in and out.



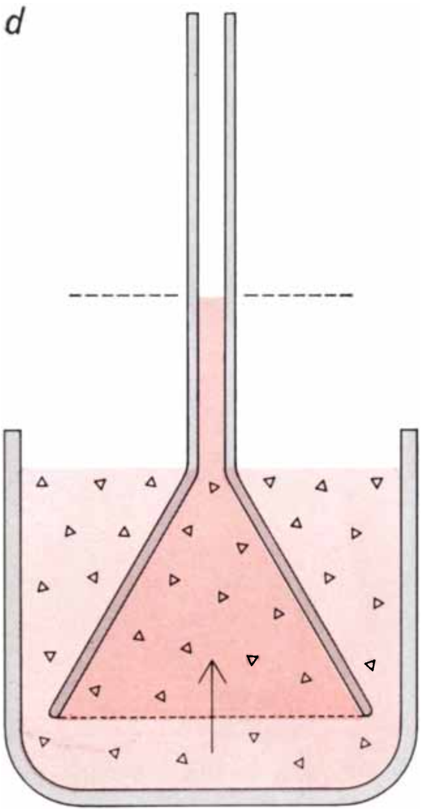
ELECTRIC CHARGE on a molecule of hemoglobin depends on the concentration of hydrogen ions. At the normal *p*H of the red blood cell (*a*) each molecule has about three net negative charges. If the content of hydrogen ions (H^+) in the external solution is increased (*b*), the net negative charge on the hemoglobin molecule decreases. Eventually (*c*) the number of negative charges on the molecule balances the number of positive charges; this is the isoelectric point of the hemoglobin molecule. If the external content



OSMOTIC PROPERTIES of hemoglobin can be measured with an artificial membrane. With hemoglobin (*darker color*) on one side of a membrane and a solution on the other (*a*), the osmotic pressure is indicated by the rise of fluid in the vertical column. Doubling the concentration of hemoglobin (*b*) somewhat more than doubles the osmotic pressure. Equal amounts of potassium chloride were added (*c*) to both sides of the membrane. According to the anomalous-water hypothesis the osmotic pressure (for a perfect membrane impermeable to salt) should have been about 120 percent of the amount that would appear under the conditions depicted at *a*; in-



of hydrogen ions is increased still more, the hemoglobin takes on a net positive charge (*d*). For clarity only *H*+ is shown outside the cell and only hemoglobin inside it.



stead there was no such effect (*d*). The experiment therefore showed that virtually all the water on both sides of the membrane was available for dissolving the potassium chloride added by the experimenters.

which relates osmotic pressure to solute concentration, is therefore greater than one for hemoglobin at red cell concentrations, and it varies with varying concentration of hemoglobin. Failure to take account of this known variation in the osmotic coefficient would cause false conclusions to be drawn from the swelling equation. The third possibility was that the swelling equation, although it is apparently derived from simple physical principles, was wrong in some subtle way. Finally, it might be possible for some form of water to exist in close association with hemoglobin and to dissolve small molecules such as glucose while at the same time excluding cations such as potassium.

Earlier David Savitz, Victor W. Sidel and I had investigated the first possibility—leakage of solute—by making careful measurements of red cell volume. We shrank a batch of cells and after 20 minutes restored them to their original environment, which was isotonic, or in osmotic balance with the interior of the cells. We did the opposite with another batch of cells, swelling them and then putting them back in the isotonic solution. Both batches of cells returned exactly to their original volume when they were replaced in the original environment. If anything had leaked out or in when the cells were in the shrunken or swollen state, they would not have returned to their original volume. We concluded from these observations that the apparent anomalous water was not an artifact to be attributed to solute leakage. (It should be noted that this set of experiments ruled out net leakage of solute but did not exclude the possibility of reversible solute leakage, which would of course have to balance exactly in each direction.)

We were able to take account of the osmotic behavior of hemoglobin by using a computer to fit Adair's observations to a smooth curve relating the osmotic pressure of hemoglobin to hemoglobin concentration. The effect of the variation in osmotic pressure that he had predicted was measurable, but it was by no means large enough to account for the volume differential of 20 percent that had led to our original conclusion about anomalous red cell water. This work ruled out the second of the four possibilities.

As for the third, our information about the predictive value of the swelling equation came from an unexpected result of another set of experiments. They entailed a study of the effect of the content of hydrogen ions (the *p*H) in the external solution on the apparent anomalous water. As is true of all proteins, so with hemoglobin the charge on the hemoglobin molecule depends on the hydrogen-ion concentration. At the normal *p*H of the red blood cell the hemoglobin molecule is negatively charged, having about three negative charges for each molecule. As the concentration of hydrogen is increased, the negative charge decreases until it falls to zero at *p*H 6.95. The level of *p*H where the number of negative charges on the protein exactly balances the number of positive charges is termed the isoelectric point. At that point the net charge on the protein is zero.

If the hydrogen-ion concentration of the external solution is increased still further, the protein begins to acquire positive charges. It was to be expected that the charge on the hemoglobin molecule would affect the properties of the water that is apparently bound to the protein, since the binding forces are primarily electrical. In the range of *p*H that we had previously studied—similar to the range in the normal environment of the red cell—20 percent of the water behaved anomalously as before. When the external *p*H approached the isoelectric point of hemoglobin, however, the amount of anomalous water fell drastically. Indeed, when the *p*H reached the region where the hemoglobin was positively charged, the osmotic equation yielded a value for the cell water higher than the amount of water actually contained by the cell!

This was a surprising result. It is one thing to predict too little osmotically effective water in the cell; that can be explained by a number of hypotheses. It is quite another matter to predict too much water, because there is no explanation. Obviously the equation was wrong. This result does not mean that the osmotic laws are wrong; it means that the interpretation of the proportionality coefficient (between cell volume and external osmotic pressure) as an index of the properties of the cell water is not justified.

We had in fact also investigated the fourth logical possibility—the question of the existence of anomalous water—before we obtained the information about the inapplicability of the osmotic equation. The amount of water sufficient to form a layer one molecule thick around a hemoglobin molecule is surprisingly large, being some 30 percent of the weight of the hemoglobin molecule itself. It followed that the properties of such a layer should be detectable outside the red cell as well as inside.

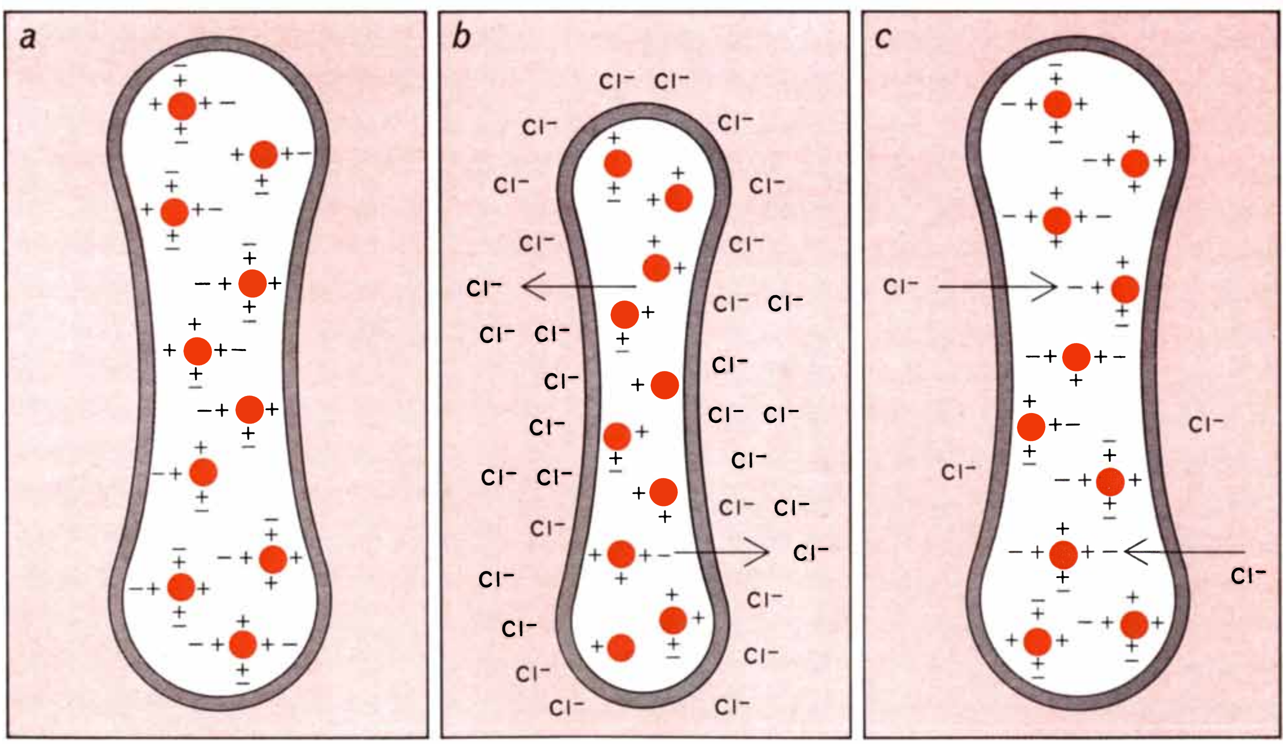
We therefore measured the osmotic properties of a hemoglobin solution placed on one side of a cellophane membrane. When we changed the concentration of hemoglobin alone, we obtained changes in the value of osmotic pressure that were in close agreement with Adair's. We then added equal concentrations of potassium chloride to the solutions on both sides of the membrane. If the potassium chloride on the hemoglobin side of the membrane had been excluded from some of the water, there would have been an immediately detectable osmotic effect. There was no effect. All the water on both sides of the membrane appeared to be available for the solution of potassium chloride.

This finding demolished the bound-water hypothesis in its original form. There still remains the possibility that some small amount of water is closely associated with the hemoglobin, because the accuracy of our measurements could not be sufficient to exclude all possibility of bound water. The accuracy is high enough, however, to make it clearly impossible for a layer of water one molecule thick to exclude potassium chloride from solution. (This finding did not cast any doubt on Perutz' observation that salts are excluded from part of the interstitial water layer in hemoglobin crystals; it merely indicated that one cannot extrapolate accurately from the properties of water in a rigid crystal to water properties in a dilute solution.)

Having demolished the foundations we had previously stood on, we faced the problem of finding the correct physical principle to account for all our observations. For a time we created and destroyed hypotheses almost daily. Clearly the swelling equation was firmly based on thermodynamic principles. Yet it had no predictive value, which meant that we were drawing wrong inferences.

In the end we returned to first principles. Using only the observation that the water activity inside the cell equaled the water activity outside, together with the principle of electroneutrality, we were able to write an equation that related cell volume to the charge on the hemoglobin molecule. In the back of our minds was the recognition that, although it was known that the charge on the hemoglobin depended primarily on the concentration of hydrogen ions, no one had ever proved that the charge did not also depend on the concentration of hemoglobin. Such a concept was not unknown in large polymers; it took on particular attraction for us because of the discontinuity we had found in the swelling curve near the isoelectric point of hemoglobin.

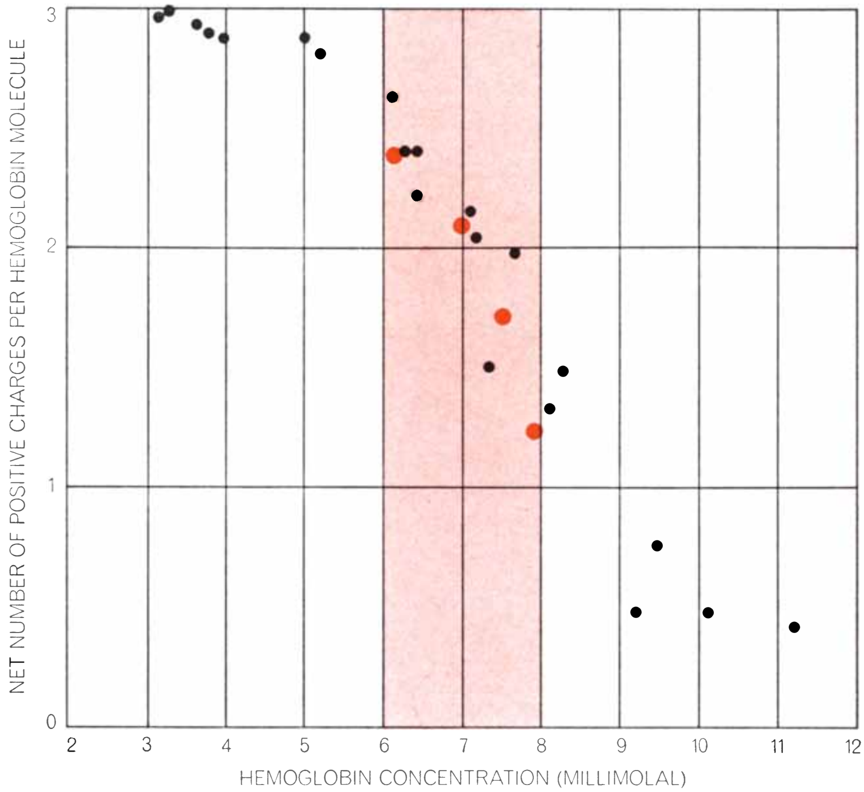
Physically the idea made sense because the hemoglobin molecules are packed very tightly in the red cell. It has been estimated that the width of the channel between hemoglobin molecules in the red cell is about 25 angstroms in the normal cell, rising to about 38 angstroms when the cell is swollen by some 40 percent. Recalling that the channel width in crystalline hemoglobin is 15 angstroms, it seemed quite possible for cooperative interactions to take place between closely packed hemoglobin molecules in the red cell. It also seemed possible for these interactions, which would be electrical in nature, to effect a reduction in the net hemoglobin charge.



CHANGE OF CHARGE due to the spacing of hemoglobin molecules turned out to be the reason for the apparently anomalous behavior of water in red cells. In a normal cell at low *p*H (*a*) the number of positive charges on each hemoglobin molecule is larger than the number of negative ones, creating a net positive charge. If the cell is shrunk osmotically (*b*), the hemoglobin molecules approach one another and interact electrically so that the net positive charge on each molecule is reduced. Negative chloride counterions (Cl^-) therefore move out of the cell. If the cell is returned to its normal size (*c*), the chloride counterions return. This balanced movement of chloride ions explains why the cells do not expand or contract as much as would be expected if all the salt stayed in the cell. The explanation is not that the salt does not dissolve in all the cell water but rather that some of the negatively charged chloride ions of the salt move out of the cell when it shrinks. Water inside and outside the cell is therefore shown to have essentially the same properties.

The next step was to compute the expected hemoglobin charge as a function of the external osmotic pressure, which is itself an effective index of red cell volume and therefore of the concentration of hemoglobin in the red cell. This exercise was rewarding because we learned that the calculated net charge of the hemoglobin changed slowly with concentration when the cells were swollen but rapidly when the cells were shrunken.

These observations fit two quite diverse sets of facts. First, it had long been known that the apparent anomalous water was relatively unimportant when the cells were swollen but became a much larger fraction of cell volume when the cells were shrunken. Second, X-ray diffraction studies of hemoglobin spacing in human red cells showed that the molecules separated rapidly as the cells swelled, whereas when the cells shrank, the spacing changed much more slowly with external osmolality, presumably because the molecules were so close together that they could not easily become more tightly packed.



DECREASE OF CHARGE with increasing concentration of hemoglobin is shown for experiments carried out both in vivo (*colored dots*) and in vitro (*black dots*). The band of color in the graph delineates the region of normal osmolality in intact red blood cells.

The effect of changes in hemoglobin charge on red cell volume is mediated by the principle of electroneutrality: there must be a negative ion in the cell to balance every positive ion. Suppose that the only negative ions present are chloride ions and that the hemoglobin concentration in the cell is seven millimolal. Then if there are three positive charges per hemoglobin molecule, the total is 21 millimols of positive charges, so that there must be 21 millimols of negative chloride ions (counterions) to preserve electroneutrality. This is about 20 percent of the total population of mobile negative ions.

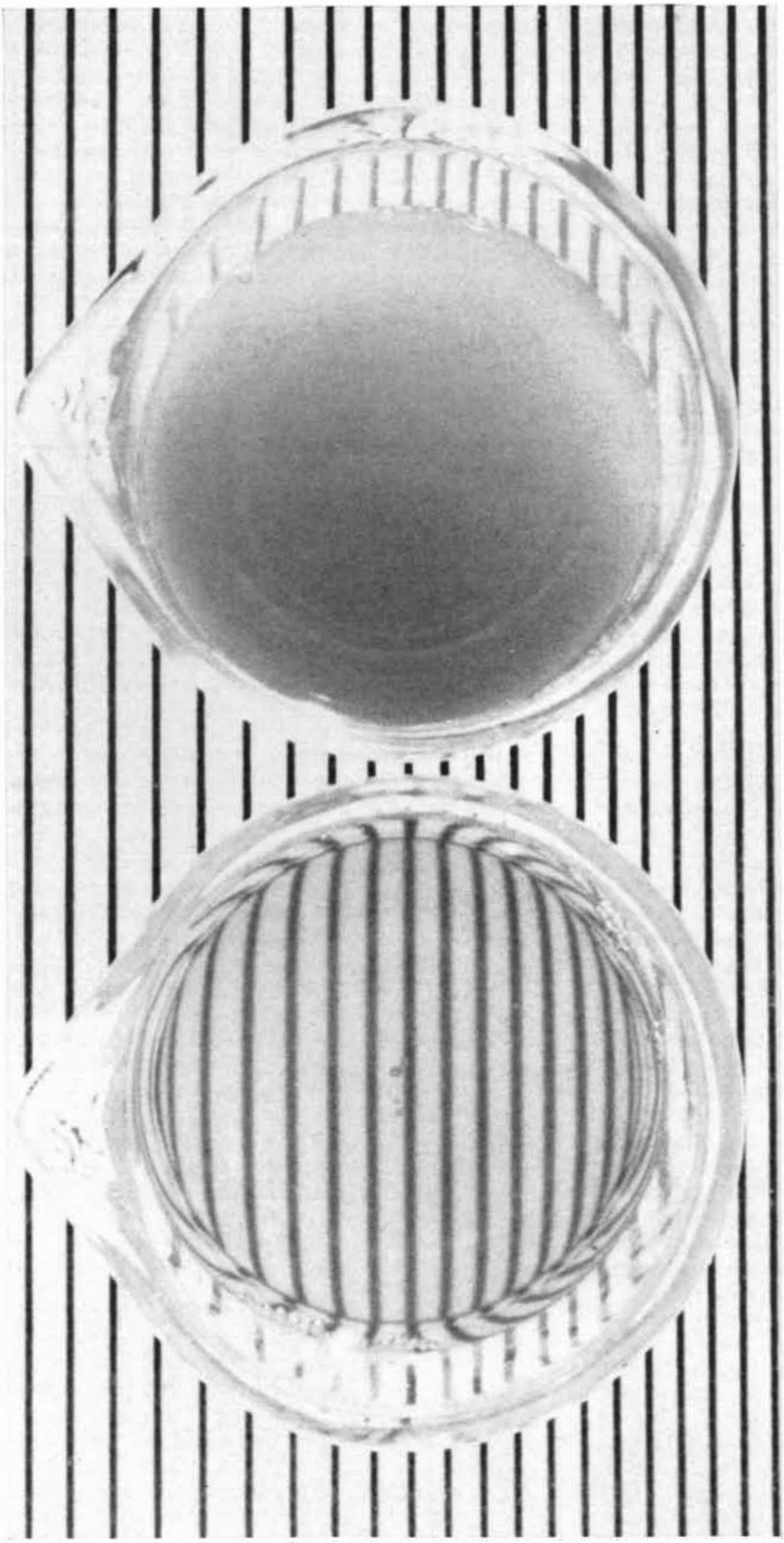
If the hemoglobin molecules now move so close together that they can interact, with the result that the net hemoglobin charge falls to zero, the chloride counterions should move out of the cell because they are no longer required there. Hence the total concentration of solute in the cell should fall and, since the osmotic balance was being maintained by the movement of solutes as well as water, less water would move than would otherwise be the case and the cell would shrink less than expected —exactly in conformity with observed behavior. If the red cell were next returned to its original osmotic environment, the cell would swell, the hemoglobin molecules would move apart and the chloride ions would return. Thus there would be no net loss of solute but rather an exactly reversible loss—the possibility that had been left open by the results of the experiments that Savitz, Sidel and I had conducted.

The hypothesis was most exciting, since it seemed to meet all the requirements of the problem. To support the hypothesis, however, it was necessary to prove that the chloride ions did indeed move. We reexamined the results of experiments we had done previously with chloride. (At the time we had put the results aside because we could not understand them.)

It is worth describing the experimental technique, since it was crucial to the proof of the hypothesis. First the red cells were washed extensively in solutions of sodium chloride to remove by anion exchange all the mobile anions (mainly bicarbonate) except chloride. Radioactive chloride and radioactive albumin were then added to the outside solution. Since the cell membrane is permeable to chloride, the radioactive chloride could move freely into and out of the cell until the radioactivity of the cell chloride was in equilibrium with the radioactivity of the chloride outside, meaning that the concentrations of chloride inside and outside the cell were in equilibrium. On the other hand, the cell membrane will not pass the large molecules of albumin. Hence if chloride moves out when the cell shrinks, the ratio of radioactive chloride to radioactive albumin outside the cell will increase, and the shift of chloride will be accurately assessed by the change.

The beauty of the method is that the hemoglobin remains in its native state and does not need to be precipitated, which is a prerequisite for the usual chemical estimates of chloride. Moreover, no correction need be made for the movement of water, since all the essential information is found in the ratio of chloride to albumin. The results of this experiment, once we understood them, were most gratifying, inasmuch as the measured shift of chloride corresponded exactly to the predicted change in the hemoglobin charge. The finding seemed to establish our hypothesis on a firm foundation.

