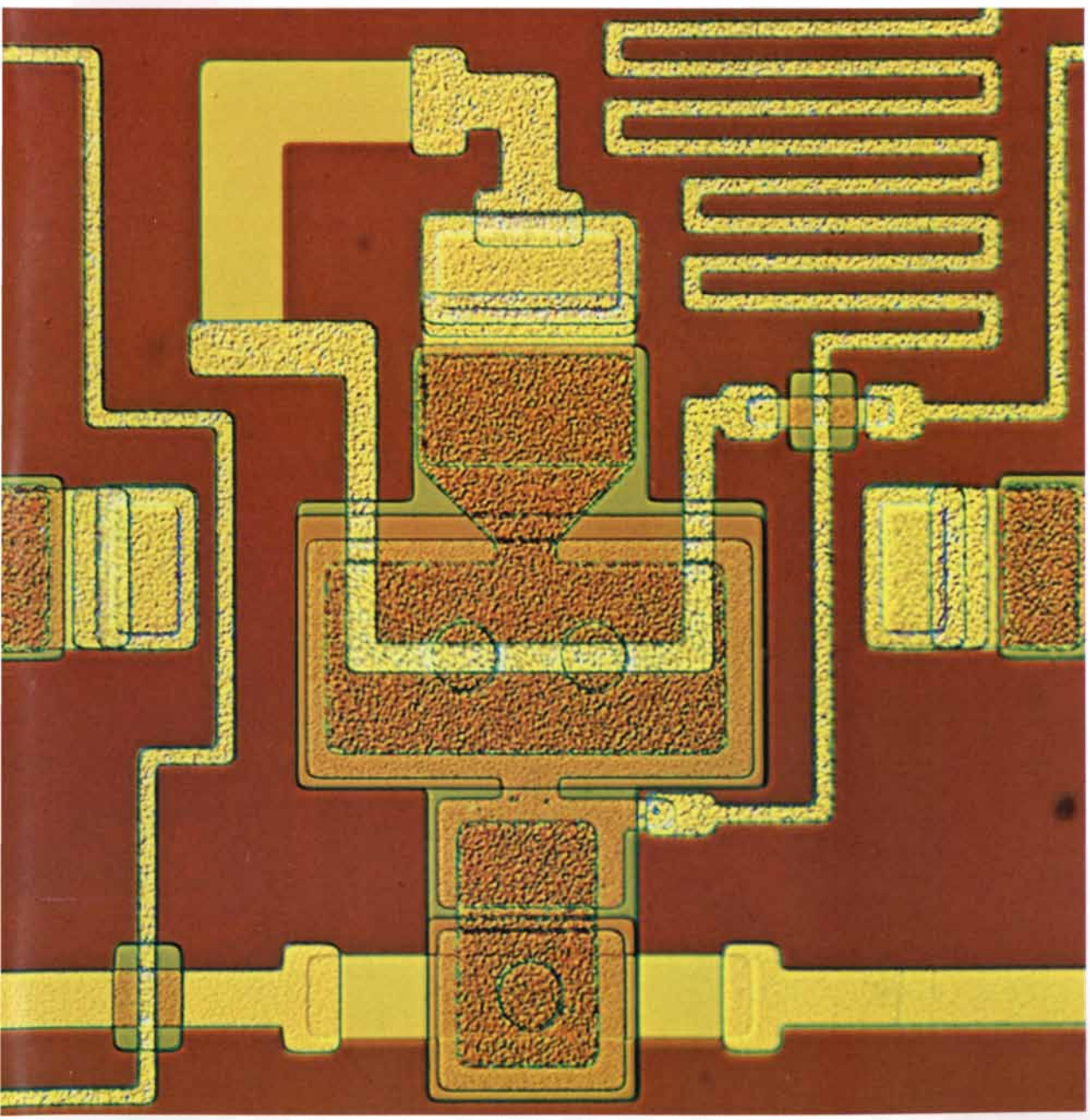
SCIENTIFIC AMERICAN



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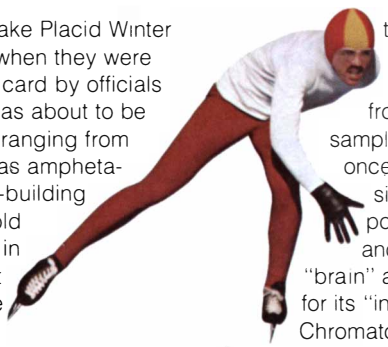
May 1980