The kind of cooperative interaction of protein molecules that we have postulated for hemoglobin had not previously been thought to be a property of protein molecules. The interaction has broad implications concerning the behavior of other proteins and other large



OSMOTIC EFFECT on red blood cells is demonstrated by changing their environment. The vessel at top contains red blood cells in an isotonic environment; the cells are intact and the solution is therefore opaque. The vessel at bottom contains red blood cells in water; the resulting osmotic imbalance has made water move into the cells and swell them. Hemoglobin leaks out and is diluted by the surrounding water; the solution thus becomes transparent.

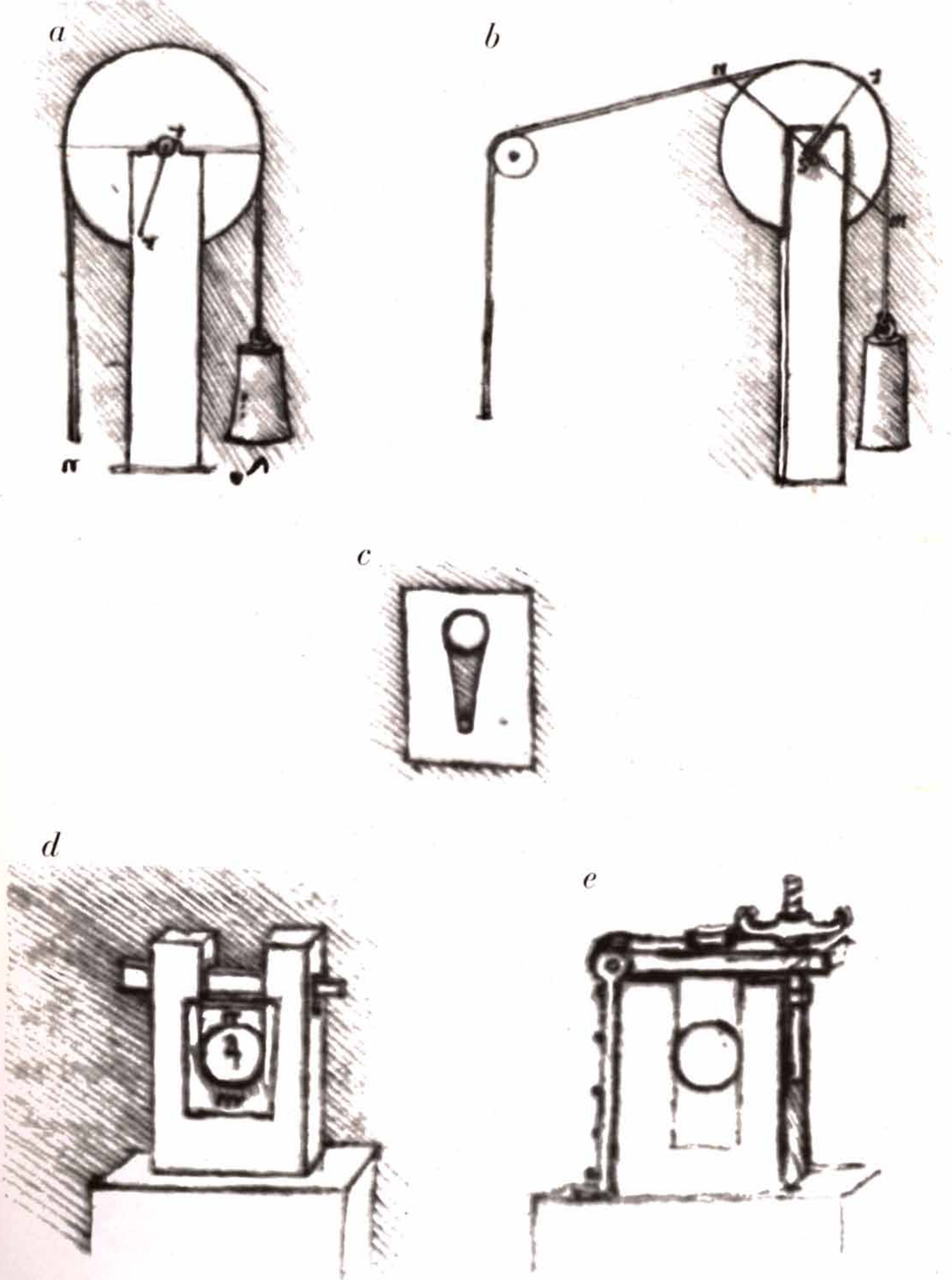
charged molecules in living systems. In view of these implications it was essential to prove that our hypothesis, based on red cell behavior, was correct. Although our conclusions seemed to rest on logical premises, the reasoning is complex. Furthermore, there might be other important properties of living red cells that should have been taken into account.

If our conclusions were correct, the same behavior should be observable in nonliving systems. In order to establish this point Gary-Bobo returned from France to spend last summer at our laboratory. We planned to measure the distribution of radioactive chloride across a cellophane bag containing highly concentrated hemoglobin solutions. By this method we could study the properties of hemoglobin over a much wider range of concentration than is found in the human red cell. The hypothesis unequivocally predicted that the chloride distribution, at a constant concentration of hydrogen ions, would depend on the concentration of hemoglobin. The results exhibited the predicted concentration dependence. Moreover, the new data agreed quantitatively with our finding on human red cells [*see illustration on preceding page*].

The implications of these observations are far-reaching. Apparent anomalous osmotic properties have been observed in muscle cells and in mitochondria, the subcellular organelles primarily responsible for the production of energy in biological systems. It would seem logical to suggest that the explanation for these observations is similar to the one we have found for red cells.

Another interesting speculation concerns the regulation of osmolality within cells and organisms. The osmotic pressure of biological fluids is closely regulated, but the nature of the transducer that provides the regulatory signal remains obscure. Our experiments show that the cooperative behavior of hemoglobin molecules serves to produce an electric signal in response to an osmotic stress. That is precisely what would be necessary for an osmotic transducer.

The most important conclusion, however, relates to the properties of water. Inside the red cell the molecules of water are physically close to the hemoglobin molecules and should be in a position to react readily with hemoglobin. Yet within the accuracy of our measurements there is no difference between the activity of the water in the cell and the activity of the bulk water outside. As far as we can tell, water is water.


a
b
c
d
e

LEONARDO ON BEARINGS AND GEARS

It is well known that Leonardo was not only an artist but also an engineer. The large corpus of his papers recently discovered in Madrid shows that his interest in technology was predominant

by Ladislao Reti

In the view of present-day historians the extraordinary versatility of Leonardo da Vinci is clouded by controversy. Was Leonardo an artist who had a keen but secondary interest in technology or was he primarily an engineer and scientist who worked as an artist to make a living? One can argue either side of the question quite seriously. In his own time Leonardo received equal recognition in both fields. Every documentary mention referred to him as an engineer as well as an artist, and the official burial certificate, in French, described him thus: *Lionard de Vincy, noble millanois, premier peinctre et ingenieur et architecte du Roy, mescanichien d'Estat, et ancien directeur du peincture du Duc de Milan.* After Leonardo's death his fame became attached to the works of art, since his painting masterpieces remained prominently in public view while his technical treatises and notebooks disappeared into libraries or private collections. The resurrection of these manuscripts and books by scholars in the past century has changed the perspective on where Leonardo's main interests lay. If we are to judge by volume of work, the evidence strongly suggests that his predominant interests were science and technology. Whereas no more than 10 paintings indisputably by his hand can be found on the walls of the world's art galleries and his purely artistic drawings number only a few hundred, Leonardo produced thousands of studies, notes, drawings and sketches on scientific and technical subjects.

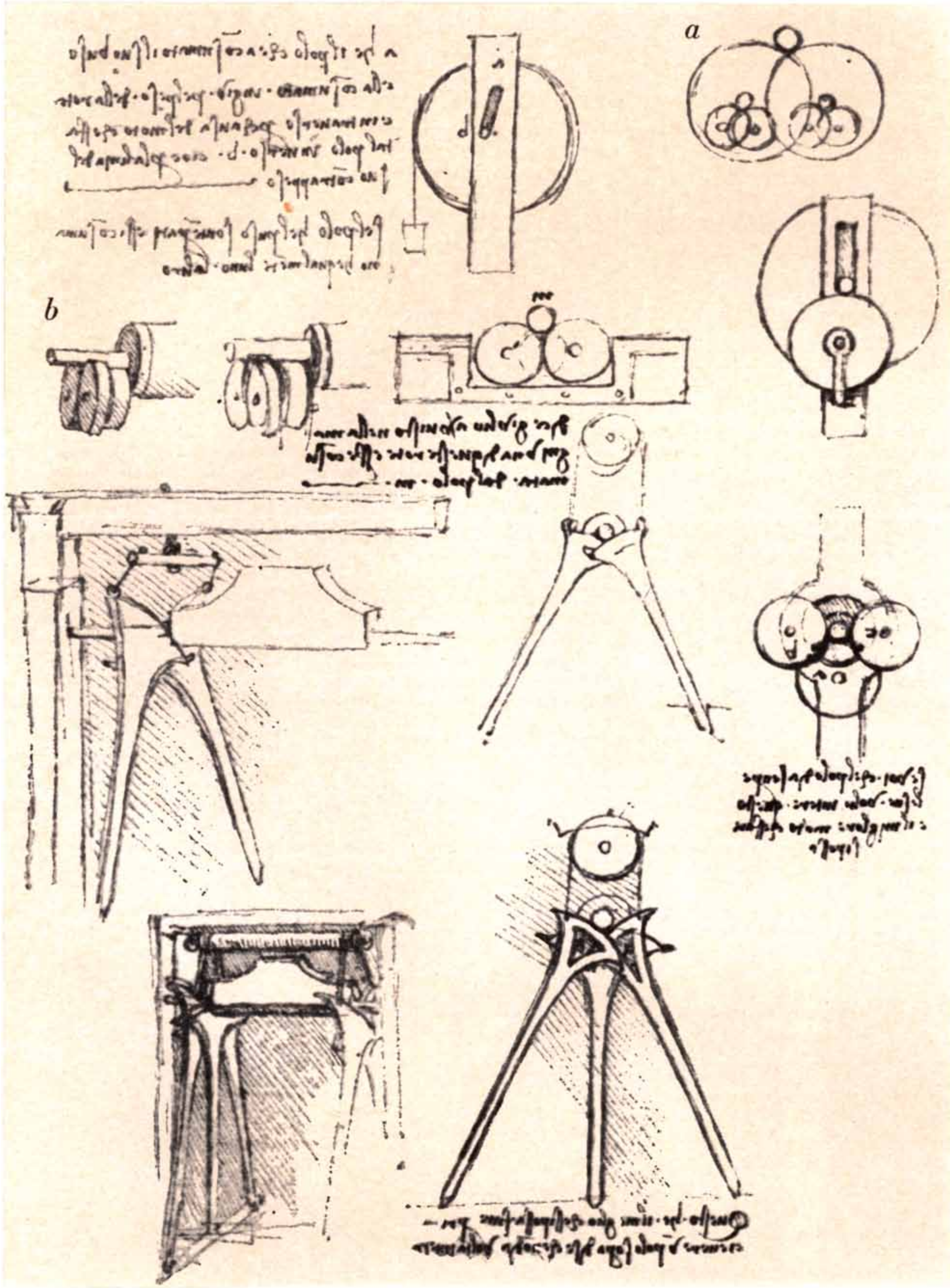
His intellectual hunger ranged over all fields of science, embracing areas as diverse as geometry, mechanics, hydraulics, human and animal anatomy, botany, geology and astronomy. Primarily, however, his works point to an intense and imaginative concern with technological development. He has been credited with the original conception, on paper, of a great number of modern inventions, from armored tanks to airplanes, from hydraulic turbines to the steam engine, from the telescope to the digital computer. Such overenthusiastic attributions to Leonardo have moved some cautious scholars to react in the opposite direction. They contend that Leonardo's machines, although pictured with meticulous precision, were no more than figments of his imagination, never actually built or tested. In short, they regard Leonardo as merely an armchair technologist.

This judgment, however, is made by historians untrained in technology. Engineers know better. Many have accepted Leonardo's machines at face value and admired the grasp of basic principles shown in their design. Among the many distinguished engineer-historians who have manifested full appreciation of Leonardo's technical genius, I shall mention in particular Theodor Beck, Franz M. Feldhaus, Ivor Hart, William Barclay Parsons, Abbott Payson Usher, Arturo Uccelli, Carlo Zammattio, Bern Dibner and Giovanni Canestrini. Canestrini, an Italian engineer, wrote a small but important book dealing with Leonardo as a constructor of machines and vehicles. One chapter of the book carefully analyzes the work of Leonardo on friction and traction.

In 1967 I had the good fortune to be one of the protagonists of a story that led to one of the greatest literary discoveries of the century: two large unpublished manuscripts by Leonardo were found in the collection of the National Library in Madrid. These manuscripts were catalogued and mentioned in several books and bibliographies, but an unfortunate slip on the part of a cataloguer in 1830 had prevented scholars from consulting them for more than a century. The McGraw-Hill Book Company, in association with the Madrid publishing house Taurus, obtained from the Spanish government the rights to a scholarly edition; this task has been entrusted to me. Since publication may take several years, the following brief account of part of the contents of the manuscripts will be welcome to many people interested in the work of Leonardo.

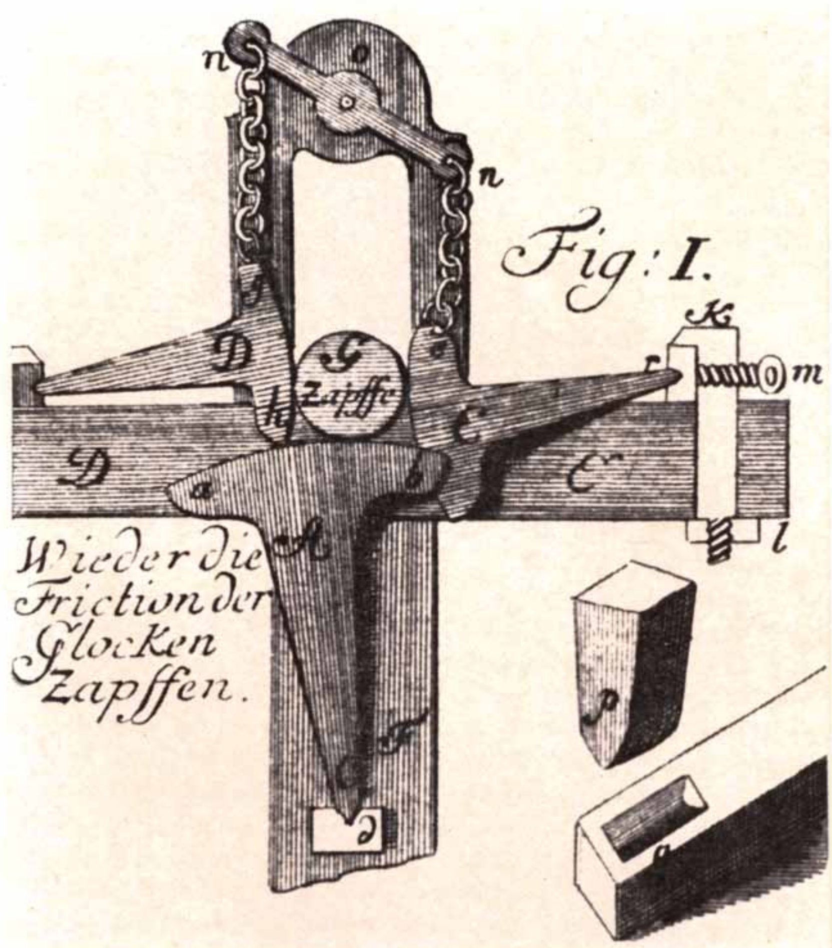
The first manuscript, known as Codex Madrid I, deals almost exclusively with theoretical and applied mechanics. Its 382 pages consist of notes accompanied by some 1,600 sketches and drawings. Codex Madrid I thus supplements another famous Leonardo collection, known as the Codex Atlanticus, but Madrid I is a systematic treatise (insofar as Leonardo's indefatigable mind, permanently aroused by new problems, could be constrained to be systematic) written between 1493 and 1497, whereas the Codex Atlanticus is an arbitrary and mutilated collection made up by Pompeo Leoni from writings and drawings by Leonardo dating to between 1483 and

WEAR ON BEARINGS was observed by Leonardo, who noted that a horizontal shaft did not erode the bearing surface vertically ("*a*," "*b*" *in illustration on opposite page*) but in a direction fixed by the direction of load. He also saw that reciprocal wear between shaft and bearing produced a tapering groove (*c*). To reduce shaft play and wear, he suggested that bushings made of a low-friction alloy, kept snugly in place with a wedge (*d*) or screw (*e*), be the only contact with the rotating shaft. The drawings appear in Codex Madrid I, one of two as yet unpublished works by Leonardo owned by the National Library in Madrid. All are reproduced by permission of the National Library and the McGraw-Hill Book Company.



TWO-DISK BEARING, a low-friction device formerly thought to be Leonardo's invention (*a*), is declared on this page of Codex Madrid I to have been observed in use in Germany by an assistant. Leonardo promptly improved on the German system by supporting the shaft on a central disk (*b*), so that the two outer disks bore only lateral pressure. Four lower drawings show a similar low-friction support for a bell, modified to suit an axle that does not rotate a full 360 degrees. Leonardo's system was soon generally adopted.

1518. The importance and the quality of Codex Madrid I reside not only in its many beautifully finished drawings and carefully written sheets but also in the fact that many pages of the Codex Atlanticus must be considered as drafts and sketches for subjects elaborated by Leonardo in Codex Madrid I.



BELL SUPPORT, devised by Leonardo in the last decade of the 15th century, was called the "oldest and most common system" in Jacob Leupold's 1724 treatise on machinery.

One cannot discuss Leonardo's attainments in mechanics with any comprehensiveness in a single article. I shall limit myself here to his investigations of friction, bearings and gears, which clearly illustrate the character and importance of his discoveries.

In all his studies Leonardo was fully as interested in theory as in applications; he was definitely not a gadgeteer or an empiricist. He remarks in Codex Madrid I: "This is called practice, but remember to first set forth the theory." Leonardo's systematic exploration of the role of friction and traction in the operation of machines led him to, among other conclusions, a full appreciation of the folly of attempting to create a perpetual motion machine, a popular pastime among inventors of his era. The first page of Codex Madrid I contains this introductory comment by Leonardo:

"Among the superfluous and impossible delusions of man there is the search for continuous motion, called by some perpetual wheel. For many centuries almost all those who worked on hydraulic machines, war engines and similar matters dedicated to this problem long research and experiments, incurring great expense. But always the same happened to them as to the alchemists: for [their oversight of] a little detail everything was lost. My little work is going to benefit those investigators, so that they will not need any more to run away because of the impossible things they promised to sovereigns and heads of state. I remember that many people, from different countries, went to Venice with great expectation of gain to make mills in dead [still] water, and after much expense and effort, unable to set the machine in motion, they were obliged to escape."

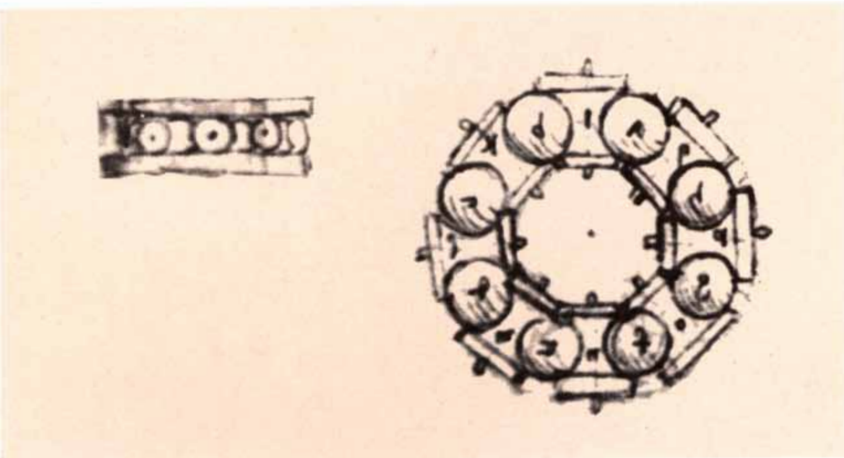
Elsewhere, in another manuscript, Leonardo declaimed: "O speculators about perpetual motion, how many vain chimeras have you created in the like quest? Go and take your place with the seekers of gold!"

It can truly be said that Leonardo was the first engineer with a modern understanding of the elementary principles that govern the functioning of a machine. Before he applied himself to analysis of this problem every machine had been regarded as *sui generis*—a unique contraption operating in its own peculiar way. Leonardo was the first to recognize that each machine was a composition of certain universal mechanisms that were common to machines in general. He succeeded in analyzing the functional anatomy of specific machines and portraying each as an organic structure made up of separate parts that operated in unison.

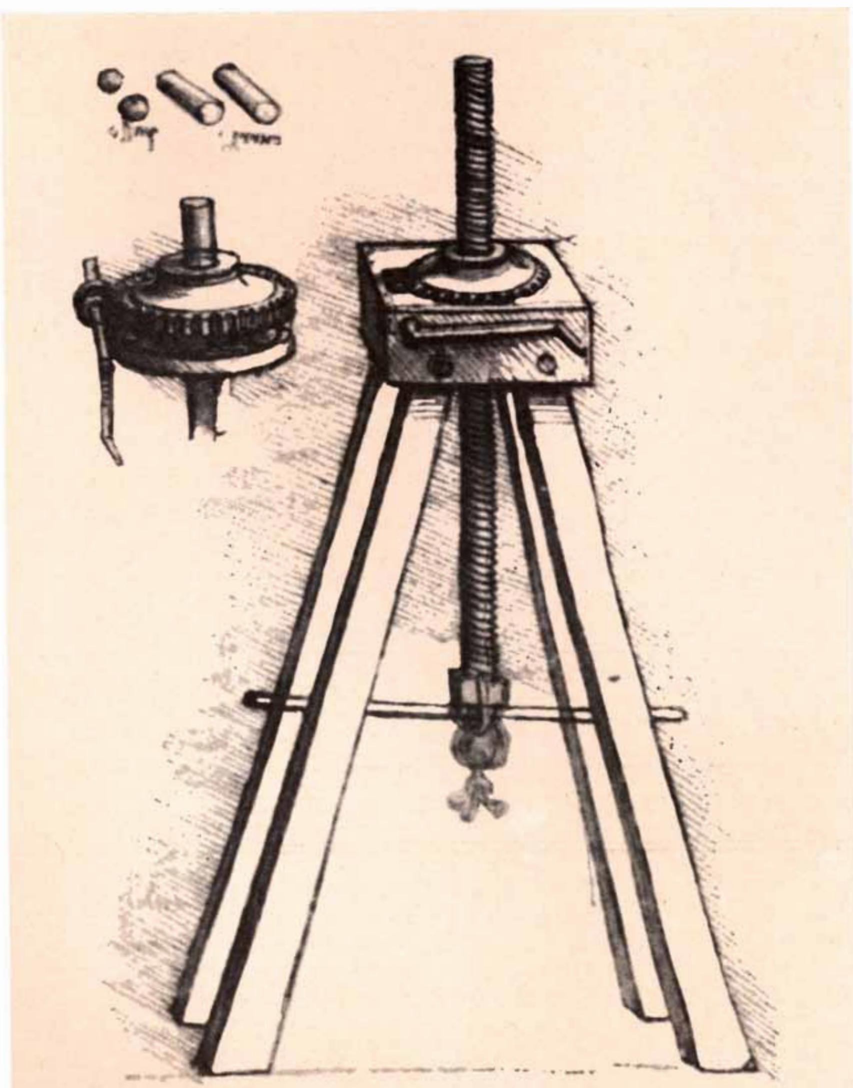
In keeping with his habit of first looking into "the theory," Leonardo prefaced his efforts to design more efficient machines with a series of studies on the nature and properties of friction between solids. For these studies he devised experimental equipment that was far ahead of his time. For example, in experiments for measurement of the influence of gravity and friction on a wheeled vehicle on an inclined plane, and for the measurement of the power of a waterwheel, Leonardo used a dynamometer—nearly three centuries before the 18th-century English engineer John Smeaton, who is generally credited with pioneering the employment of dynamometers.

Since Leonardo's principal language was graphic representation, his experimental investigations of friction can be best understood by examining his drawings [*see top illustration on page 106*]. One shows a bank device for the measurement of sliding friction (identical with a friction bank that Charles Augustin de Coulomb devised 300 years later) and also illustrates an apparatus for measuring rolling friction. Other drawings picture experiments in which Leonardo measured frictional resistance on an inclined plane, looked into the question of whether or not frictional resistance depended on the area of contact between surfaces and examined how the ease of rolling motion of a shaft might be affected by the shaft's diameter.

From his measurements Leonardo derived several general principles, namely that frictional resistance differs according to the nature of the surfaces in contact, that it depends on the degree of smoothness of those surfaces, that it is independent of the area of the surfaces



RING-SHAPED RACE for a ball bearing was devised by Leonardo to eliminate the loss to friction that results when the individual balls in a bearing come in contact with one another.



USE OF BALL BEARING to overcome the friction that normally immobilized any overloaded screw jack is illustrated in this drawing from Codex Madrid I. The screw is advanced by a rotating, toothed nut that engages with a crank-driven worm gear (*detail at left*). Balls or rollers (*detail at top left*) minimize the friction between the nut and its support.

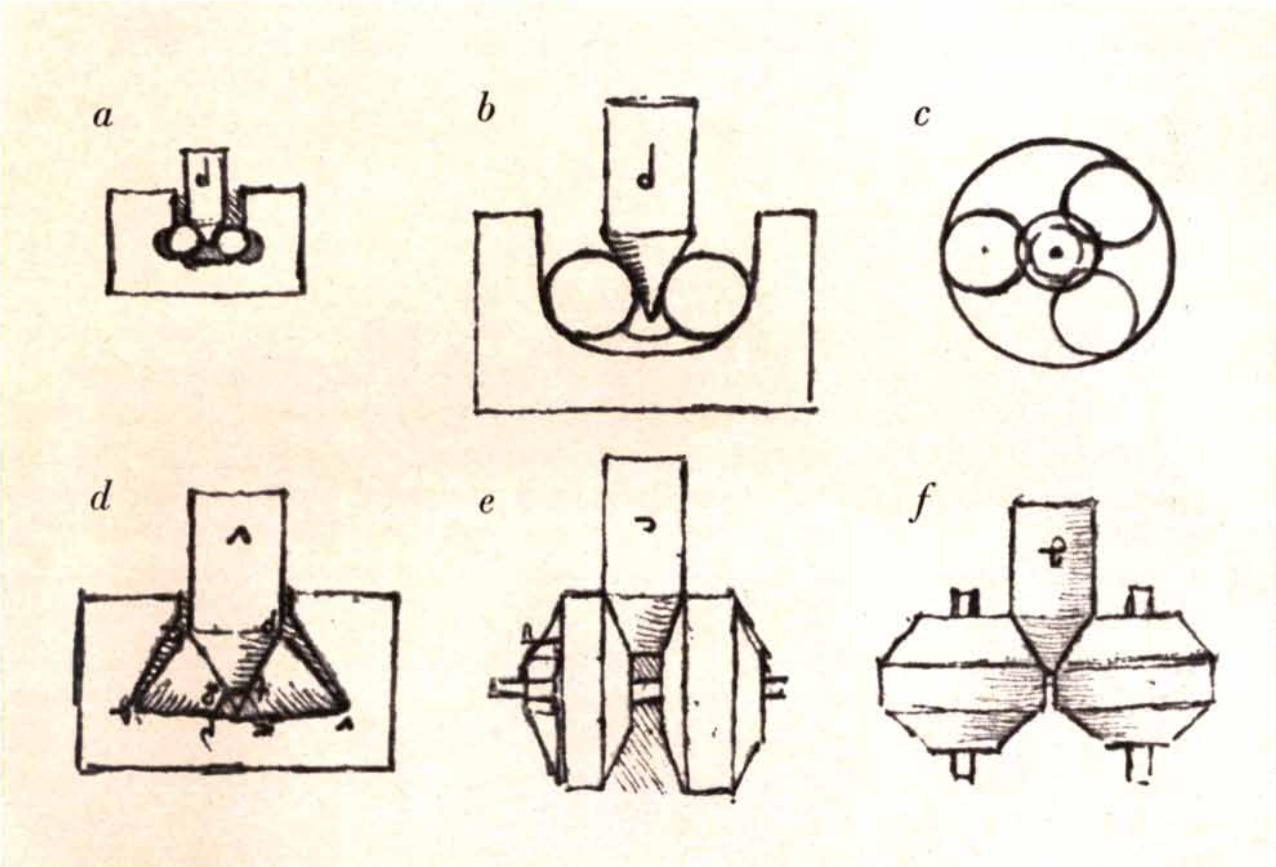
in contact, that it increases in direct proportion to the load and that it can be reduced by interposing rollers or a lubricating fluid between the sliding surfaces. These laws sound obvious today, but one should bear in mind that Leonardo demonstrated them quantitatively two centuries before scientists initiated the modern study of friction and three centuries before the study of this subject was elaborated by Coulomb.

It was Leonardo who introduced the important and immensely useful concept of the coefficient of friction, which is defined as the ratio between the force required to slide one horizontal surface over another and the load, or pressure, between the surfaces. Leonardo estimated that for "polished and smooth" surfaces this ratio, F/P, was .25 (one fourth). This value is reasonably accurate for hardwood on hardwood, bronze on steel and certain other materials with which Leonardo most likely operated. The accuracy of his estimate is remarkable in the light of the fact that the study of friction between unlubricated surfaces is difficult even today.

Having learned some general principles about friction as an isolated phenomenon, Leonardo proceeded to examine the specific problems of friction in machines. Codex Madrid I and some of his other writings give much attention to bearings, and it is clear from these writings and drawings that Leonardo was the first to conceive of the use of roller bearings and ball bearings, although these devices were not commonly adopted in machines until about 1900.

In Leonardo's day and later the bearings in which shafts and axles rotated were generally little more than holes bored in the wood or metal frame of the machine. The grinding action of a rotating shaft produced severe wear, of course, in the hole and on the shaft turning in it, and efforts were made to reduce the wear by spreading tallow or injecting oil between the surfaces in contact. In records of a complex machine used in Spanish waterworks of the 16th century I have found two items of heavy expense for maintenance: tallow for lubrication and charcoal for the forges that had to be operated constantly to repair the machine elements that broke down or wore out.

Leonardo investigated the problem of wear on bearings experimentally and discovered several interesting rules, depicted in the accompanying illustrations [*see page 100*]. One pair of experiments showed that the amount of wear in a



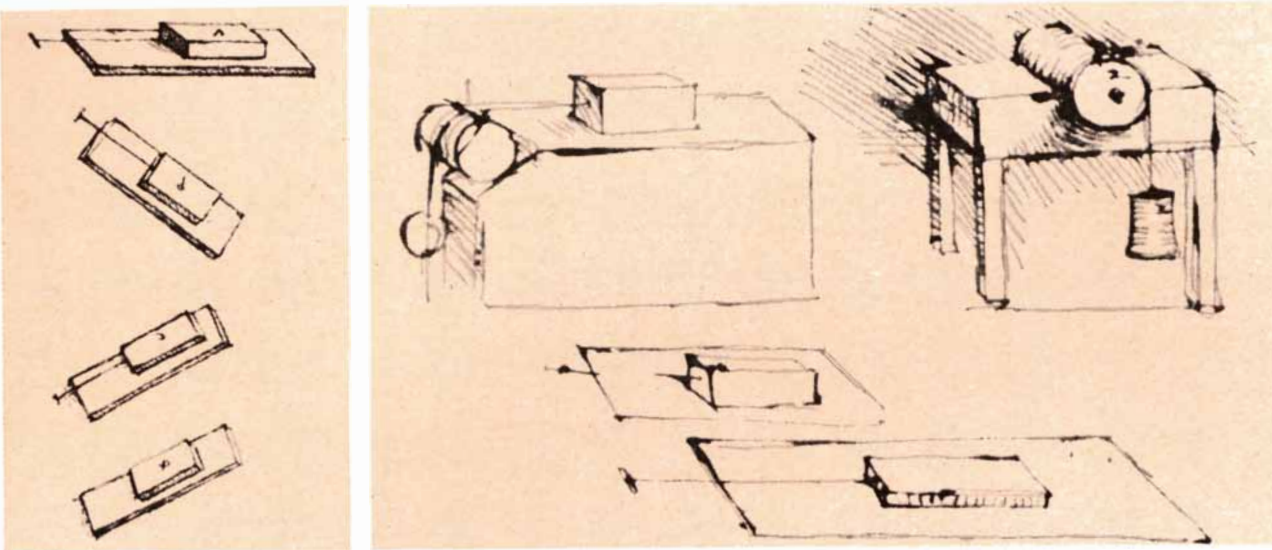
USE OF BALLS (*a–c*), cones (*d*) or rollers shaped like segments of cones (*e, f*) as thrust bearings to support a tapered vertical axle is another of Leonardo's antifriction proposals. It preceded by five centuries the use of a similar bearing in navigational gyroscopes.

bearing supporting a horizontal axle depended on the load, and that the direction of wear was not necessarily vertically downward but depended on the main vector, or direction, of the load. Leonardo found further that, since the wear progressively narrowed the shaft, the groove worn in the bearing had a tapering shape. His practical turn of mind is demonstrated in a pair of drawings showing two different methods of lubricating a bearing; he pointed out that a self-oiling system in which oil was delivered to the bearing from a cup by way of orifices would not work because filings from the wear, dust and oil would soon clog the outlets.

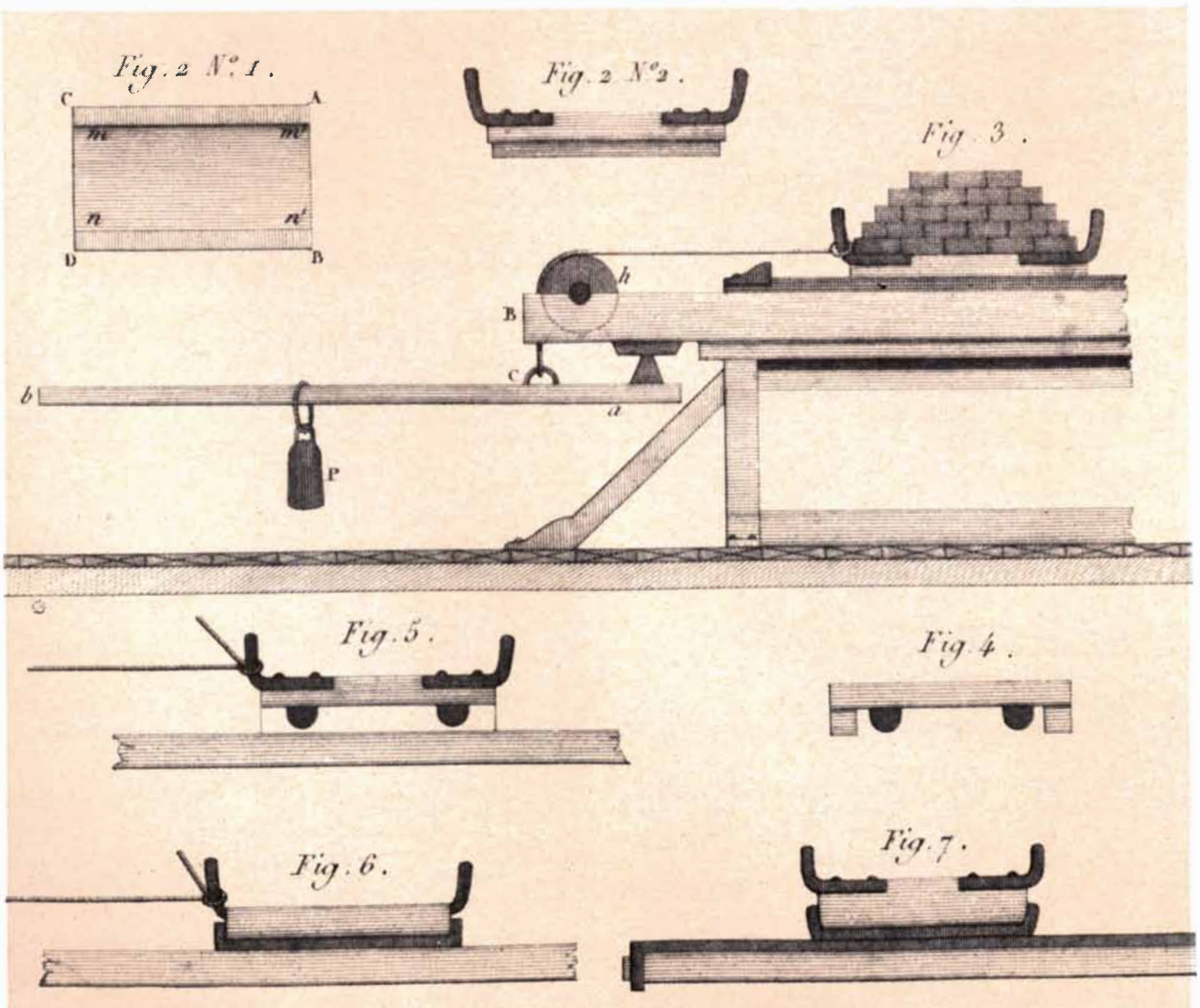
Realizing that lubrication alone could not prevent rapid wear of an axle and its bearing, Leonardo began to explore new ideas, such as the use of materials that would minimize friction and the development of designs that would compensate for the inevitable wear. In Codex Madrid I we find a surprisingly modern concept along these lines. Leonardo devised a bearing in the form of a two-piece block that would prevent an axle from jumping out of the bearing "in spite of any strain." As he described this system, the cheeks of the block, in which the axle rotated, would be made of a smooth "mirror metal" consisting of "three parts of copper and seven of tin melted together." This "mother," as Leonardo called it, would be closed at the top with a wedge for tightening or with a cover that could be adjusted with a screw. Thus the cheeks, or bushings, could be tightened around the axle as wear progressed. We have here, in Leonardo's detailed description, the first suggestion of a bearing block with split, adjustable bushings of antifriction metal, almost 200 years before Robert Hooke proposed the use of such a metal to the Royal Society of London and more than two centuries before the split-bushing idea was embodied in hardware.

Leonardo went on to study the possibilities for minimizing friction by the use of rolling elements, as his experiments had shown that rolling friction was always preferable to sliding friction. The use of rollers and balls to facilitate movement in machines was by no means new with Leonardo; such devices had been employed in machines as early as the ancient Greek period. Nor was Leonardo the first to apply the idea of rolling motion to bearings; in Codex Madrid I he remarked that bearings in the form of disks (whose invention has heretofore been credited to Leonardo) had been seen in Germany by his assistant, a German mechanic named Giulio. Nevertheless, it remains a fact that Leonardo was the first to design true roller bearings and ball bearings of the modern kind.

He began with a number of different schemes for the use of disk bearings, but he soon perceived that the wear in the bearing would be more evenly distributed if rollers were used instead of narrow disks. Thus he was led to designs for bearings based on rollers and balls. Jacks operated by the turning of a screw for lifting heavy loads were then in wide use; their usefulness was limited, however, because under a heavy load severe friction developed between the turning nut and the plate on which it weighed. Leonardo introduced a worm gear to turn the nut, and his drawings in Codex Madrid I suggested that this nut would rest on a ring of roller bearings or ball bearings. Commenting on the use of such



FRICTION BANKS devised by Leonardo enabled him to measure the forces required to slide one surface across another when both are level or on an incline or when a rolling motion is involved. The illustrations are from the Codex Atlanticus and the Codex Arundel.



SIMILAR EXPERIMENTS with friction banks were conducted by Charles Augustin de Coulomb 300 years after Leonardo, using the apparatus illustrated here. Some of it bears a remarkable resemblance to Leonardo's sketches (*see illustration at top of page*).

bearings in general, he remarked in the accompanying text:

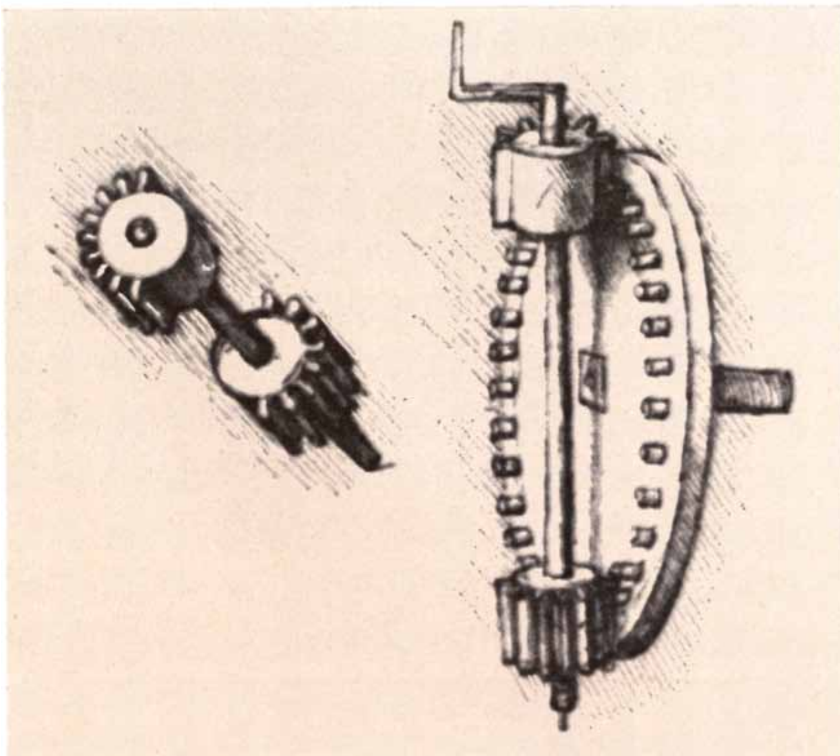
"I affirm that if a weight with a flat surface moves on a similar surface, the movement will be facilitated by interposing between them balls or rollers... and I do not see any difference between balls or rollers save the fact that balls have universal motion whereas rollers can move only in one direction. But if balls or rollers touch each other in their motion, their movement will be more difficult than if there were no contact between them, because when they touch, the friction causes a contrariwise motion and for this reason the movements contradict each other. But if the balls or the rollers are kept at a distance from each other, they will touch at only one point between the load and its resistance... and consequently it will be easy to produce this movement."

Elsewhere in the manuscript Leonardo suggests one solution for this problem: the balls are held between two rotating rings that keep them a set distance apart [*see top illustration on page 104*].