Olympic lab gets results in record time



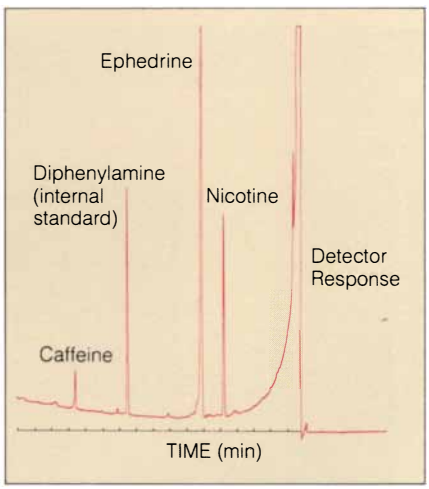
Athletes at the Lake Placid Winter Olympics knew when they were handed a green card by officials that their urine was about to be tested for drugs ranging from stimulants such as amphetamines to muscle-building steroids. With gold medals hanging in the balance, test results had to be fast and reliable.

Much of the drug screening was carried out by chromatography, a technique for separating mixtures of compounds so they can be identified and measured. To handle the heavy volume of test data, the Olympic laboratories were automated with a dozen Perkin-Elmer gas chromatographs linked to six Perkin-Elmer SIGMA 10 Chromatography Data Stations.

By bringing the power of the small computer into the laboratory, the SIGMA 10 makes it possible to collect and analyze data from a number of samples in less time than it once took to perform a single analysis. With a powerful microcomputer and memory for its "brain" and versatile software for its "intelligence," a single Chromatography Data Station can guide the operator and handle up to four simultaneous analyses.

At Lake Placid, data stations controlled operation of the chromatographs, processed the data generated, and printed the final reports. In other environments, they also can function as part of a network of "distributed intelligence," trading data with a computer and interacting with other "intelligent" laboratory instruments.

Write to Perkin-Elmer for a free booklet about laboratory data handling and automation systems.



Chromatogram reveals presence of ephedrine, which dilates respiratory passages to increase oxygen intake. Other peaks indicate smoking and coffee drinking.

Data station automates trace metal search

How much sulfur is in this coal? Does this canned milk contain lead? Is this well water too high in iron?

To answer such tough questions, analytical chemists turn to atomic spectroscopy, a method of measuring traces of metals in concentrations as low as one part per billion.

The three most common atomic spectroscopy techniques are flame

atomic absorption (for rapid determination of up to six elements), graphite furnace atomic absorption (for trace and microsample analysis), and the newer inductively-coupled plasma emission (for multielement analysis and for elements that can't be readily determined by atomic absorption).

In the new ICP/5000 System, all three techniques are combined for the first time, automated by microprocessors and controlled by a Perkin-Elmer intelligent data station.

It can answer those tough questions by using the best analytical technique for each: inductively-coupled plasma emission for analyzing sulfur in coal, graphite furnace for measuring lead in canned milk, and flame for analyzing iron in well water.

Once optimum parameters have been recalled from memory by the analyst, the data station takes over. It selects wavelengths, calibrates, tells the operator when to analyze the sample, indicates any error, displays and prints the results.

With its Autosampler, the ICP/5000 System can also sequentially analyze as many as 50 samples for up to 20 elements automatically.

The results will tell you whether the coal is harmful to the environment, whether the milk is safe for your child, and whether you should drink the water.

For your copy of a free brochure on the ICP/5000 System, write to the address below.