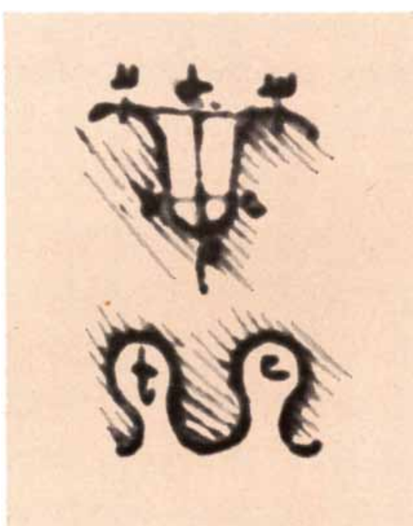
An outstanding example of Leonardo's imaginative applications of roller bearings is a design he offered as being most appropriate for a vertical axle or pivot. The pivot has a conical head that rests in a nest of three balls or three conical rollers of the same size and shape [*see illustration on page 105*]. Leonardo observes: "This way we shall have three equal cones that are identical with the cone of the spindle, and with each turn of the spindle the supporting cones will each have made a complete revolution." On seeing these drawings reproduced in a magazine, Preston Bassett, former president of the Sperry Gyroscope Company, wrote (March 8, 1967) to his friend Bern Dibner, founder of the Burndy Library of the history of science in Norwalk, Conn.:

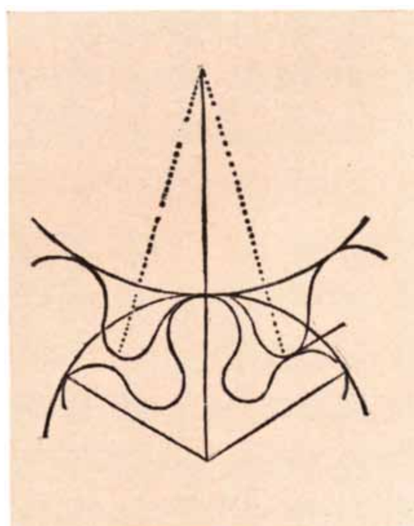
"I must tell you my greatest shock in looking over the Da Vinci sketches was the ball bearing sketch of the balls nested around a conical pivot. When we were developing our blind-flying gyro instruments in the 1920's we had the problem of designing a ball bearing that would have absolutely no end play. We thought we had an innovation with our conical pivot ball bearing, but it is a dead ringer of Da Vinci's sketch!"

Leonardo's remarkable gift of insight into problems in mechanics is most brilliantly exhibited in his studies of gearing and gears. In Codex Madrid I there is a discussion of toothed wheels (gears), illustrated with drawings, that is astonishing in its sophistication. Seeking the best possible shape for gear teeth to minimize frictional resistance, Leonardo shows that teeth of cycloidal shape are superior to ordinary peg teeth, and he illustrates his thesis with a graphic rendering of the circles involved in the contacts between the teeth (now called the addendum, dedendum and pitch circles) that can be considered thoroughly up to date today. Pursuing his analysis of frictional wear in gear trains, he goes on to design gears with teeth of epicycloidal shape—a full two centuries before Olaus Roemer of Denmark and the French mathematician Gérard Desargues demonstrated the merits of this shape. It was not until



CONVERSION OF ROTARY MOTION into reciprocating motion is achieved by the use of a pair of "mutilated" (only partly toothed) gears on a single crankshaft. As the crank turns, the wheel moves first left and then right. Leonardo used but did not invent mutilated gears.





BEST SHAPE FOR GEAR TEETH, resulting in a minimum of frictional resistance, was calculated by Leonardo from observations of the wear shown by flour-mill gears. The shape is epicycloidal (*left*). The ideally shaped gear teeth (*right*), designed two centuries later by Philippe de La Hire, a pioneer in the field, show a strong similarity to Leonardo's sketch.

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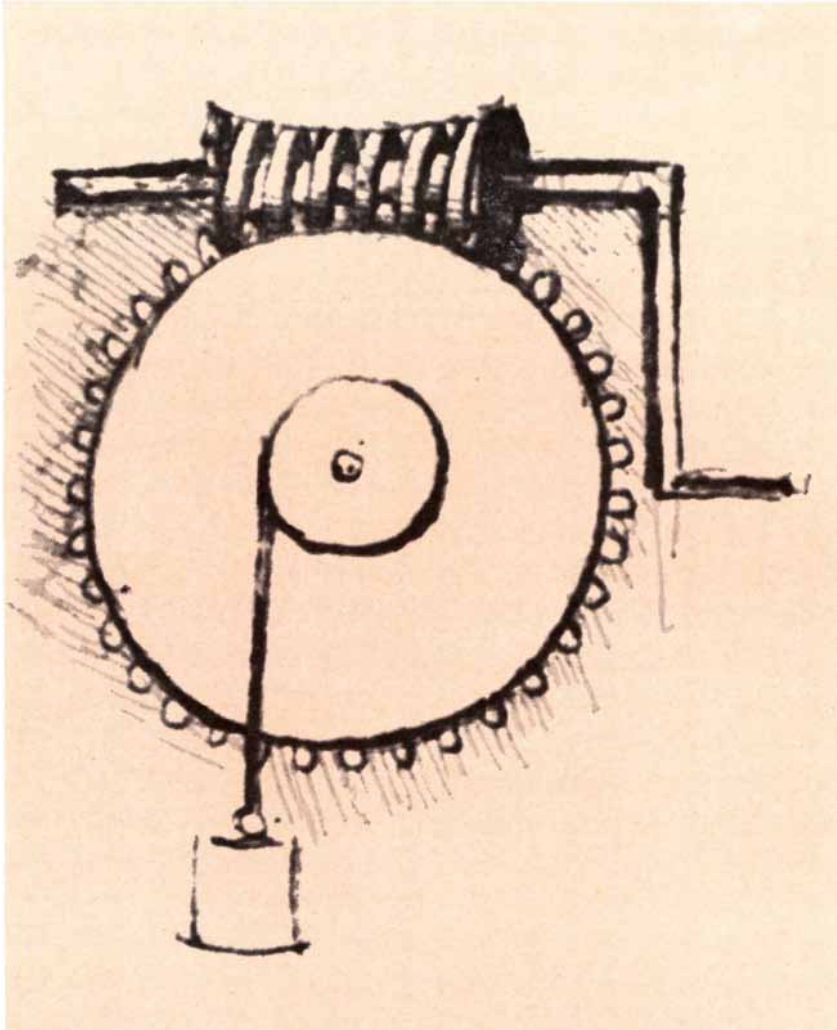
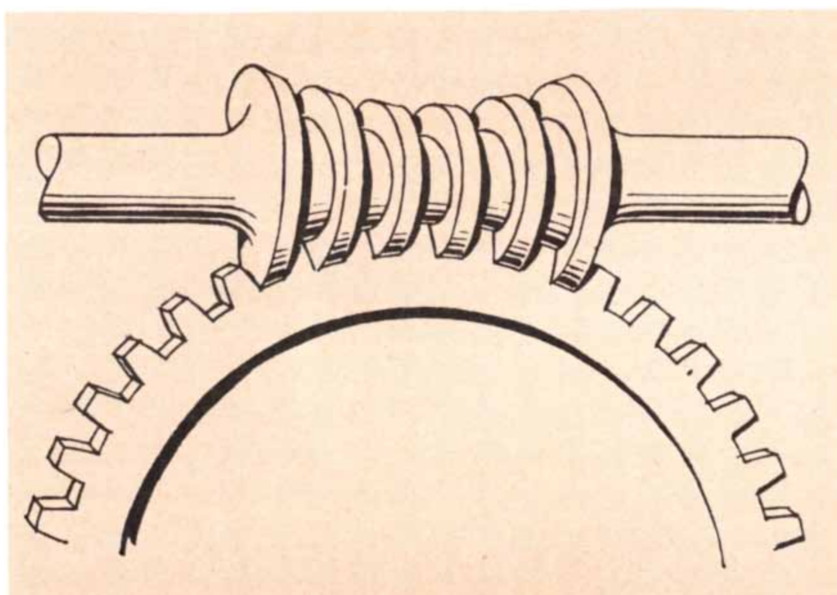
1694, however, that Philippe de La Hire systematically applied the epicycloidal shapes to gear teeth. Like inventors of later times, Leonardo arrived at his rational designs for gear profiles by studying the wear in the traditional gears of flour mills. The most convincing testimony to his matchless capacity for the intuitive solution of complex mechanical problems is that he conceived solutions centuries ahead of anyone else. A comparison of Leonardo's epicycloidal gear teeth with the teeth described two centuries later by La Hire offers dramatic evidence of this [*see lower illustration on page 107*].

Leonardo labored persistently on designs to simplify gearing in order to overcome the bugbear of frictional resistance, observing: "The more wheels you will have in your instrument, the more toothing you will need, and the more teeth, the greater will be the friction of the wheels with the spindles of their pinions. And the larger the friction, the more power is lost by the motor." He introduced a great variety of new gear forms, among them the "mutilated" (partly toothed), trapezoidal, helical and conical bevel gears. Particularly notable was his invention of the globoidal gear, which is generally credited to the 18th-century English engineer Henry Hindley but which we now discover to have been pictured in the Leonardo manuscript found in Madrid [*see illustrations at right*]. Leonardo drafted several designs of the globoidal gear in the form of a worm gear, or "endless screw," and discussed its advantages for a number of applications, including timekeeping.

In closing this brief account I need only mention what is already well known: that Leonardo was actively interested in the uses of friction as well as the problems posed by frictional resistance. His invention of band brakes has often been cited, and his interest in the use of cord drives for various machines also is a matter of fairly common knowledge. In Codex Madrid I, Leonardo remarks that "every motion made with cords is quieter than one that is made with toothed wheels and pinions." In some of his drawings in this manuscript he introduces the use of belts in place of cords, and he pictures a number of cord-driven or belt-driven machines of his invention. The most fanciful use of frictional resistance, perhaps presented with tongue in cheek, is a shock absorber for breaking the fall of a man from a height. A system of interlocking wedges slows the fall by frictional resistance, and at the bottom is a bale of wool to cushion the final impact; its resistance to the im-



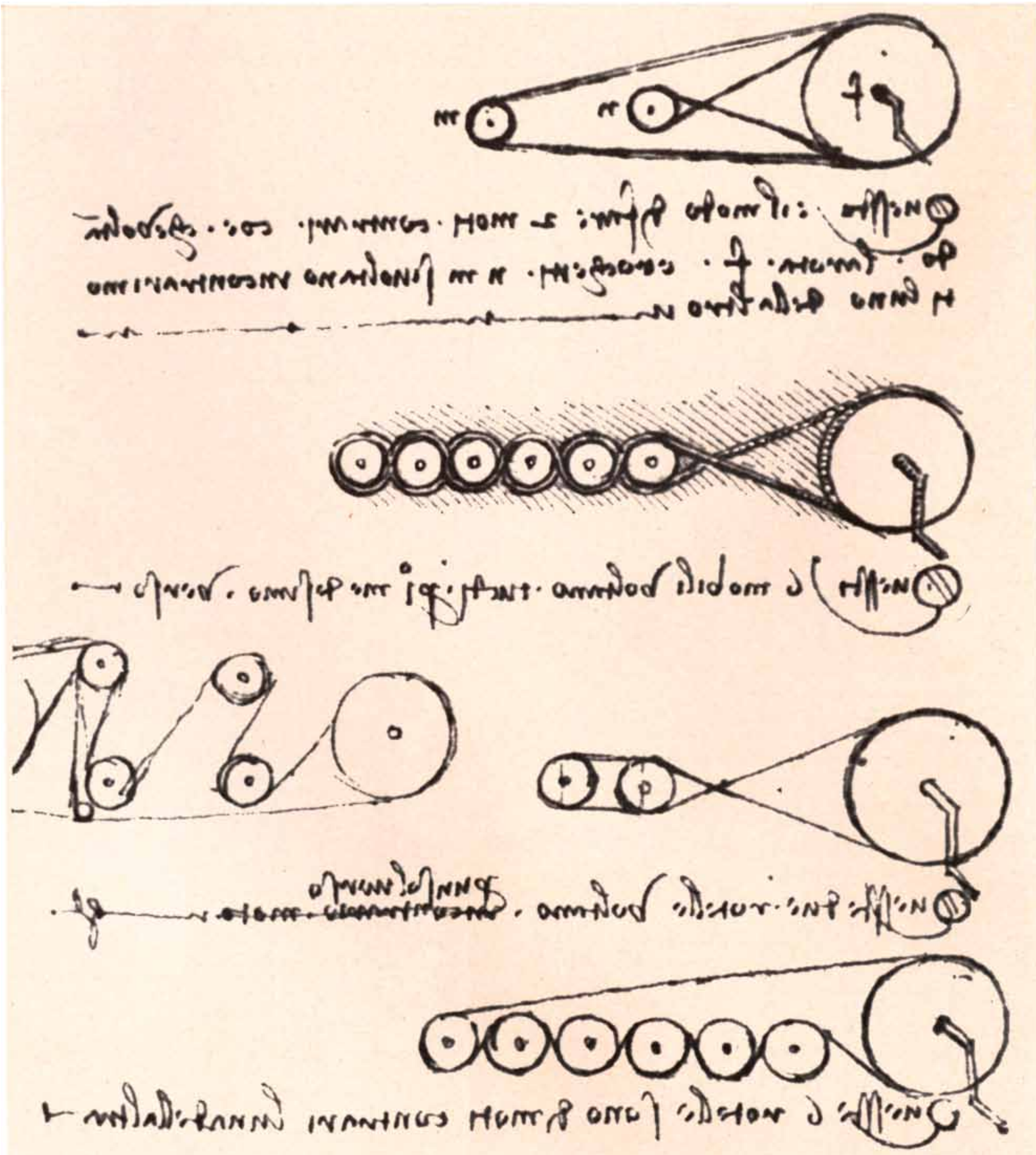
WORM GEAR, shaped to match the curve of the toothed wheel it drives, was designed by Leonardo to overcome the risk inherent in an endless screw that engages only a single tooth.



SIMILAR WORM GEAR was invented by the English engineer Henry Hindley around 1740, nearly 250 years after Leonardo sketched his version of the screw drive in Codex Madrid I.

pact is controlled by means of a wedge that, acting like a pincer, compresses the wool as the fall proceeds.

With this outline of evidence from Codex Madrid I, pictorial and textual, I rest my case and leave it to the readers of *Scientific American* to decide for themselves whether Leonardo da Vinci was an armchair technologist or a serious student who actually performed experiments and built apparatus and machines to test his ideas. Those who wish to look into the matter further can do so in extensive collections of Vinciana in the U.S., particularly those at the Elmer Belt Library of Vinciana of the University of California at Los Angeles, which contains probably the most complete assemblage of writings by and about Leonardo in the world, donated by the surgeon and physician Elmer Belt; at the Burndy Library, founded by Bern Dibner, and at the Stevens Institute of Technology in Hoboken, N.J., the gift of the electrical engineer John W. Lieb. Unfortunately after the donor's death this last collection was not updated by the important recent literature on the subject.



FORCE OF FRICTION was put to useful work by Leonardo in a variety of cord-driven and belt-driven machines that he admired for their quietness in comparison to devices driven by gears. Here he shows how motions may be altered by changing cord arrangements.

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MATHEMATICAL GAMES

On cellular automata, self-reproduction, the Garden of Eden and the game "life"

by Martin Gardner

John Horton Conway's game "life," last October's topic, stirred such interest among computer scientists that this month's department will again be devoted to the game. Before reporting as many new discoveries as possible I should like to discuss some highlights in the history of "cellular automata theory," the field in which games similar to Conway's are being investigated.

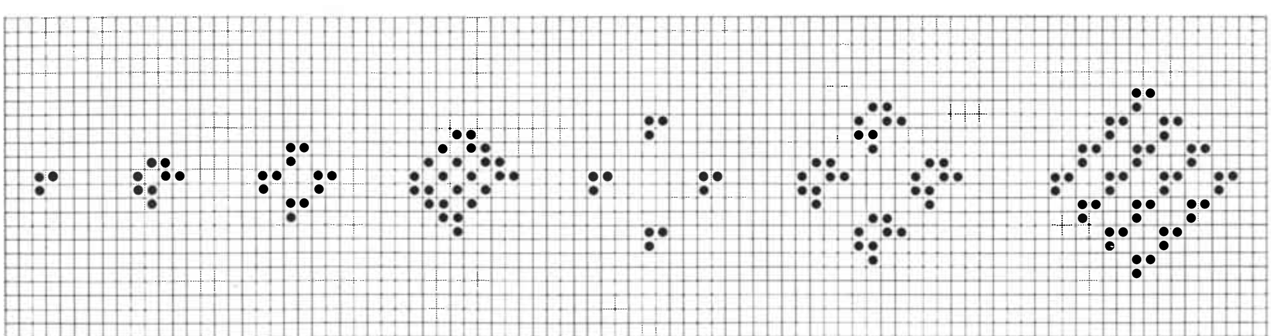
It all began about 1950, when John von Neumann set himself the task of proving the possibility of self-duplicating automata. Such a machine, given proper instructions, would build an exact duplicate of itself. Each of the two machines would then build another, the four would become eight, and so on. (This proliferation of self-replicating automata is the basis of Lord Dunsany's amusing 1951 novel *The Last Revolution.*) Von Neumann first proved his case with "kinematic" models of a machine that could roam through a warehouse of parts, select needed components and put together a copy of itself. Later, adopting an inspired suggestion by his friend Stanislaw M. Ulam, he showed the possibility of such machines in a more elegant and abstract way.

Von Neumann's new proof used what is now called a "uniform cellular space" equivalent to an infinite checkerboard. Each cell can have any finite number of "states," including a "quiescent" (or empty) state, and a finite set of "neighbor" cells that can influence its state. The pattern of states changes in discrete time steps according to a set of "transition rules" that apply simultaneously to every cell. The cells symbolize the basic parts of a finite-state automaton and a configuration of live cells is an idealized model of such a machine. Conway's game is based on just such a space. His neighborhood consists of the eight cells surrounding a cell; each cell has two states (empty or filled), and his transition rules are the birth, death and survival rules I explained in October. Von Neumann, applying transition rules to a space in which each cell has 29 states and four orthogonally adjacent neighbors, proved the existence of a configuration of about 200,000 cells that would self-reproduce.

The reason for such an enormous configuration is that, for von Neumann's proof to apply to actual automata, it was necessary that his cellular space be capable of simulating a Turing machine: an idealized automaton, named for its inventor, the British mathematician A. M. Turing, capable of performing any desired calculation. By embedding this universal computer in his configuration, von Neumann was able to produce a universal constructor. Because it could in principle construct any desired configuration by stretching "arms" into an empty region of the cellular space, it would self-replicate when given a blueprint of itself. Since von Neumann's death in 1957 his existence proof (the actual configuration is too vast to construct and manipulate) has been greatly simplified. The latest and best reduction, by Edwin Roger Banks, a mechanical engineering graduate student at the Massachusetts Institute of Technology, does the job with cells of only four states.

Self-replication in a trivial sense—without using configurations that contain Turing machines—is easy to achieve. A delightfully simple example, discovered by Edward Fredkin of M.I.T. about 10 years ago, uses two-state cells, the von Neumann neighborhood of four orthogonally adjacent cells and the following parity rule: Each cell with an even number of live neighbors (0, 2, 4) at time t becomes or remains empty at time $t + 1$, and each cell with an odd number of neighbors (1, 3) at time t becomes or remains live at time $t + 1$. It is not hard to show that after 2^n moves (n varying with different patterns) any initial pattern of live cells will reproduce itself four times—above, below, left and right of an empty space that it formerly occupied. The four replicas will be displaced 2^n cells from the vanished original. The new pattern will, of course, replicate again after another 2^n steps, so that the duplicates keep quadrupling in the endless series 1, 4, 16, 64, ... The illustration below shows two quadruplings of a right tromino. Terry Winograd, in a 1967 term paper written when he was an M.I.T. student, generalized Fredkin's rule to other neighborhoods, any number of dimensions and cells with any prime number of states.

Ulam investigated a variety of cellular automata games, experimenting with different neighborhoods, numbers of states and transition rules. In a 1967 paper "On Recursively Defined Geomet-



The replication of a tromino

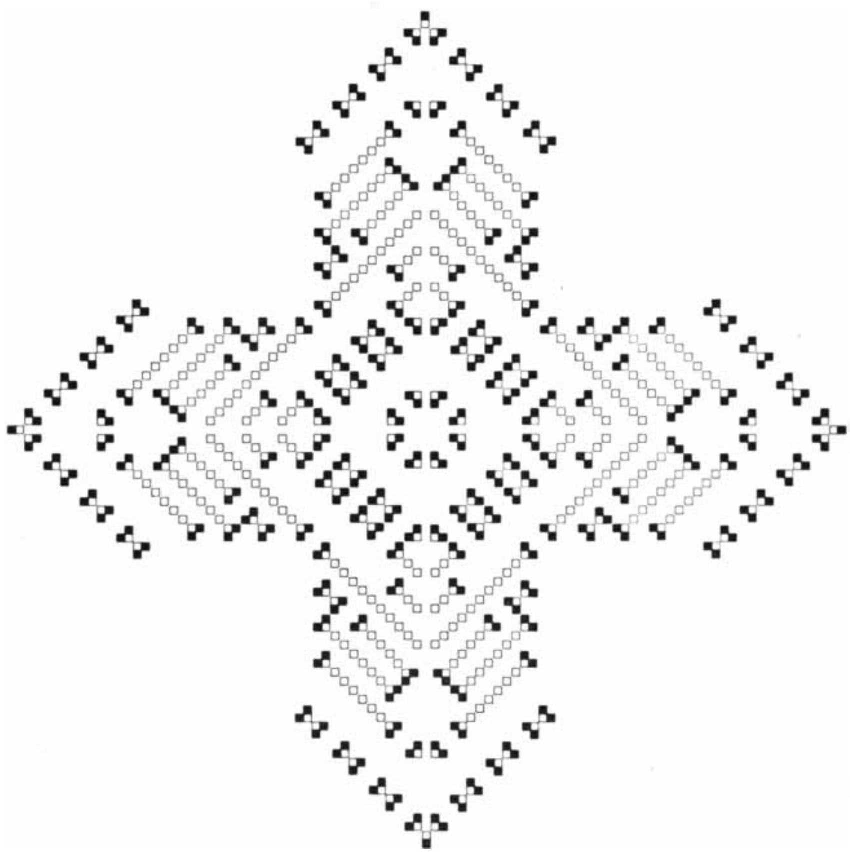
rical Objects and Patterns of Growth," written with Robert G. Schrandt, Ulam described a number of different games. The upper illustration on this page shows generation 45 of a history that began with one counter on the central cell. As in Conway's game, the cells are two-state, but the neighborhood is that of von Neumann (four adjacent orthogonal cells). Births occur on cells that have one and only one neighbor, and all live cells of generation n vanish when generation $n + 2$ is born. In other words, only the last two generations survive at any step. In the illustration the 444 new births are shown as black cells. The 404 white cells of the preceding generation will all disappear on the next move. Note the characteristic subpattern, which Ulam calls a "dog bone." Ulam experimented with games in which two configurations were allowed to grow until they collided. In the ensuing "battle" one side would sometimes wipe out the other; sometimes both armies would be annihilated. Ulam also explored games on three-dimensional cubical tessellations. His major papers on cellular automata are in *Essays on Cellular Automata* (University of Illinois Press, 1970), edited by Arthur W. Burks.