Perkin-Elmer computers speed lab data to doctors

The clinical laboratory of Houston's M.D. Anderson Hospital and Tumor Institute, one of the largest cancer centers in the world, performed more than two million tests last year. Data from these tests and thousands more on file must be instantly available via CRT terminals to doctors throughout the hospital.

But as the volume of tests climbed over the two million mark, the computer in the clinical laboratory began to blink "overload." In a comprehensive reliability study to choose new computers, the hospital ran extensive equipment tests. Two Perkin-Elmer 32-bit "supermini" computers were chosen on the basis of reliability, cost/performance factors and the ability to handle the hospital's growing needs.

Using system software developed by the hospital, lab data is input via 44 CRT terminals and 18 on-line instruments in the laboratory. The computers output data to the medical staff through 97 CRT terminals throughout the hospital.

Medical team views terminal outside operating room to check patient's test file stored in lab computer.

With 512 K bytes of memory each, the computers have increased total system memory tenfold. Capacity of the patient data file has been increased from 6,000 to 42,000 patients

Despite this major upgrading in performance, the new equipment is easy for the staff to use: a few simple instructions are all that's required to enter or retrieve data from the computers.

For a free booklet about 32-bit computers, write to the address below.

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Established 1845 **SCIENTIFIC AMERICAN** May 1980 Volume 242 Number 5

ARTICLES

DEPARTMENTS

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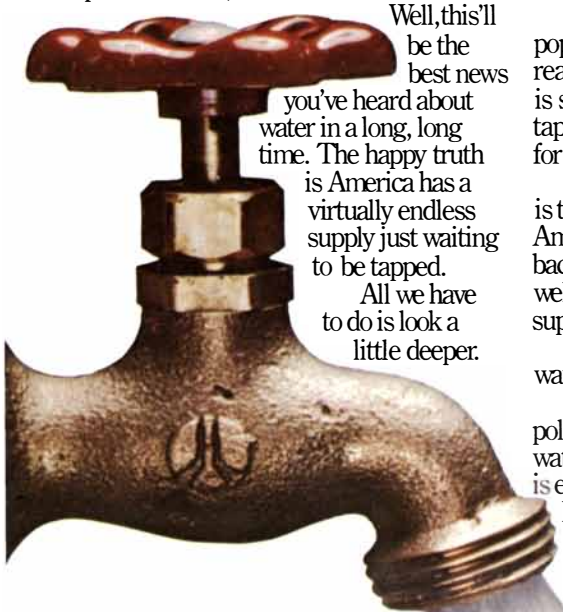
The Happy Truth About Th Tales Of The Unexpected

Droughts. Water shortages. Deserts encroaching on once-fertile land.

It's about time America had some good news about water. It's about time we found a supply that could take the burden off the country's overtaxed and often polluted lakes, rivers and reservoirs.

Well, this'll be the best news you've heard about water in a long, long time. The happy truth is America has a virtually endless supply just waiting to be tapped.

All we have to do is look a little deeper.



AMERICA'S BEST WATER IS ALWAYS GETTING UNDERFOOT.

The earth has as much water today as it had in prehistoric times. The water may sometime change forms, but the supply itself is constant. So where is all the water today?

An amazing percentage is where it's always been. Underground.

An incredible 95% of all the fresh water on earth is ground water. In the United States, there's 20 or 30 times as much water underground as there is in all the lakes, streams and rivers *combined.*

What's more, it's a completely renewable supply: Although the rate of replenishing varies greatly, water is seeping into the ground constantly, every hour of the day, every day of the year.

WELL WATER IS A NATURAL DELIGHT.

The American public is using more than 90 *billion* gallons of well water a day.

Approximately 700,000 new wells are drilled every year. Wells now provide almost 35 percent of the water used by municipalities—and over 80% of the water used in rural areas for homes and livestock.

Why is it so incredibly popular now? Part of the reason is the very fact that it is so plentiful—and that once tapped, the water is available for as long as it's sensibly used.

But part of the reason, too, is that well water is part of America's healthy drive to get back to its roots. After all, wells tap America's purest supply of natural water.

Does that mean this water's 100% pure? Absolutely not.

Although it rarely suffers from the pollution that so often afflicts surface water, nine times out of ten, well water is even better than totally pure water. It's enriched with dissolved natural minerals. Those minerals give well water in every part of the country its distinct, regional flavor. (If those minerals impart too strong a flavor, a simple filtering device can usually purify the water automatically.)

It's called the hydrologic cycle. It means that billions of gallons of water are entering underground reservoirs every day.

AMERICA'S MOST FERTILE FIELDS ARE ALL WET.

Many of the irrigation systems in the arid and semi-arid regions of the United States rely exclusively on huge underground reservoirs that have been collecting water for centuries. Without those rich water supplies, many of the most fertile fields in the country would soon become barren. In the 17 western states, for example, about 70 percent of the water used for irrigation comes from wells.

e Endless Well And Other From The Underground.

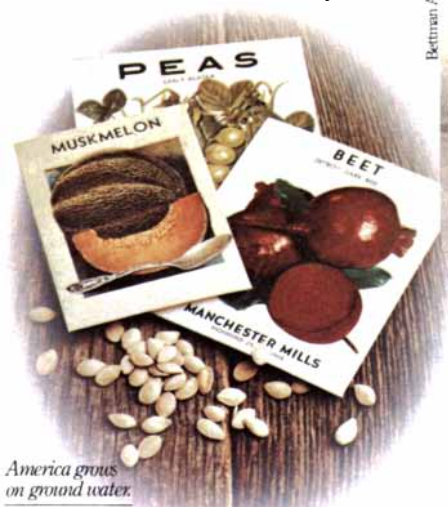
As long as that water isn't pumped faster than it's naturally replaced, there will always be plenty for the fields—and for the factories, homes and entire cities that rely on our underground resource.

WHY YOU SHOULD ALWAYS LOOK BELOW THE SURFACE.

Let's say you're looking for a new water supply. Maybe you're building a new home, factory or office building. Maybe you're planning a multi-acre farm or a quarter-acre garden. Maybe you're on the board of a regional or municipal water authority. Or maybe you'd just like the secure feeling that comes with knowing that no one can turn off or limit your water supply.

The first place to look is your own backyard.

Ground water in some quantity can be found under almost every tract

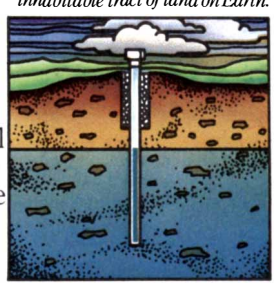


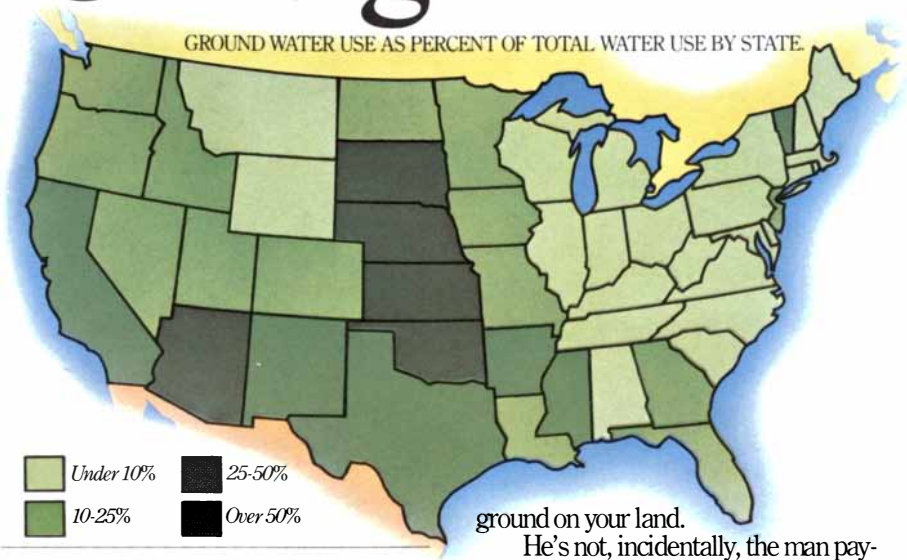
America grows on ground water.