Similar games can be devised for triangular and hexagonal tessellations but, although they *look* different, they are not essentially so. All can be translated into equivalent games on a square tessellation by a suitable definition of "neighborhood." A neighborhood need not be made up of touching cells. In chess, for instance, a knight's neighborhood consists of the squares to which it can leap and squares on which there are pieces that can attack it. As Burks has pointed out, games such as chess, checkers and go can be regarded as cellular automata games in which there are complicated neighborhoods and transition rules and in which players choose among alternative next states in an attempt to be first to reach a certain final state that wins.

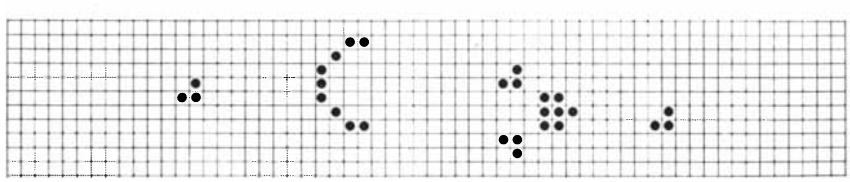
Among the notable contributions of Edward F. Moore to cellular automata theory the best-known is a technique for proving the existence of what John W. Tukey named "Garden of Eden" patterns. These are configurations that cannot arise in a game because no preceding generation can form them. They appear only if given in the initial (zero) generation. Because such a configuration has no predecessor, it cannot be self-reproducing. I shall not describe Moore's ingenious technique because he explained it informally in an article in this magazine [see "Mathematics in the Biological Sciences," by Edward F. Moore; September, 1964] and more formally in a paper that is included in Burks's anthology.

Alvy Ray Smith III, a cellular automata expert at New York University's School of Engineering and Science, found a simple application of Moore's technique to Conway's game. Consider two five-by-five squares, one with all cells empty, the other with one counter in the center. Because, in one move, the central nine cells of both squares are certain to become identical (in this case all cells empty) they are said to be "mutually erasable." It follows from Moore's theorem that a Garden of Eden configuration must exist in Conway's game. Unfortunately the proof does not tell how to find such a pattern and so far none is known. It may be simple or it may be enormously complex. Using one of Moore's formulas, Smith has been able to calculate that such a pattern exists within a square of 10 billion cells on a side, which does not help much in finding one.

Smith has been working on cellular automata that simulate pattern-recognition machines. Although this is now only of theoretical interest, the time may come when robots will need "retinas" for recognizing patterns. The speeds of scanning devices are slow compared with the speeds obtainable by the "parallel computation" of animal retinas, which simultaneously transmit thousands of messages to the brain. Parallel computation is the only way new computers can increase significantly in speed because without it they are limited by the speed of light through miniaturized circuitry [see "The Fastest Computer," by D. L.



Generation 45 in a cellular game devised by Stanislaw M. Ulam



A configuration that grows into a glider gun

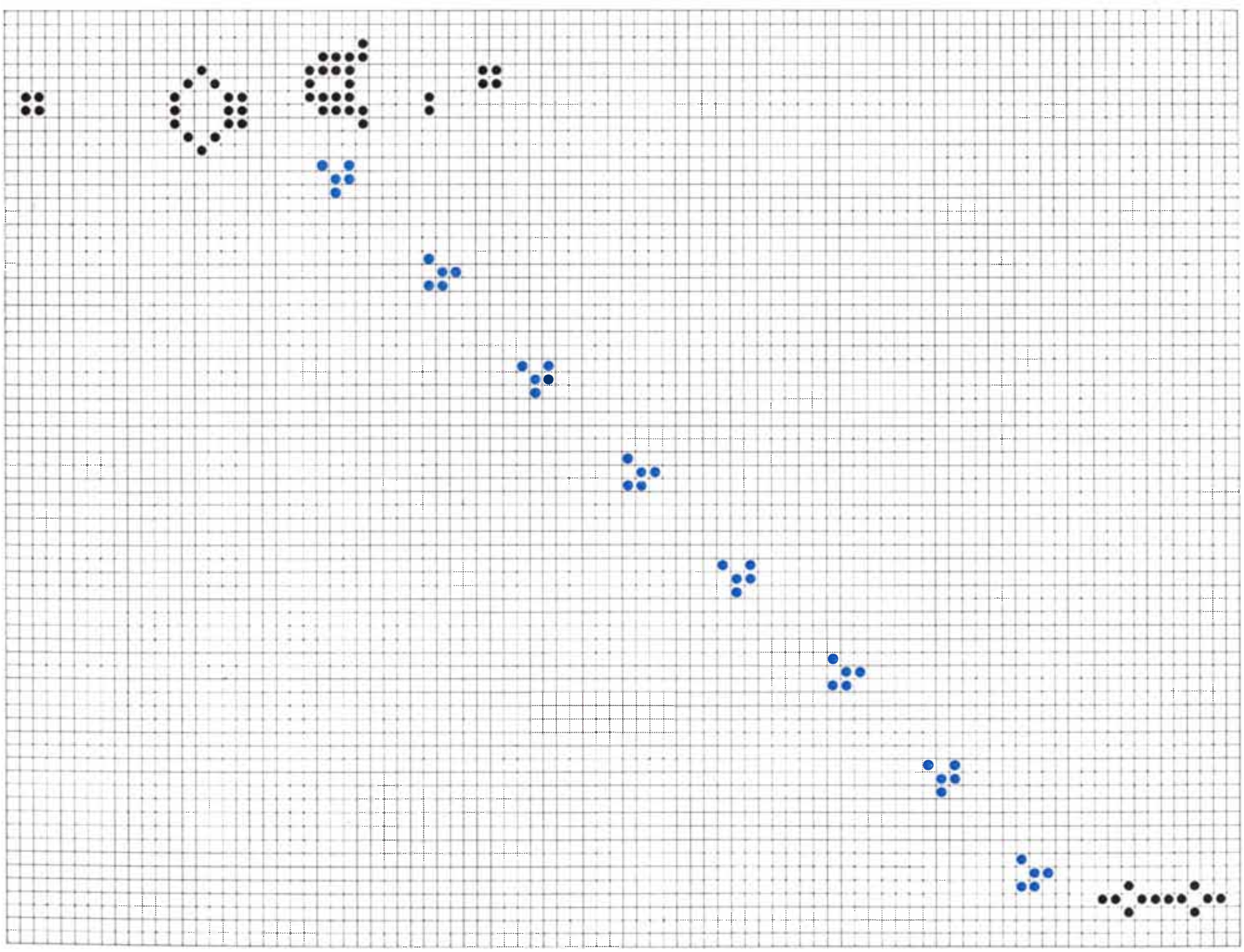
Slotnick, page 76]. The cover of this issue of SCIENTIFIC AMERICAN shows a simple procedure, devised by Smith, by which a finite one-dimensional cellular space employs parallel computation for recognizing palindromic symmetry. Each cell has many possible states, the number depending on the number of different symbols in the palindrome, and a cell's neighborhood is the two cells on each side.

On the cover, which Smith designed, he symbolizes the palindrome TOO HOT TO HOOT with four states of cells in the top row. *T*, *O* and *H* are represented by blue, red and yellow respectively, and black marks the palindrome's two ends. The white cells in the other rows are in the quiescent state. The horizontal rows below the top row are successive generations of the top configuration when certain transition rules are followed in discrete time steps. In other words, the picture is a space-time diagram of a single row, each successive row indicating the next generation.

In the first transition each color travels one cell to the left and one cell to the right, except for the end colors, which are blocked by black; black moves inward at each step. Each cell on which two colors land acquires a new state, symbolized by a cell divided into four triangles. The left triangle has the color that was previously on the left, the right triangle has the color previously on the right. The result of this first move is shown in the second row. When an adjacent pair of cells forms a tilted square in the center that is a solid color, it indicates a "collision" of like colors and is symbolized by black dots in the two white triangles of the left cell. Dots remain in that cell for all subsequent generations unless a collision of unlike colors occurs to the immediate right of the dotted cell, in which case the dots are erased. When collisions of *unlike* colors occur, the left cell of the pair remains undotted for all subsequent generations even though like colors may later collide on its right.

At each move the colors continue to travel one cell left or right (the direction in which the colored triangles point) and all rules apply. If the palindrome has n letters, with n even as in this example (the scheme is modified slightly if n is odd), it is easy to see that after $n/2$ moves only two adjacent nonquiescent cells remain. If the left cell of this pair is dotted, the automaton has recognized the initial row as being palindromic. Down the diagram's center you see the colliding pairs of like colors in the same order as they appear on the palindrome from the center to each end. As soon as recognition occurs the left cell of the last pair is erased and the right cell is altered to an "accept" state, here symbolized by nested squares. An undotted left cell would signal a nonpalindrome, in which case the left cell would become blank and the right cell would go into a "reject" state.

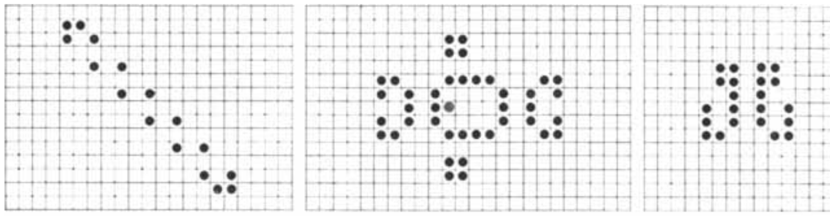
A Turing machine, which computes serially, requires in general n^2 steps to recognize a palindrome of length n. Al-



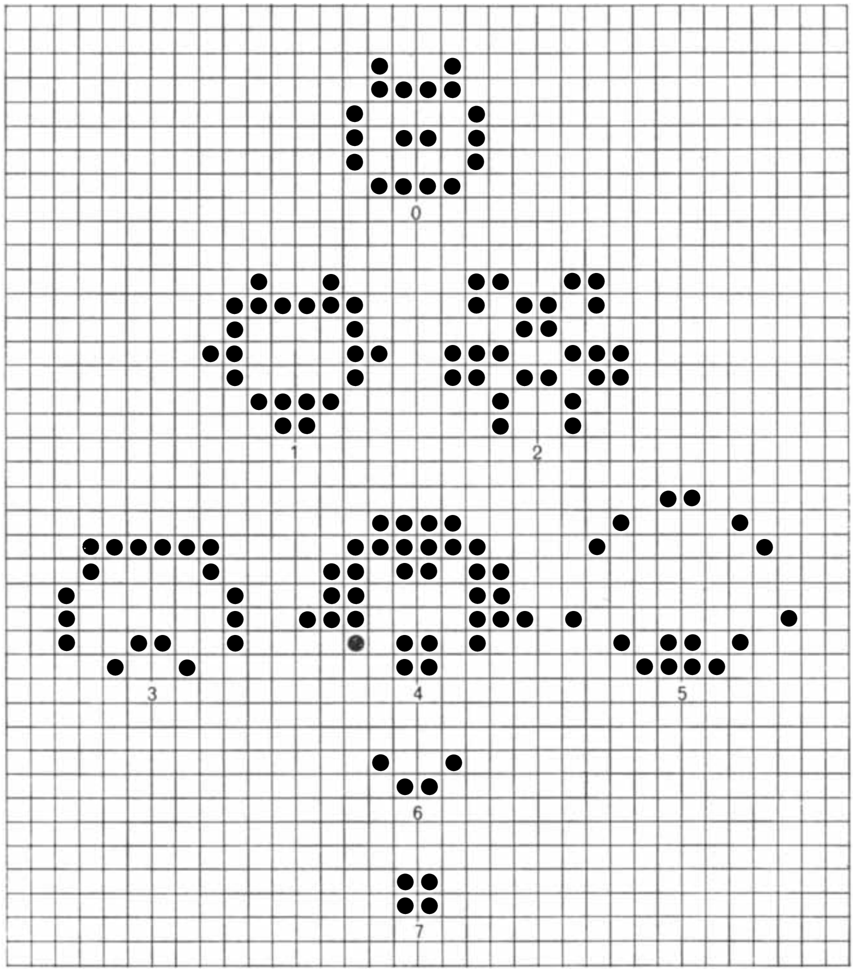
Pentadecathlon (bottom right) *"eats" gliders* (color) *fired by the gun* though recognition occurs here at step $n/2$, the accept state is shown moving in subsequent generations to the right to symbolize the cell-by-cell transmission of the acceptance to an output boundary of the cellular space. Of course it is easy to construct more efficient palindrome-recognizing devices with actual electronic hardware, but the point here is to do it with a highly abstract, one-dimensional cellular space in which information can pass only from a cell to adjacent cells and not even the center of the initial series of symbols is known at the outset. As Smith puts it anthropomorphically, after the first step each of the three dotted cells thinks it is at the center of a palindrome. The dotted cells at each end are disillusioned on the next move because of the collision of unlike colors at their right. Not until generation $n/2$ does the dotted cell at the center know it actually *is* at the center.

Now for some startling new results concerning Conway's game. Conway was fully aware of earlier games and it was with them in mind that he selected his recursive rules with great care to avoid two extremes: too many patterns that grow quickly without limit and too many that fade quickly. By striking a delicate balance he designed a game of surprising unpredictability and one that produced such remarkable figures as oscillators and moving spaceships. He conjectured that no finite population could grow (in number of members) without limit, and he offered $50 for the first proof or disproof. The prize was won in November by a group in the Artificial Intelligence Project at M.I.T. consisting of (in alphabetical order) Robert April, Michael Beeler, R. William Gosper, Jr., Richard Howell, Rich Schroeppel and Michael Speciner. Using a program devised by Speciner for displaying moves on an oscilloscope, Gosper made a truly astounding discovery: he found a glider gun! The configuration in the lower illustration on page 113 grows into such a gun, firing its first glider on move 40. The gun is an oscillator of period 30 that ejects a new glider every 30 moves. Since each glider adds five more counters to the field, the population obviously grows without limit.

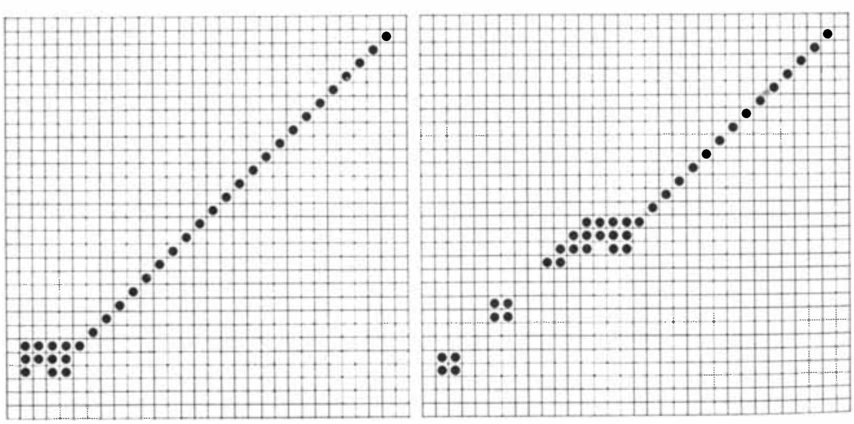
The glider gun led the M.I.T. group to many other amazing discoveries. A series of printouts (supplied by Robert T. Wainwright of Yorktown Heights, N.Y.) shows how 13 gliders crash to form a glider gun [*see illustration on page 117*]. The last five printouts show the gun in full action. The group also found a way to position a pentadecathlon [*see*



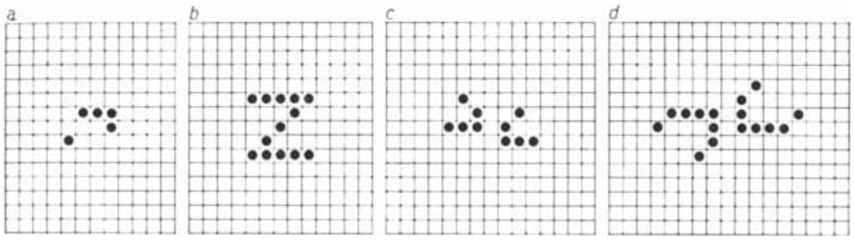
Barber pole (left), *Hertz oscillator* (middle) *and tumbler* (right)



The Cheshire cat (0) *fades to a grin* (6) *and disappears, leaving a paw print* (7)



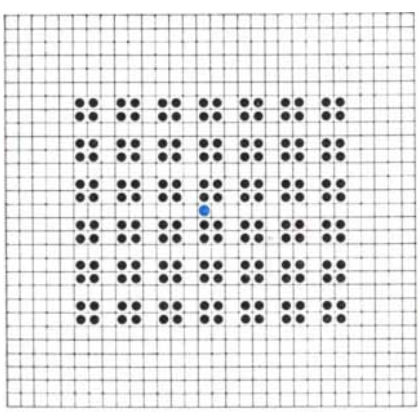
The harvester, shown at generations 0 (left) *and 10* (right)



Two spawners of gliders and two collision courses

illustration on page 114], an oscillator of period 15, so that it "eats" every glider that strikes it. A pentadecathlon can also reflect a glider 180 degrees, making it possible for two pentadecathlons to shuttle a glider back and forth forever. Streams of intersecting gliders produce fantastic results. Strange patterns can be created that in turn emit gliders. Sometimes collision configurations grow until they ingest all guns. In other cases the collision mass destroys one or more guns by shooting back. The group's latest burst of virtuosity is a way of placing guns so that the intersecting streams of gliders build a factory that assembles and fires a lightweight spaceship every 300 moves.

The existence of glider guns raises the exciting possibility that Conway's game will allow the simulation of a Turing machine, a universal calculator capable in principle of doing anything the most powerful computer can do. The trick would be to use gliders as unit pulses for storing and transmitting information and performing the required logic operations that are handled in actual computers by their circuitry. If Conway's game allows a universal calculator, the next question will be whether it allows a universal constructor, from which nontrivial self-replication would follow. So far this has not been achieved with a two-state space and Conway's neighborhood, although it has been proved impossible with two states and the von Neumann neighborhood.



Pattern doomed by a virus (color)

The M.I.T. group found many new oscillators [*see top illustration on preceding page*]. One of them, the barber pole, can be stretched to any length and is a flip-flop, with each state a mirror image of the other. Another, which they rediscovered, is a pattern Conway's group had found earlier and called a Hertz oscillator. Every four moves the colored "bit" switches from one side of the central frame to the other, making it an oscillator of period 8. The tumbler, which was found by George D. Collins, Jr., of McLean, Va., turns upside down every seven moves.

The Cheshire cat [*see middle illustration on preceding page*] was discovered by C. R. Tompkins of Corona, Calif. On the sixth move the face vanishes, leaving only a grin; the grin fades on the next move and only a permanent paw print (block) remains. The harvester was constructed by David W. Poyner of Basildon in England. It plows up an infinite diagonal at the speed of light, oscillating with period 4 and ejecting stable packages along the way [*see bottom illustration on preceding page*]. "Unfortunately," writes Poyner, "I have been unable to develop a propagator that will sow as fast as the harvester will reap."

Wainwright has made a number of intriguing investigations. He filled a 120-by-120 square field with 4,800 randomly placed bits (a density of one-third) and tracked their history for 450 generations, by which time the density of this primordial soup, as Wainwright calls it, had thinned steadily to one-sixth. Whether it would eventually vanish or, as Wainwright says, percolate at a constant minimum density is anybody's guess. At any rate, during the 450 generations 42 short-lived gliders were formed. Wainwright found 14 different patterns that became glider states on the next move. The pattern that produced the greatest number of gliders (14 in all) is shown [*"a" in illustration above*]. A Z-pattern found by Collins and by Jeffrey Lund of Pewaukee, Wis., after 12 moves becomes two gliders that sail off in opposite directions [*b*]. Wainwright and others set two gliders on a collision course that causes all bits to vanish on the fourth move [*c*]. Wallace W. Wagner of Anaheim, Calif., found a collision course for two lightweight spaceships that also ends (on the seventh move) in total blankness [*d*].

Wainwright has experimented with various infinite fields of regular stable patterns, which he calls agars—rich culture mediums. When, for instance, a single "virus," or bit, is placed in the agar of blocks shown in the illustration at bottom left so that it touches the corners of four blocks, the agar eliminates the virus and repairs itself in two moves. If, however, the alien bit is positioned as shown (or at any of the seven other symmetrically equivalent spots), it initiates an inexorable disintegration of the pattern. The portion eaten away contains active debris that has overall bilateral symmetry along one axis and a roughly oval border that expands, probably forever, in the four compass directions at the speed of light.

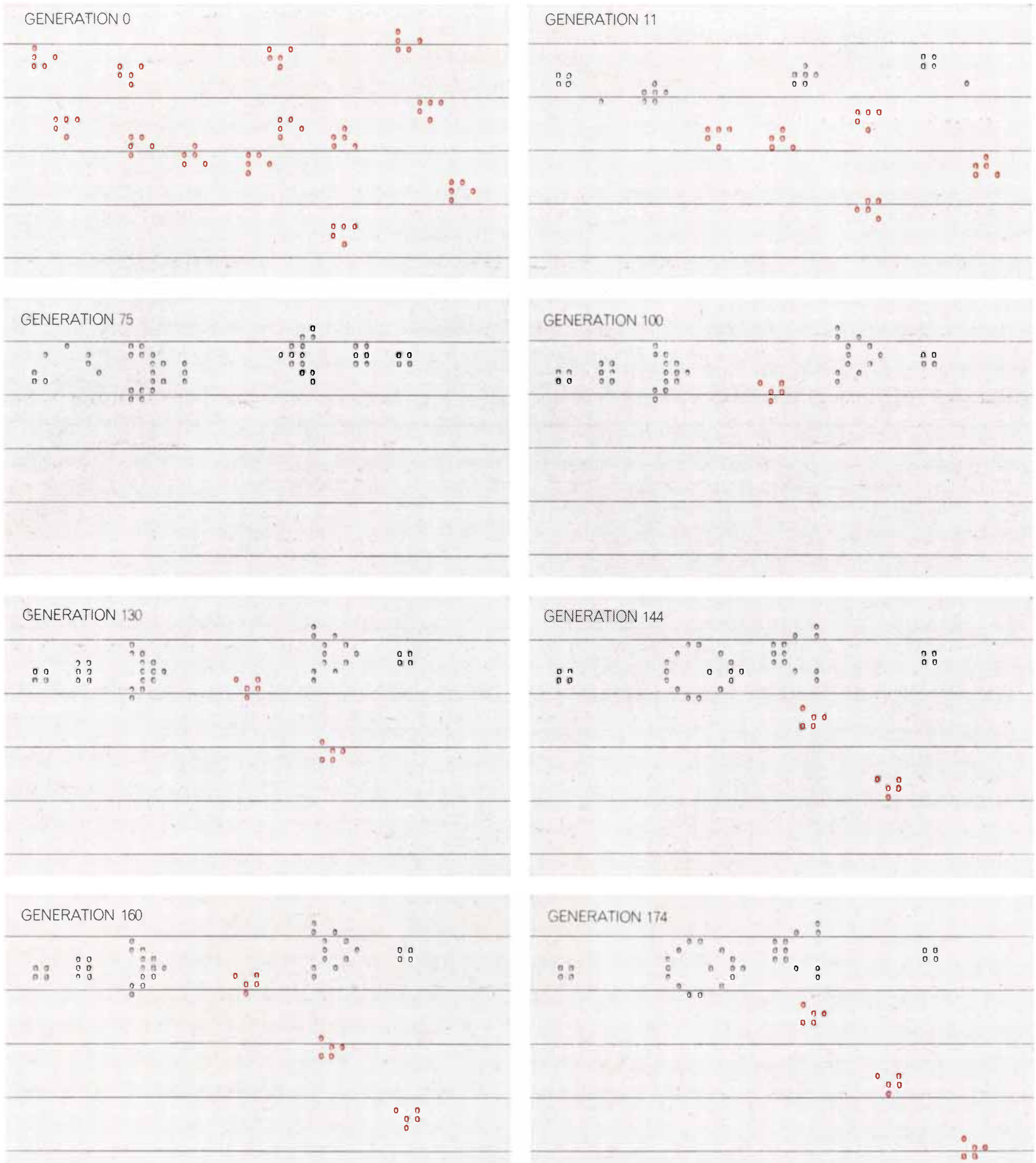
The most immediate practical application of automata theory, Banks believes, is likely to be in the design of circuits capable of self-repair or the wiring of any specified type of new circuit. No one can say how significant the theory may eventually become for the physical and biological sciences. It may have important bearings on cell growth in embryos, the replication of DNA molecules, the operation of nerve nets, genetic changes in evolving populations and so on. Analogies with life processes are impossible to resist. If a primordial broth of amino acids is large enough, and there is sufficient time, self-replicating, moving automata may result from complex transition rules built into the structure of matter and the laws of nature. There is even the possibility that space-time itself is granular, composed of discrete units, and that the universe, as Fredkin and others have suggested, is a cellular automaton run by an enormous computer. If so, what we call motion may be only simulated motion. A moving spaceship, on the ultimate microlevel, may be essentially the same as one of Conway's spaceships, appearing to move on the macrolevel whereas actually there is only an alteration of states of basic space-time cells in obedience to transition rules that have not yet been discovered.

To the corrections given last month for the original discussion of Conway's game the following should be added. An orthogonal row of eight adjacent counters ends as four blocks and four beehives, and the 5–5–5 row ends as four blocks and two blinkers. In November's illustration of a large spaceship escorted by two smaller ones, the top ship should have been separated by three cells from the middle one. Readers too numerous to mention have confirmed all three corrections.

The number puzzles posed last month by Dr. Matrix have the following answers. In addition to 9,240, the only other number smaller than 10,000 that has 63 proper divisors (including 1 but not the number itself) is 7,560. No other number of four or fewer digits has this many proper divisors. Here is the only way to arrange two three-digit square numbers in a two-by-three matrix so that each column, read from the top down, is a two-digit square:

841
196 .

A newsletter, *The Soma Addict*, is now available at no charge on request from Parker Brothers, P.O. Box 900, Salem, Mass. 01970.



How 13 gliders (color) *crash to form a glider gun* (generation 75) *that oscillates with a period of 30, firing a glider in each cycle*

THE AMATEUR SCIENTIST

Experiments with a new standard filter material that has extremely fine pores

Conducted by C. L. Stong

On the farm where the editor of this department grew up we tried to purify drinking water by pumping it through several layers of cheesecloth. We changed the cloth when it became clogged with water bugs that lived in our well. Our neighbors used similar filters.

After some years we learned that smaller bugs came through the cheesecloth: organisms that spread dysentery and typhoid fever through town and country alike in the days of the open well, the privy, the open sewer and the manure pile. Subsequent events have proved that the idea of purifying water with a filter is perfectly sound. All we needed on the farm was a sieve with smaller holes, such as those in the filters used by the Apollo astronauts for screening bacteria out of their drinking water. This novel filtering material consists of a plastic membrane that contains millions of holes per square inch, all exactly the same size. The development of the membrane filter has given rise to a dozen new fields of experimentation that should appeal to amateurs, particularly those who have an interest in pollution control.

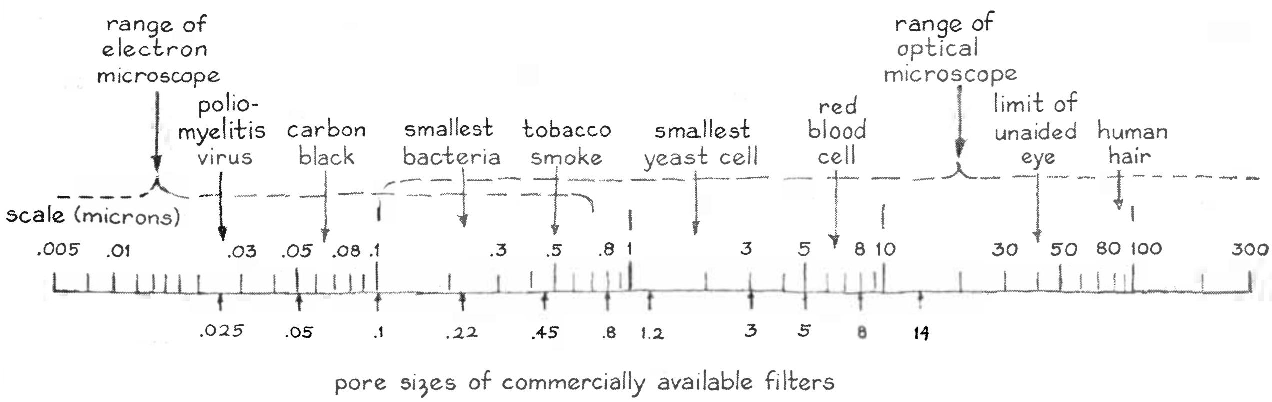
The new filtering material is made by mixing two kinds of plastic and forming the mixture into a membrane. The molecules of one plastic are stable. The molecules of the other plastic are relatively volatile, but they can be stabilized. To perforate the sheet the manufacturer allows molecules of the volatile plastic to evaporate until holes of the desired size form in the membrane; volatilization is then halted.

The filters are available commercially with uniform holes in a range of sizes down to a diameter of a millionth of an inch. Pores that small, which are beyond the resolving power of optical microscopes, will hold back particles as small as the virus of poliomyelitis. Although the membrane is actually clear, it resembles white paper because the perforations scatter light. Twenty percent of the membrane is solid; the rest is empty space. In contrast, the porosity of ordinary window screening is less than 55 percent.

Water passes through the membrane some 40 times faster than it does through filter paper that would retain particles of the same size. When the membrane is saturated with clear oil with a matching index of refraction, it becomes almost as transparent as glass. Indeed, a filter on which organisms have collected can be converted into the equivalent of a glass microscope slide with a drop of immersion oil.

One might assume that a plastic membrane containing 80 percent holes would be easily crushed. In actuality membranes that are properly supported withstand pressure differentials of up to five tons per square inch. Most filter papers become unreliable at pressures above 20 pounds per square inch. Incidentally, all filters can be put in two basic categories, depth filters and screen filters, according to the filtering mechanism. Depth filters consist of a thick mass of fibers, grains or fragmented substances that create a maze of flow passages where particles become lodged. Screen filters, of which the plastic membrane is an example, consist of a perforated sheet—a sieve—on which the particles collect in an accessible layer. Particles are retained on a screen filter rather than in it, with at least one important consequence: all the collected particles are exposed to view.

The fact that filtered particles collect as a uniformly distributed layer on a relatively inert sheet of porous plastic makes the membrane a convenient surface for culturing microorganisms. It takes only seconds to saturate a pad with nutrient solution and put a filter of organisms on it for growth. Nutrient reaches the organisms by diffusing through the porous membrane. When growth is complete, colonies of organisms can be examined



Pore size of typical membranes

with a microscope. They can also be converted into a permanent record of the experiment by fixing the colony with a solution of phenol glycerin.

Membrane filters are available commercially from the Millipore Corporation, Bedford, Mass. 01730. They are available in a range of sizes from about half an inch to 12 inches in diameter (and also in tubular form) and are .006 inch thick. Normally the fluid to be filtered is passed through the membrane under pressure.

Most specimen fluids can be filtered with greatest convenience by the use of a vacuum apparatus, which typically consists of a funnel provided with an outlet that supports the filter. The outlet, in turn, must make an airtight fit with a flask that receives the filtrate [*see bottom illustration at right*]. Atmospheric pressure is exerted on the specimen fluid when air is pumped from the receiver flask.

It is possible to build the vacuum filtering apparatus at home. Alternatively, an apparatus specially designed for membrane filtration is available inexpensively from the Millipore Corporation, which also sells a kit that includes the vacuum filtering apparatus, a plastic syringe that functions as a vacuum pump, an alcohol lamp, an apparatus for sterilizing water, a variety of culture mediums, membrane filters, pipettes, Petri dishes and all other essentials for performing a broad range of experiments. The kit, which is called the Experiments in Environmental Microbiology Kit, includes a carrying case for convenience in making pollution tests in the field. The experiments to be described were done with the kit.

An introductory experiment that demonstrates something of the power and versatility of the filters involves the analysis of water for pollution by organisms that cause disease. Pathogenic organisms, such as *Salmonella typhosa* (the cause of typhoid fever), can be extremely difficult to identify. For this reason specialists routinely check water for the presence of indicator organisms that are easy to detect. Reliable indicators are the coliform bacteria that live in the intestines of animals. Their presence indicates pollution by sewage. Forty-two of the 50 states employ this test as a standard method of analyzing water pollution.

Coliform bacteria are easy to identify because they have the unique ability to transform the complex sugar known as lactose into a known sequence of simpler compounds, some of which are aldehydes. The presence of aldehydes in a growing culture positively confirms the existence in the culture of coliform bacteria. The test for aldehydes involves the use of an ingeniously contrived culture fluid known as MF-Endo medium, which contains lactose, other nutrients and basic fuchsin, a stain that is normally red but is bleached in the medium to a pale pink by the addition of sodium sulfite.

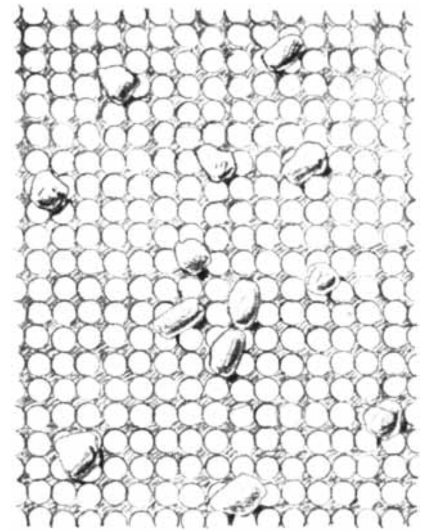
The first action of bacteria that are grown in MF-Endo medium is to partly reverse the effect of the sulfite. Some of the fuchsin and sulfite react, and the fluid turns a medium red. Most colonies of multiplying bacteria take on the red stain, but no species is distinguished by color until aldehydes form. When the aldehydes appear, some of the unreacted fuchsin-sulfite complex, the portion that did not react to change the color of the medium from red to pink, attaches itself to the aldehyde molecules and forms a shiny green coating. Only coliform bacteria convert lactose into aldehydes. Therefore colonies in the growing culture that change from red to green are coliform bacteria and provide proof that the specimen is polluted by sewage.

The analysis of water for sewage pollution proceeds in a series of steps. It begins with the selection of a specimen that is large enough to genuinely represent the water source. The specimen is filtered. Organisms that collect on the membrane filter are cultured in MF-Endo medium, and the culture is examined for the presence of coliform colonies.

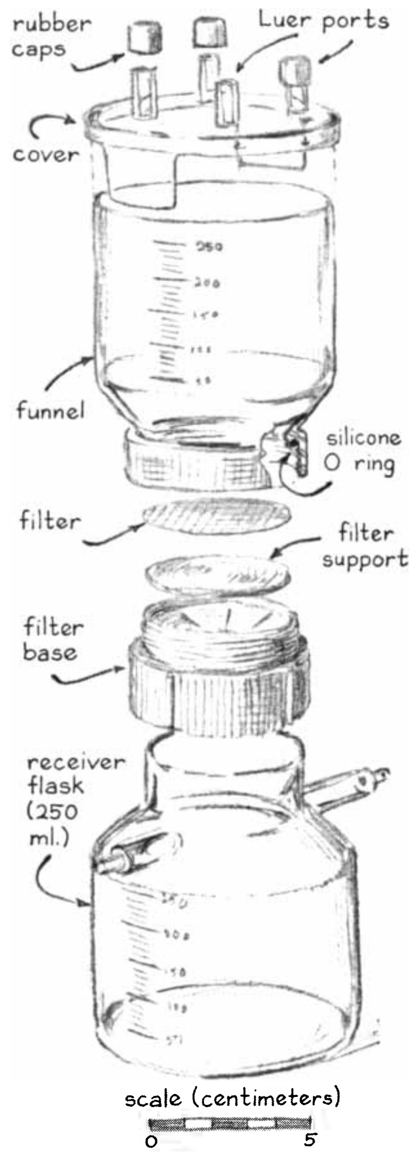
How many milliliters of specimen water should be passed through the filter? The answer depends on the nature of the water. The specimen of polluted water should be sufficiently large to yield (after culturing) not more than 200 colonies, of which from 20 to 80 colonies are coliform bacteria. In the case of potable drinking water a specimen of from 100 to 200 milliliters is usually adequate. It is likely that from 50 to 100 milliliters of untreated potable water, such as water drawn from a well or a spring, would yield an equivalent count.

When testing raw water, as from rivers or lakes, the experimenter might try three volumes serially: .1 milliliter, 1 milliliter and 10 milliliters. To ensure an even distribution of the organisms across the surface of the porous membrane such small volumes of specimen water would be mixed with at least 10 milliliters of sterile water before they were filtered. In the extreme case of raw sewage the dilution would be made serially to perhaps 10^{-5} or 10^{-6} to provide a significant coliform count.

The concentration of organisms in water from various sources varies so widely



Structure of a membrane



Apparatus for filtration

that no hard and fast rule can be established for determining the optimum volume of a specimen to be filtered. The experimenter must exercise common sense, based on experience, and rely on trial and error when that procedure is necessary. Collect a bulk sample of water to be analyzed in a sterile container with a tight lid. Sterilize all apparatus that will come in contact with the specimen by boiling the parts for three minutes in a container of water. Sterilization should include the vacuum filtering apparatus.

The vacuum filtering apparatus that comes with the Millipore kit consists of the funnel, the filter holder, a receiving vessel, a plastic syringe, flexible tubing, a plastic valve mechanism and a funnel lid that has four tubular ports. Three of the ports are closed with plastic caps. The fourth is fitted with a filter holder, known as a "Swinnex," which is similar to a pipe union. Its two halves screw together. A filter clamped between the halves admits air to the funnel but catches contaminating particles and airborne organisms.

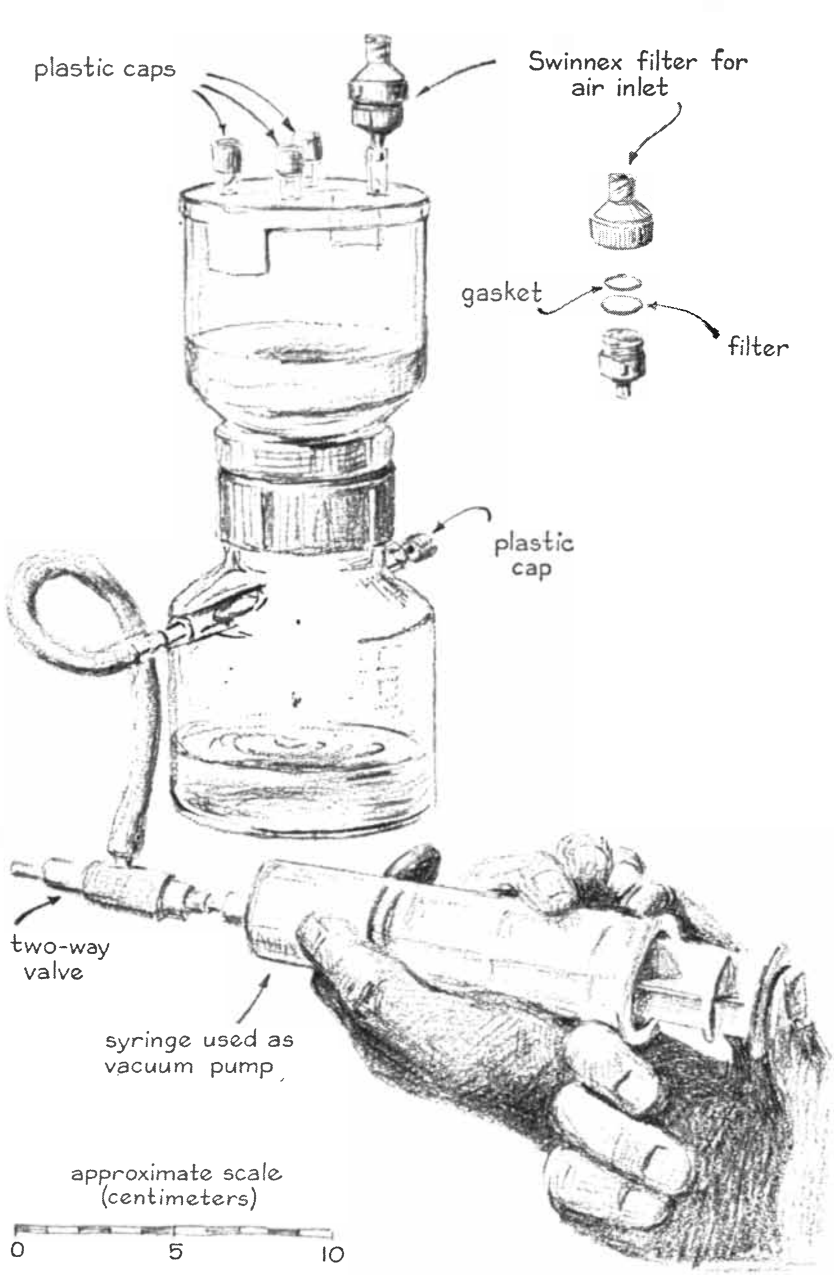
The syringe functions as a vacuum pump. A tapered hole in one end of the valve mechanism makes an airtight fit with the inlet of the syringe. A sidearm on the valve mechanism mates with the flexible tubing. The opposite end of the tubing fits an inlet port in the receiving vessel of the filtering apparatus. Air is pumped from the receiving vessel by operating the plunger of the syringe. A dozen strokes usually will reduce the pressure sufficiently for an adequate rate of filtering.

The Millipore kit includes a supply of Type HAWG filters and Type GS filters. The Type HAWG membrane disks are 47 millimeters in diameter and have uniform pores .45 micron (about 18 millionths of an inch) in diameter. A single 47-millimeter membrane filter is therefore perforated with some 960 million uniform pores. These membranes fit the filter holder of the vacuum filtering apparatus. The Type GS filters are 25 millimeters in diameter and have .22-micron pores. They fit a special Swinnex filter holder in the kit that mates with a companion plastic syringe. The syringe is used to force tap water through the GS filter, thus sterilizing it for experiments.

Sterilize all parts of the filtering apparatus, including the Swinnex fitting that admits air to the funnel but excluding the receiver flask. The receiver does not require sterilization because the experimenter is concerned only with the specimen organisms that remain on top of the filter membrane and anything that touches them. After boiling lift the funnel and filter base from the water with tongs. Put them on a clean sheet of wrapping paper that has been sterilized by heating to 250 degrees Fahrenheit in an oven. The funnel should rest upside down, on its larger rim, and the filter base rests with the filter-support area up. Do not wipe these units or touch the inside of the funnel or the top of the filter support.