of inhabitable land on earth. The cost of getting that water is almost always lower than the cost of relying on any other water supply.

If you have a professional, experienced water well contractor inspect your site to determine the feasibility of using ground water, you'll be doing yourself and your locality a favor, because you'll be relying on a water storage system that doesn't drain the public reservoirs. A system that doesn't require major

There's water under almost every inhabitable tract of land on Earth.





Wells can help lessen the horrible effects of drought.

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construction. A system that never becomes clogged with silt or weeds. One that never loses water by evaporation. One that doesn't remove productive land from other beneficial uses.

The fact is, ground water is a virtually untapped, unfailing resource. A priceless resource that's so vast, its potential has just begun to surface.

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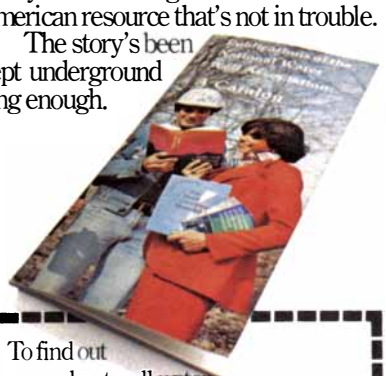
We're doing it because we think it's time you knew the good news about one American resource that's not in trouble.

The story's been kept underground long enough.



To find out more about well water, ground water contractors and ground water pumping techniques, just send this coupon to Franklin Electric, 400 E. Spring St., Bluffton, IN 46714. We'll work with the National Water Well Association to send you more good news from the underground.

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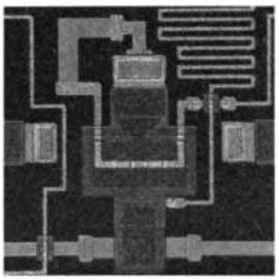

THE COVER

The photomicrograph on the cover shows part of a microelectronic device in which the basic circuit elements are not semiconductors but superconductors. Such devices operate extremely fast and dissipate little power, attributes that suit them for use in a high-speed digital computer (see "The Superconducting Computer," by Juri Matisoo, page 50). The switching function essential to any digital computer is carried out by Josephson junctions, which depend for their operation on two quantum-mechanical phenomena: superconductivity and the "tunneling" of electrons across an insulating barrier. The junctions, visible here as circular features within the dark brown rectangles, consist of two superconductors laid down one on top of the other with a thin layer of insulator between them. The superconductors, which can be recognized by their metallic sheen, are made of a lead alloy. Regions with a pebbly texture are covered by an insulating layer. A computer made up of Josephson-junction devices would be quite small, with a volume of a few cubic inches or less, and would operate some 50 times faster than most of the high-performance computers now being made. Because superconductivity occurs only at temperatures near absolute zero, the computer would be immersed in a bath of liquid helium. The device shown is a measurement circuit in the power supply of an experimental array of Josephson-junction devices. It was fabricated at the Thomas J. Watson Research Center of the International Business Machines Corporation.