After the pieces have drained for a short time, press the filter base down firmly over the top of the receiver flask. If the red silicone rubber O ring should fall out of its groove during the boiling, put it back with sterile forceps. Screw the blue filter base into the funnel until the O ring seats firmly. Sterilize the forceps by dipping the tips in alcohol and passing them immediately through the flame of an alcohol burner. The ignited alcohol will sterilize the tips. When the tips have cooled, use them to lift a single HAWG filter from its packet, close the packet immediately and with the forceps center the filter carefully on the holder.

Incidentally, the filters are white but are inscribed with a grid of fine dark lines that are convenient for counting colonies. The packets contain, in addition to filters, a supply of relatively thick pads in the form of disks that match the



Assembled filtering apparatus

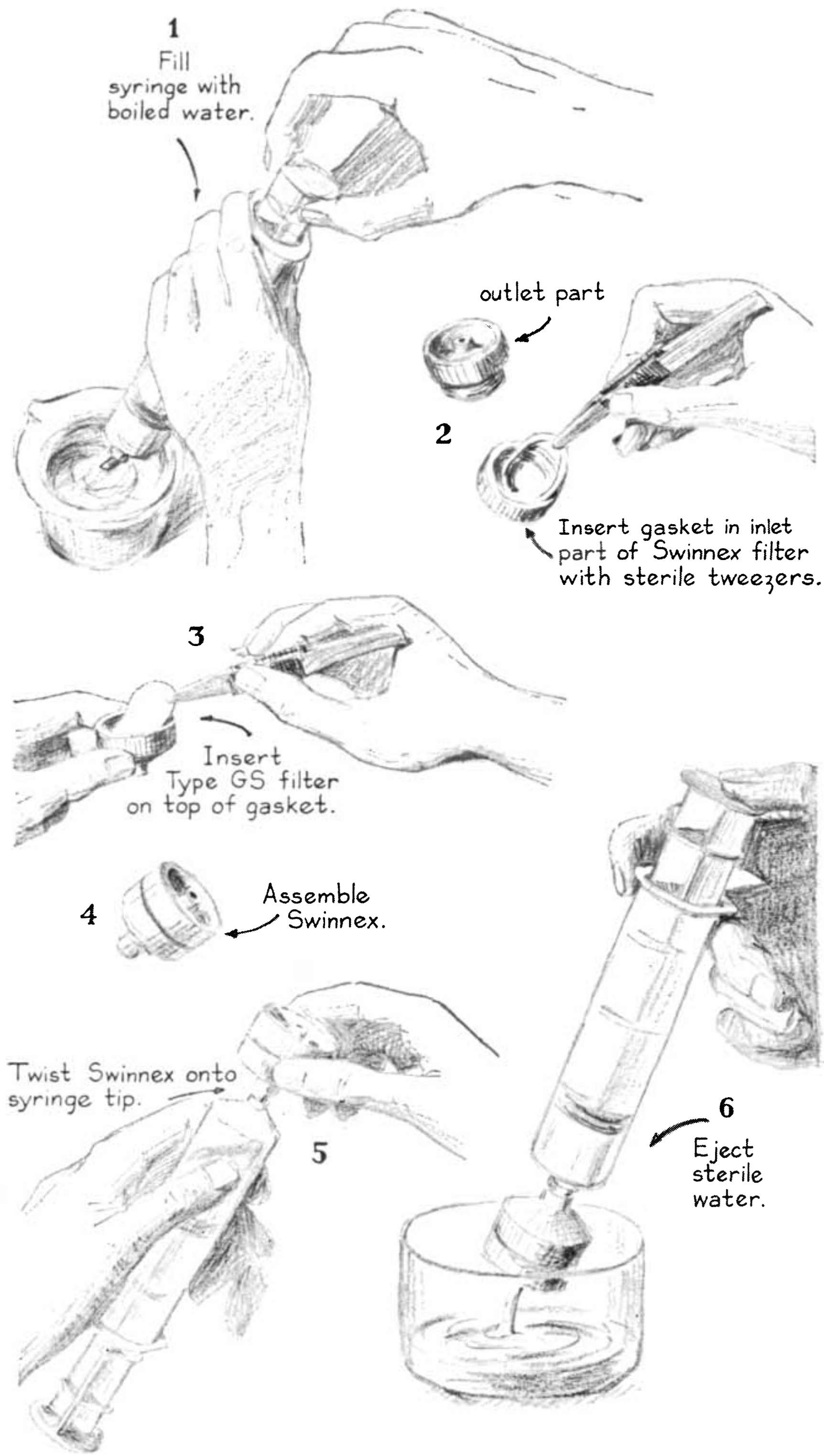
diameter of the filters. They are used for supplying nutrient to the cultures.

A pad is put in a Petri dish and saturated with nutrient solution. A filter with its collection of organisms is placed on top of the pad. Nutrient from the pad diffuses through the filter to the organisms. Remove one of the pads with the sterilized forceps and store it in a sterilized Petri dish. The packet also contains disks of blue waxed paper. They are separators and can be discarded.

Most experiments require a supply of sterile water for diluting the specimens. The sterile water can be prepared from ordinary tap water. Usually tap water has been treated with chlorine, which must be removed or it will retard the growth of the cultures. Boil the water for a minute or two to remove the chlorine. Water thus dechlorinated can be stored in a stoppered glass bottle. Sterilize the dechlorinated water immediately before use by passing it through a Type GS filter.

Put a filter in the 25-millimeter Swinnex. Observe sterile procedure. Draw a quantity of dechlorinated water into the mating syringe. Insert the tip of the syringe in the Swinnex. By operating the plunger of the syringe, force the water through the filter and into a sterilized container. Remove the syringe from the Swinnex before withdrawing the plunger. If the plunger is withdrawn while the Swinnex is joined to the syringe, air pressure will act against the porous membrane from its supported side, causing it to bend toward the unsupported side and rupture.

Assume that the initial experiment involves the analysis of water from a reasonably clean pond or stream. With the 25-millimeter Swinnex, filter 10 milliliters of dechlorinated water into the funnel of the vacuum filtering apparatus. Add about one milliliter of specimen water to the funnel and mix the solution thoroughly by swirling the funnel. Cap the funnel with its cover. It is assumed that the Swinnex admitting air to the funnel has been equipped with a filter and that the three remaining ports of the cover are closed by removable plastic caps. Connect the vacuum pump to the receiver flask with the flexible tube. Operate the plunger of the syringe to induce a brisk flow of filtrate.



Steps in assembly of "Swinnex" filter holder

Break the top from an ampule of pink MF-Endo medium and with the contents saturate the absorbent pad that was formerly stored in the Petri dish. After admitting air to the receiving flask uncouple the funnel. With sterilized forceps lift the cover from the Petri dish and transfer the membrane holding organisms from the filtering apparatus to the absorbent pad. Replace the cover with the forceps and let the culture incubate for 48 hours at room temperature (or for 24 hours at 37 degrees Celsius if you have access to an incubator). After incubation remove the membrane with flamed forceps and put it on a clean blotter for 30 minutes. With a hand magnifier count the number of colonies that have a greenish sheen. Each of the colonies will have started as a single bacterium. Multiply the number of colonies by

3,785 (the number of milliliters in a gallon) to find the number of coliform bacteria that would be present in a gallon of water.

Cultures, particularly those that disclose the presence of coliform bacteria, are potentially hazardous. They should be handled with the utmost care. If they are to be retained as records, they should be treated with phenol glycerin and sealed between sheets of glass. Otherwise they should be promptly destroyed. Using forceps, remove the covers from the Petri dishes, put the dishes and their covers and contents in a large beaker or pan and cover them with liquid household bleach, straight from the bottle. After 10 minutes, and while wearing rubber gloves, remove all the parts and rinse them thoroughly under running tap water. The wet pads and filters can be put in a plastic bag for disposal.

Immerse the Petri dishes and their covers in a 70 percent (by volume) solution of alcohol diluted with tap water for 10 minutes. Rubbing alcohol of the kind that is available in drugstores is adequate. Remove the dishes and stack them upside down with the edge of each dish resting on top of its neighbor so that air circulates freely on the under surface. When the dishes dry, replace the covers and store the dishes for use.

Culture mediums have been compounded to help the experimenter in gathering specific information of various kinds. MF-Endo medium is an example of what is termed a "tagging" medium. In effect it tags coliform bacteria by imparting a distinctive color to colonies of this organism. It is also classed as a selective medium, meaning that it favors the growth of coliform bacteria and discourages the growth of other microorganisms.

Culture mediums that are similarly selective and to which chemicals or dyes have been added for imparting a distinctive color to a specific kind of organism or to its surroundings have been compounded for identifying a number of bacteria. The use of these preparations enables the experimenter to make a census of a mixed population without resorting to more laborious techniques, such as microscopic examination. Information concerning the techniques of using these and other mediums is available, particularly in publications such as the *Difco Manual,* published by Difco Laboratories, Detroit, Mich. 48201.

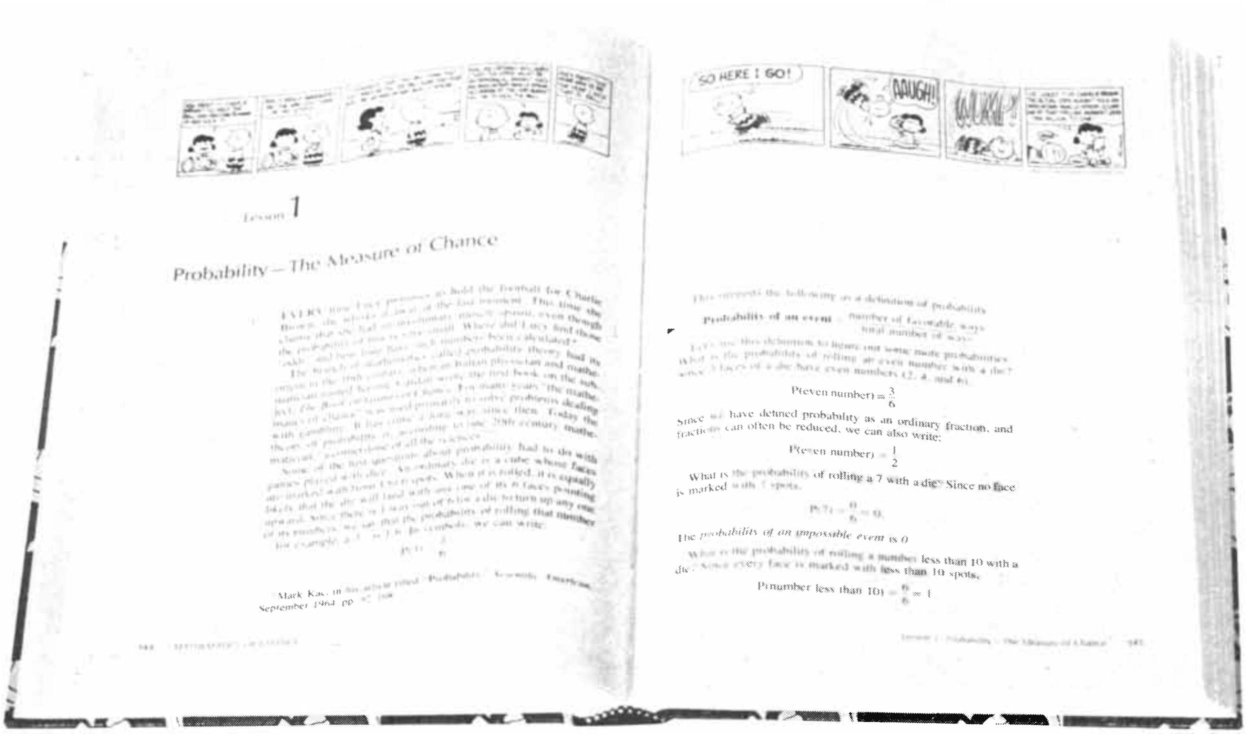
At the other extreme are mediums that impartially encourage the growth of most organisms. These compounds are useful when the experimenter wants to make a total count of all organisms in a specimen. For example, the analysis of a milliliter of pond water may turn out to contain 26 colonies of coliform bacteria. Are other bacteria present? If so, how many? In order to make a complete census of the microscopic population follow the procedure of the introductory experiment but substitute Total Count medium for MF-Endo medium. A supply of Total Count medium is included in the Millipore kit.

In general, cultures that are grown for making a total count of organisms require smaller specimens than those grown on selective mediums. For example, a specimen that yielded 200 colonies when cultured with MF-Endo medium might display several times that number when grown on Total Count medium. Most colonies, including those of coliform bacteria, are colored red by Total Count medium.

Membrane filters can of course be used for separating particles from fluids other than water. Aerosols such as pollen, particles of smoke, spherules of tar, minute crystals of chemical compounds and numerous similar suspensions can be collected from the air, particularly in metropolitan areas and in the vicinity of industrial establishments. The collected particles can be examined microscopically by applying a drop of immersion oil to a sheet of glass of the kind used for protecting color slides, and placing the filter membrane on top of the oil. The membrane will appear to vanish as oil saturates the pores. The particles can then be viewed as if they were mounted on a conventional glass slide.

Readers who are not disposed to undertake experiments of this kind should not overlook a practical application of the membrane filter: its use as a mechanism for the cold sterilization of water. Campers, hunters and people on vacation in underdeveloped countries may have occasion in emergencies to drink raw water. A Swinnex equipped with a .22-micron filter of the GS type will separate the smallest-known pathogenic bacterium from the filtrate. With this device and a 22-cubic-centimeter syringe one can remove the bacteria from a quart of water in a matter of minutes. (There is a slight risk that polluted water will contain viruses, such as the one that causes hepatitis. They will pass through a pore structure of .22 micron.) Slime, algae and similar gross suspensions may quickly clog a membrane filter. Raw water of this kind should be cleared by passing it through a few layers of cloth or conventional filter paper before cold sterilization.

"I had been to school . . . and could say the multiplication table up to 6 x 7 = 35, and I don't reckon I could get any further than that if I was to live forever. I don't take stock in mathematics, anyway."—Mark Twain, *Huckleberry Finn*



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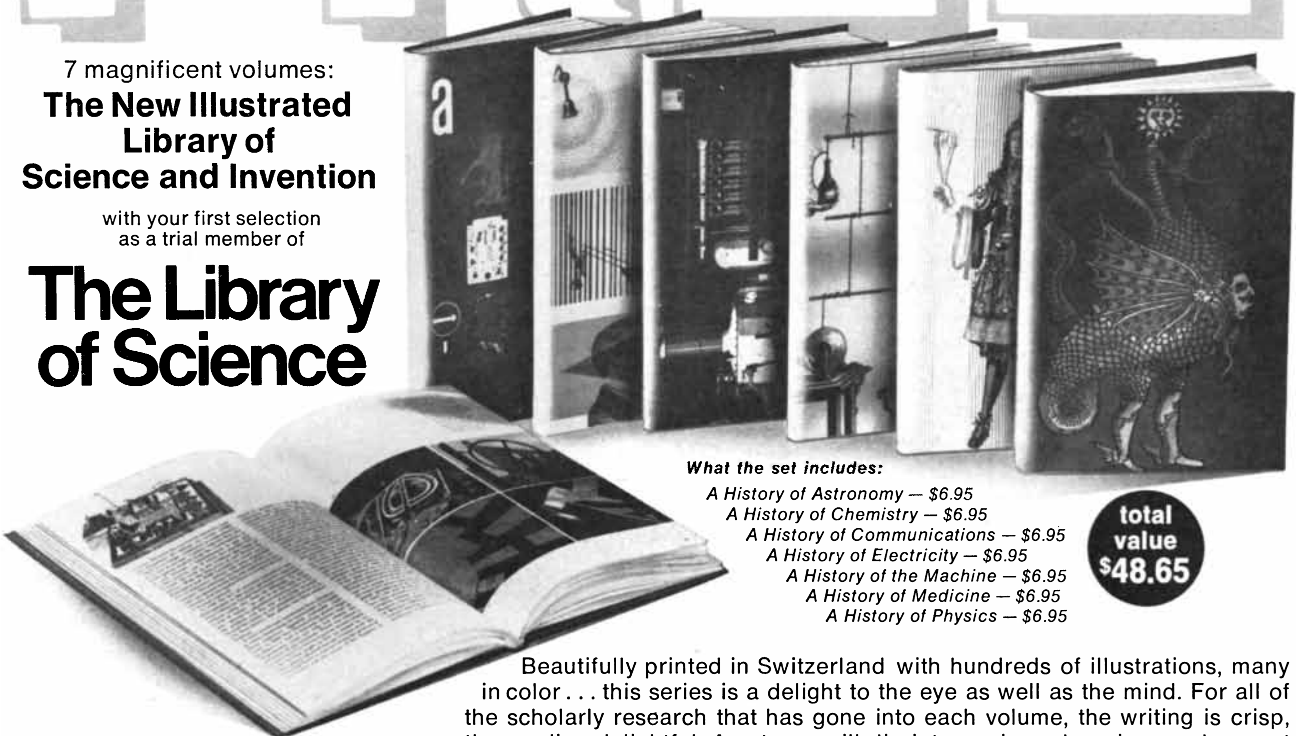

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BOOKS

The lessons (so far) of the moon samples

by Philip Morrison

THE LUNAR ROCKS, by Brian Mason and William G. Melson. Wiley-Interscience ($8.95). SOVIET ROCKETRY: PAST, PRESENT, AND FUTURE, by Michael Stoiko. Holt, Rinehart and Winston ($7.95). THE MOON AS VIEWED BY LUNAR ORBITER, by L. J. Kosofsky and Farouk El-Baz. NASA SP-200, U.S. Government Printing Office ($7.75). Meaningful, even exciting analyses of the samples brought back from the moon in 1969 are still being published week after week; this compact and accessible book is the first review of what those samples hold and what they may mean. The review, completed in the spring of 1970, is based on the heavy volumes of original papers, released a couple of months earlier, that were the cargo of the first six months' laboratory study under forced draft. The energetic authors are meteorite mineralogists and geochemists of the Smithsonian Institution; Mason's classic introductory textbook on geochemistry has for a decade marked him as a man able to make real nourishment out of that heap of food for thought his science serves up to the nonspecialist. After a swift summary of pre-Apollo ideas and a helpful précis of the two landings and their detailed accomplishments, the chapters describe in detail the minerals of the moon (not one uniquely lunar on a list of 25); the rocks of the moon (both the igneous bedrock and the complex "soil"), and the geochemistry of the moon (with comment on about 80 elements). A brave six or eight final pages list the implications, and what the authors had to say seems to have been strengthened by nearly every new result since their manuscript went to press.

The main facts are these: The lunar rocks are waterless, hydrogen-poor and free of organic matter. They are igneous in origin, but since quartz is rare on the moon they build a world of feldspars. Basaltic lava has flooded the lunar maria, not sediment or dust, although the fragmentation of meteorites and the chemistry of shock are vividly apparent in the rock and soil. Much of the mass of the moon has been melted and differentiated. The lunar highlands are low-density, riding high, like the terrestrial continents, above the dry seas of the maria. They are as poor in iron, magnesium and titanium as the floors of the maria are rich.

We cannot quite see the earth in a grain of sand, but we have seen the melting of the moon in a few thousand pinhead-sized grains of mineral among the Apollo finds. Analysis has shown that the rare earth europium is depleted with respect to the other rare-earth elements in most Apollo materials. That sharp nick in the otherwise smooth rare-earth abundance curve is in itself no mystery. Europium has unique geochemical properties among the rare earths: it separates in melts on the earth too. Just such an anomaly is found in rocks from deep in the earth's mantle. Where, however, has the missing europium of the maria gone? Mason and Melson think it should be found in rocks rich in light-colored and lower-density feldspars: the plagioclases. John A. Wood of the Smithsonian had already found grains of such rocks in the Apollo samples, making up a few percent of the dark lunar soil. The grains were foreign to the Sea of Tranquillity, where they were collected. They had migrated there, surely flung by meteor bombardment from the light-colored highlands 50 or 100 miles away. By December, 1970, a group at Oregon State University was able to show europium enrichment—now not a nick but a peak—in 100 milligrams of hand-sorted highland grains.

The moon was not torn from the earth's present mantle: its composition is distinct from the composition of the earth. It was not a twin of the earth's at birth, because its low density arises from the absence of iron. What could concentrate iron in one twin of a pair? The moon is even low in iron compared with the mutual parent of the earth and the moon, the sun, so that it does not seem to have been born independently out of the primordial solar nebula and then somehow been captured by the earth. The remaining hypothesis—it may or may not survive to become a theory—suggests that the moon was formed in the last stages of accretion of the earth. Most of the iron was held inside the system, but some kind of Saturnian ring condensed outside to make the moon out of the silicate "atmosphere" of the nascent earth. Thus the moon may have been born of the earth after all, although not of the present earth but of the embryo.

Russian analysts are hard at work on lunar samples too, although no Russian cosmonaut has reached the moon. *Soviet Rocketry,* based mainly on published Russian sources up to 1968, implies how those samples came home. (There is a whiff of declassification about this unofficial, somewhat rough volume by an engineer with a paramilitary background.) The book begins with a review of the long history of rocketry in Russia. In 1881 young Nikolai I. Kibalchich was executed for making the bomb that killed Tsar Alexander II. Kibalchich left papers that were denied publication and were held in the police archives until 1917. He had conceived of full-scale rocket ships propelled by successive explosions of gunpowder. The most devoted and penetrating of Russian amateurs was the famous Konstantin Eduardovich Tsiolkovsky, a deaf dropout, a schoolteacher of the lowest rank and in 1890 the maker of the first wind tunnel in Russia. By the time of his death in 1935 he had become known for a long series of imaginative books and papers on plausible and implausible means of space travel.

In Russia between the world wars there grew mainly around military rocketry a community of men interested in and publishing on space flight. By the early 1930's there were official centers in Leningrad and Moscow working on liquid-fuel rockets and jet engines. Out of these groups of engineers came the Chief Designer of Carrier Rockets and Spacecraft, Sergei P. Korolyov, who died in 1966, the Chief Theoretician of Cosmonautics, unofficially identified as Mikhail K. Tikhonravov, and the Chief Designer of Rocket Engines, said to be Valentin Glushko. These men and their organizations went by way of army bombardment rockets and the captured German V-2's to the Russian ICBM, Sputnik and the moon-crawling Lunokhod. It seems likely "that all Soviet boosters from the first ICBM through the Vostok were designed by the same organization under... S. P. Korolyov." That means all the manned flights, the missions to the planets and the lunar probes.

The succession of add-on rocket engines, liquid- and solid-fueled, and the similarly modular spacecraft are well illustrated and described in the book. The maximum thrust reached in the known booster series seems to be about the same as that of the Saturn I-B, which is capable of putting eight or 10 tons into earth orbit. No booster of higher thrust has yet become public knowledge. The Proton series of four heavy satellites was described as using a new and more powerful booster—one not with the same origins as Vostok. This vehicle is surmised to be able to put 30 tons into orbit, which is not enough for a manned lunar landing and return.

Plenty of television, telephone, weather and reconnaissance satellites are listed, illustrated and described. The book also has photographs, tables of organization and maps that give a picture of Russian space efforts at a level of detail quite adequate for a general appraisal. The author predicts (with some ambiguity) a Russian manned landing on the moon by means of an unknown new lunar launch vehicle comparable to Saturn V sometime between 1972 and "the end of the 70's."

The intonation of this useful book is a little too pressing and conflict-centered. It may be that some cooperation in explorational space flight lies ahead, with a mutual slowdown. Three cheers for the joint Soviet-American unmanned grand tour to the outer planets in 1978!

Displayed in *The Moon as Viewed by Lunar Orbiter* are the lifeless landscapes of the moon, viewed on a fitting geological scale not from far earth but from near orbit, some from an altitude of 50 to 100 miles and some from 10 times higher. This large, thin NASA volume has more than 125 pages of black-and-white photographs showing substantially the entire lunar surface at one or another level of detail. In 1968 *Scientific American* carried an account of the almost flawless flights of five successive Lunar Orbiters, accompanied by 15 Orbiter photographs. The work is a testimonial particularly to the managers, engineers and craftsmen of NASA's Langley Research Center, which directed the project, and of the Boeing Company, the prime contractor. Four dazzling anaglyphs (to be viewed with the two-color glasses included) embellish and conclude the book. See a canyon, Schröter's Valley, stand out in depth! A vacuum is always favorable for cloudless photography. There are excellent indexes, and a careful account of how to obtain prints of any of the 3,100 20-by-24-inch usable pictures in the complete Lunar Orbiter set.

BEHIND APPEARANCE: A STUDY OF THE RELATIONS BETWEEN PAINTING AND THE NATURAL SCIENCES IN THIS CENTURY, by C. H. Waddington. The M.I.T. Press ($25). Professor Waddington is a distinguished University of Edinburgh geneticist who is married to the architect Justin White. He is a lifelong gallery-goer, a friend of many avant-garde painters since about 1930 and a tireless reader and conversationalist. A generation ago he wrote well on his present theme. So equipped, he finds it natural not to mourn the chasm between the cultures but to seek a place where "the chasm turns out to be quite a narrow and shallow cleft across which it is easy to step." The reader can follow him almost as easily in that step with the aid of this engaging book, beautiful in its vivid illustrations and engrossing in its persuasive line of thought.

The crevasse seems narrow for at least one strong reason: Both the laboratory scientist and the painter must coax certain components of the material world to do what they want them to. That is never enough. For the scientist the test of excellence is not mainly the skill in measurement but the depth in the choice of the problem. For the artist too it is not the mere execution but the forms he chooses to paint that count. For both it is really "which problems are worth tackling." The book is not about aesthetics, nor is it about how to judge the importance of painters, nor, except incidentally, about the history of modern art. It is aimed at showing how painting and natural science have communicated, not at the shallow level of mere isomorphism of form but nearer the roots of thought and feeling in both enterprises. There are many such roots, but those topics that are spread widely over history and society are not discussed here.

A formulation devised by M. C. Goodall serves Waddington well. Goodall sees three sciences. First science, what we call Greek science, dealt in axioms; like Euclid, a man could infer consequences about perceptible things from self-evident axioms. Second science was born of the Renaissance; it was a systematization based on the results of diverse experiments. Third science is the science of our century, in which the classical boundaries are overrun in an entire collection of new developments. This bursting forth is the hallmark of our century, both for painters and for scientists.

It is not inappropriate in a review to summarize the themes set forth by this large and fluent book. It would be wrong, however, to convey the impression that a few comparisons can sum up the wisdom and the interest of the work. Far from it; Waddington's argument is strong not because it unexpectedly juxtaposes Einstein and Picasso (Apollinaire did that as an insider 60 years ago) but for its texture, its detail, its very qualifications and its tensions. That makes for a less engaging summary but for a far more thoughtful book. "The scientist does not go to the painter for a representation of scientific objects, but for the enrichment and deepening of his consciousness, which comes when he finds a painter in whom the climate of scientific thought has penetrated into the spirit, leading to the production of works in which some of the deeper, less easily expressible, features of the scientific outlook are 'shown forth.' "

Some lines are clear in third science and in painting. Take the strange filiation of Claude Monet, Wassily Kandinsky, Willem de Kooning and Jackson Pollock. This is the road of "all-overness," the "breakdown of billiard ball theories," the dissolution of static matter. It includes clearly, ever since Hans Arp and Francis Picabia, the creativity of chance itself. All of this remains even though Kandinsky had set himself explicitly against science and its positivism. Yet his painting knew no horizontal; he first freed painters from gravity, to enter the electrical microcosm ruled by Charles Augustin de Coulomb.

The forms perceived by our instruments are not at issue. It is not the shapes of waves or mineral grains that matter, however attractive they may be, or however much like some paintings they are. Such forms could have been seen in 1890. No one painted them then. It was the fact that significance, meaning—in short, theory—had been invested in such forms by the scientists that in the end drew the artists, consciously or unconsciously, to make such images themselves. The newest painters, those who have arrived since World War II, know the strength of chance. They recognize that the dichotomy of the observer and the observed is not clean and simple. They see the world as being interrelated and Heraclitean, not isolated, impenetrable lumps swinging in orbit. The almost figurative Alberto Giacometti saw his world as consisting of forms under tension, full of contained energy, and exactly so did he draw it. Giacometti himself invokes the calm Cézanne, whose search for an inner geometric structure seems not to be on the path mapped in this book. Yet the inward "representation of the mountain or the apple" was the only essential for Cézanne. His cubes and cones were mere "means by which to get a little nearer to reality." Giacometti, in his words, in his appraisal of himself, his past and his images, comes "close to the world-picture of modern physics, and indeed of modern science as a whole." That picture is not single but manifold, like the paintings themselves.

There are 70 excellent tipped-in color plates and about 150 black-and-white halftones in this fine, expensive volume. Think of just four: a purple-and-green lily pond of Monet, a scattered garden world of Kandinsky, a black and luminous Pierre Soulages and a woven Pollock that might be "the electrons buzzing ...a winter meadow [seen] through the eyes of an ant, the hair of the Virgin Mary...the whips of the Fates." What diversity lies behind appearances!

THE BIOLOGY OF TWINNING IN MAN, by M. G. Bulmer. Oxford University Press ($6.50). For a century it has been realized that there are two types of twinning in man: the genetically identical twins, derived from a single fertilized egg that divided in some later stage of its development, and the twins derived from two different eggs, no more alike genetically than brothers and sisters normally are. The argument is carried by clear genetic characteristics such as sex ratio, blood group and whether or not skin grafts "take." (The last two might be criticized as possibly resulting from shared fetal blood circulation, as is commonly the case in cattle. The effect is known but rare in man.) A third, intermediate type of twin has been suggested and long been sought; this type would grow from eggs that had themselves twinned in some manner before fertilization. Such twins would be genetically identical on the mother's side but not on the father's. They would be "uniovular dispermatic twins" in the concise jargon of the trade and this book. (Sperm hardly seem to have the equipment for twinning.) Depending on the stage of twinning, various genetic patterns might occur, all less similar than those of the familiar identical twins. Human "mosaics" are known: "a girl with a hazel left eye and a brown right eye" and two different blood groups is genetically known to have been fathered by two sperm. There are thus possibilities for the intermediate types, but they are surely rare, and so far they are undemonstrated. Even a case of fraternal twins with two different fathers—very rare—was described in Italy in 1947.

The human litter size is typically one. Fraternal twinning is quite variable in frequency depending on circumstances, but the one-egg identical twins are found at a constant rate of three or four births per 1,000 under remarkably diverse conditions throughout our species. The Yoruba of Nigeria have a fraternal-twin rate eight or 10 times the universal rate of identical twins. Among the Japanese, fraternal twins are not even as frequent as identical ones. Drugs that affect the hormone system can now induce multiple-egg births freely.

Twins have it hard. They have "a greatly increased mortality both before and after birth." If they survive, they are smaller (in Sweden twins called up for army service were half an inch below average) and rather more likely to show various congenital or developing mental and physical defects. "The mean birth weights of singletons, twins, triplets, and quadruplets are about seven, five, four, and three pounds respectively." Twelve pounds is about the limiting total delivery weight.

Single births are the rule in all anthropoid apes and in most other primates. The typical brood size is the optimum size for survival, demonstrably in some bird species and arguably in all animals. Organisms that do not care for their young after birth, such as fish, have struck some kind of compromise between size and viability of egg and number. The primates, mainly arboreal and long-nurturing, have cut their litter size sharply to one. Even simple scaling implies that large mammals cannot have large litters: the fetus is nourished through the area of the placenta and the infant's needs tend to grow with its volume. Why, then, has twinning persisted in man? Random gene drift in small groups? Or some concealed advantage, analogous to that of the sickle-cell gene in certain populations? No one knows.

Bulmer is a biomathematician at the University of Oxford. His compact, beautifully clear, rather technical book is a fine example of what one might call general epidemiology. To expound his topic he employs papers on embryology, statistical theory, genetics, odd topics such as the infant-mortality data among the royal houses of Europe, and the medical records of many countries. In one cool, brief chapter he reviews the vexed question of the use of twins to study "the relative powers of nature and nurture." Fingerprint ridges are plainly genetic; single-egg twins show the same correlation coefficient as the right and left hands of one person, about 95 percent, whereas two-egg twins are correlated only 50 percent, as parent and child or brother and sister are. I.Q. is far more complicated, whatever that measure may mean. Bulmer concludes very tentatively that "about two-thirds of the variability in intelligence [he means I.Q. score] is of genetic origin." Parent and child (with the parent given the same test as the child) have a correlation coefficient rather like husband and wife, nearly 50 percent; identical twins reared together, almost 90 percent, and identical twins reared apart, less than 80 percent. It would be easy, however, to use different figures in his various estimates to come out with a much lower value for the genetic component of I.Q. variability.

The delightful suspicion that identical twins tend to be mirror images of each other, left- and right-handed, or even with mirrored internal organs, seems to be false. The effect occurs, but not "more frequently than would be expected by chance," according to fairly recent French and Swedish workers.

The Shark: Splendid Savage of the Sea, by Jacques-Yves Cousteau and Philippe Cousteau, with 124 photographs in full color. Translated by Francis Price. Doubleday & Company, Inc. ($7.95). The *Calypso,* once a minesweeper, then an oceanographic ship and now a cinematographic studio, sailed out of Monaco almost four years ago, bound on a glorious voyage without schedule or goal, a voyage of the purest romance. She was off to make the dozen splendid films now known to millions of television viewers. "Our only task, our profession, was to see." So writes Philippe Cousteau, son of the Commandant himself and the author of most of these pages. This book, a personal and wholly engaging tale, neither chronicle, essay nor science, follows one theme for two years, from the Gulf of Aden to the Gulf of California. That theme is sharks and divers, those frog-like intruders into the realm of the sleek shark.

The world's warm seas have been ruled by sharks since the Cretaceous period. A big shark cannot even survive once it has been hauled up on dry land or the deck of a ship; with the pressure removed from its ribless cartilaginous flanks it is condemned to death by internal injury even if it is returned to sea at once and swims off vigorously. In the water, however, the shark is clearly adapted and adept. A streamlined block of muscle cased in leather, with jaws whose triangular teeth cut a smooth half-cylinder out of any large prey it bites, it is a formidable and fierce predator. Acute of hearing, able to taste with organs in muzzle and body, responsive to sound and pressure waves, capable of following odors with sensitivity and apparent directionality (because of wide-spaced nostrils?), seeing without color but with considerable detail in poor light, the shark, large or small, tracks the sea. "When [that] formidable silhouette glides along the populated coral cliffs, fish do not panic; they quietly clear the lord's path, and keep an eye on him. So do we." There are many and diverse species. Even a tiny live-born shark, seconds old, will seize a target and hang on.

The divers of *Calypso* respect sharks now; they dare to watch and photograph and touch and test them, with forethought, while nearby in the water sharkproof cages with metal bars serve as an eyrie and a refuge. (Sharks small enough to swim between the bars and millimeter-sized isopods bloodily attacking bare ankles between flippers and pants cuffs have brought the *Calypso* divers a few painful and anxious experiences even inside the safety cages, but so far there has been no tragedy.)

Shark behavior is still far from well known. Sharks appear to a degree stupid and unpredictable, partly because of the different sensory world they inhabit and partly because they are creatures of a relatively simple kind, reflexively programmed to fulfill tasks we do not yet fully understand. They often brush and nuzzle many times before striking, presumably to "taste" the prey. Once blood flows, or some rapid fearful fluttering begins, or the sound of crunching bone is heard, all nearby sharks will rapidly home on the source. If the animals are numerous enough, an impressive "frenzy" may begin. Sharks will sometimes retreat from a wounded fellow shark, but never from any other wounded fish. On other occasions they are fierce cannibals.

The *Calypso* sails the wide seas in a kind of purity. We hear of no conflict or problem aboard or ashore. She does no harm. Only the adventures of the sea and its wondrous life add any real tension to the limpid blue days and the even bluer seas in these marvelous pictures.

Surely she brings us some hopeful report, not only from the sea but also out of our future. She is of our age: collective, technological, mobile, even worldly. The ancient adventure of one brave man alone is not missing, as long as some lonely diver feels the nuzzle of a blue shark. Yet the romance is basically a modern one, a widely shared task, aided by the work of millions and contributing to their dreams. What a good hour of a winter night is spent in a look at the fecund masses of the squid, at the hungry striped pilot fish, jackals to their great master, or at Raymond Coll clinging to the dorsal fin of a whale shark, the fin alone almost as tall as the man, and the diver riding the huge, tranquil plankton-eating beast down 150 feet into the deep ocean off Mombasa!

A Field Guide to the Larger Mammals of Africa, by Jean Dorst, with 44 color plates by Pierre Dandelot. Houghton Mifflin Company ($8.50). With the format and even the organization of the small, stout bird guides familiar in suburb and park, this book deals not with cardinal, sandpiper and finch but with dik-dik, impala, giraffe, potto and 240 other species of mammals, all shown in crisp, annotated paintings. The book treats those mammals of Africa south of the Sahara that are likely to be seen by eager watchers in the field. Bats and other nocturnal forms, and many small inconspicuous species, chiefly rodents, have been omitted. The author and the artist are zoologists of Paris; they have sought out their models in the zoos and museums of western Europe and in the wild all over the African continent. The volume takes up each species briefly, giving field marks, variations, habitat, distribution maps and an account of behavior. Consider the stocky ratel, the honey badger *Mellivora capensis*. There is his picture, black beneath, whitish above, all his 25 pounds and powerful claws. He "does not know the meaning of fear" and will attack big game ("up to a buffalo"), biting the groin and causing fatal bleeding. He is very fond of honey and breaks open bees' nests for it, ignoring their sting. Sometimes he is guided to the hive by the bird *Indicator indicator*, who shares the spoils of the hunt, "but this is not essential to the ratel," who can find honey on his own quite well. The beast is called Nyegere in Kiswahili; the species is found almost everywhere in sub-Saharan Africa. This is a book for travelers and for residents, and it would be indispensable for anyone who visits the great game plains of the eastern highlands.

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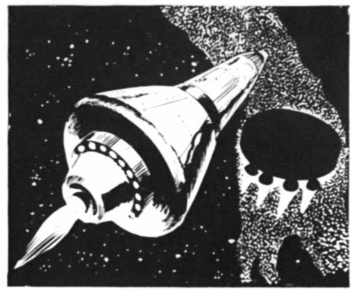

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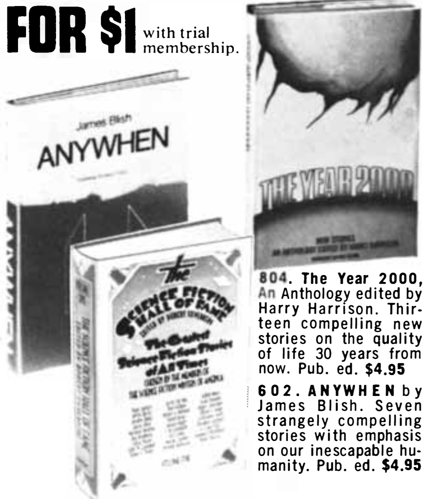

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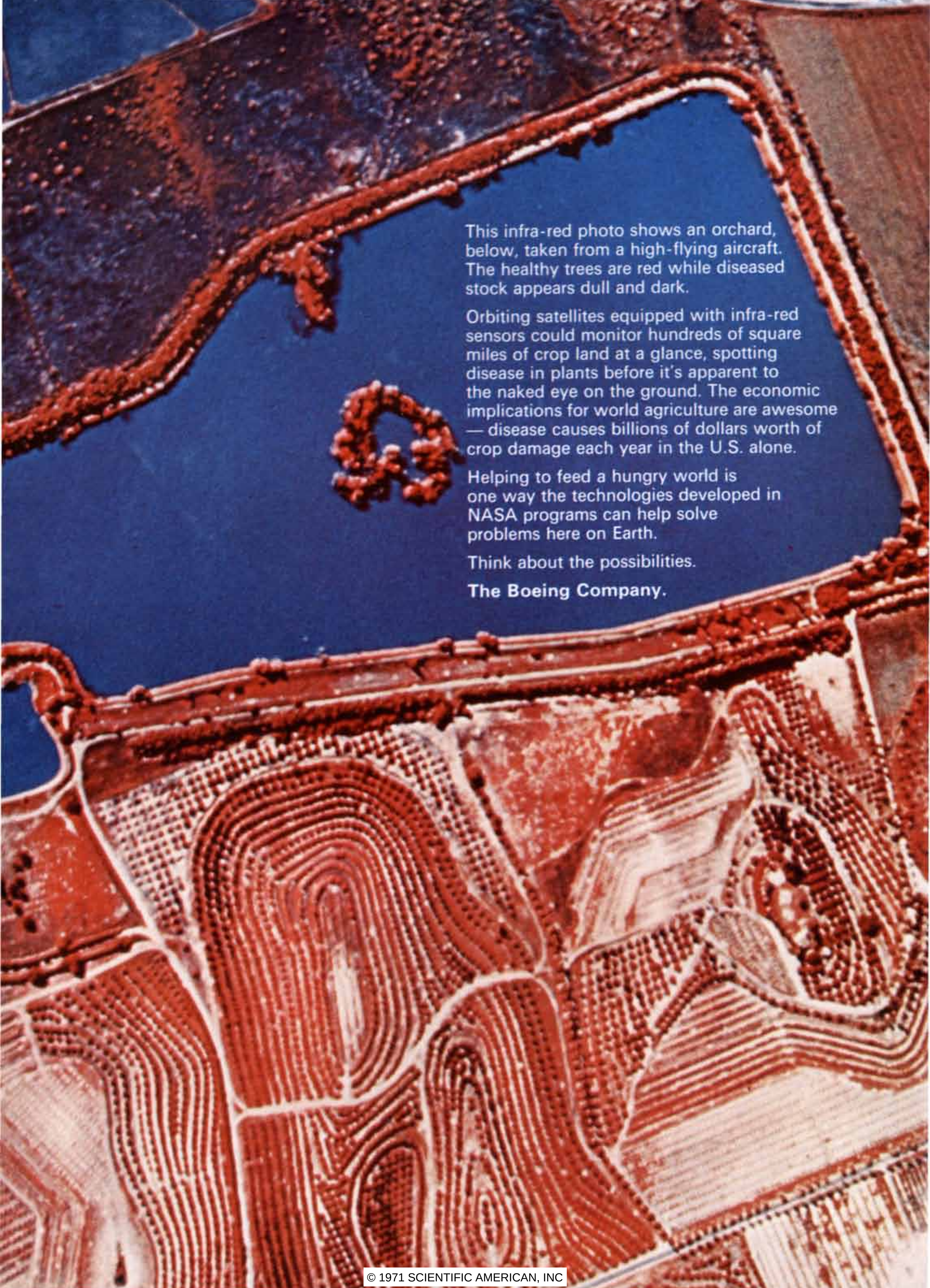
This infra-red photo shows an orchard, below, taken from a high-flying aircraft. The healthy trees are red while diseased stock appears dull and dark.
Orbiting satellites equipped with infra-red sensors could monitor hundreds of square miles of crop land at a glance, spotting disease in plants before it's apparent to the naked eye on the ground. The economic implications for world agriculture are awesome — disease causes billions of dollars worth of crop damage each year in the U.S. alone.
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