THE ILLUSTRATIONS

Cover photograph by Fritz Goro

Page	Source
16–28	Ilil Arbel
43	François Bota, Gamma-Liaison
44–49	Albert Miller
51	Fritz Goro
52–59	Gabor Kiss
60	International Business Machines Corporation (*top left*), Gabor Kiss (*top right and bottom*)
61–65	Gabor Kiss
67	Fritz Goro
68–76	Dan Todd
89	Cedric S. Raine
90–102	Tom Prentiss
106	Albert Miller
111	Cedric S. Raine and Dikran S. Horoupian (*left*), Albert Miller (*right*)
114–116	Cedric S. Raine
121	National Aeronautics and Space Administration/ U.S. Geological Survey, EROS Data Center
123–132	Andrew Tomko
135	Roger D. Meicenheimer
136–137	Ilil Arbel
139	Robert Walker
140	Ralph O. Erickson
142	Ilil Arbel
144	Ilil Arbel (*top*), Ralph O. Erickson (*bottom*)
146–148	Ilil Arbel
153	Patricia J. Wynne
154	Patricia J. Wynne (*top*), Borislav Jovanović (*bottom*)
159–164	Borislav Jovanović
167	Patricia J. Wynne
169–170	Gabor Kiss
173	Archives of the French Academy of Sciences
174	Johns Hopkins University
175	Gabor Kiss
176–184	Michael Goodman

LETTERS

Sirs:

Bernard d'Espagnat's article "The Quantum Theory and Reality" [SCIENTIFIC AMERICAN, November, 1979] may leave some readers with a distorted impression of the essence of quantum mechanics. In particular the subtitle and the descriptive line in the table of contents for the issue are misleading; the first states that the world is made up of objects whose existence depends on human consciousness, and the second maintains that quantum mechanics disagrees with the doctrine that the world is independent of the mind. How can that be? Quantum mechanics deals with the properties of a piece of metal, with the processes in the interior of distant stars or with the nature of rocks that existed before humankind evolved. The article itself does not even support those questionable statements. It does, however, contribute to these misunderstandings—it did lead the editors to formulate the subtitle and the line in the table of contents.

The article is based on a rather narrow definition of reality, namely the applicability of concepts we use in dealing with macroscopic objects, such as position, velocity and angular momentum. Quantum mechanics, however, has shown that classical concepts are insufficient for the description of atomic phenomena. We are dealing with quantum states: states that have a particular way of escaping ordinary observation because such observations in many cases obliterate the conditions of the states' existence. The quantum states are described by wave functions implying the coexistence of waves and particles in the nature of electrons or other physical entities, a situation that would be impossible within a classical framework. There are well-defined rules of how the properties of atomic systems are determined from those wave functions.

The ideas of quantum mechanics do not contain any reasons whatsoever for giving up the concept of a reality that is independent of the mind. On the contrary, without the existence of quantum states we could not explain the specific properties of the elements, the structure of molecules and the existence of life. It is indeed true that the reality of the quantum state is different from the reality we would ascribe to a system of ordinary particles.

Heisenberg's uncertainty relations are the warning signs that tell us how far we are allowed to apply classical concepts to a quantum situation. In the case of the spin of a proton these relations say that it makes no sense to talk about the value of the y component of the spin when the x component is well defined. This warning was not heeded in d'Espagnat's "realistic" interpretation of the Einstein-Podolsky-Rosen experiment. Whoever disregards Heisenberg's warning signals ends up in a web of contradictions.

D'Espagnat is right when he says that one of his three premises quoted on the first page of his article must be violated in quantum mechanics. The first premise states that any observed regularities should be "caused by some physical reality." This premise is upheld. I consider the quantum state to be a physical reality even though it cannot be described with classical concepts. D'Espagnat's second premise about inductive inference is certainly upheld, but one must be careful when one draws what he calls "legitimate conclusions" from observations. The conclusions must be legitimate within the framework of quantum mechanics. For example, it is not legitimate to assume the existence of definite values for two components of angular momentum.

The third premise, that of "separability" or "locality," is surely not fulfilled. It postulates that there should be no connection between measurements on two separated protons except those measurements that could be considered arranged before the protons separate. Such unexpected connections do indeed occur, because the quantum state extends from one proton to the other even when the protons have separated. Such extended quantum states are nothing unusual. In the famous experiment of a beam of electrons passing through two slits of a diaphragm and forming interference patterns on a screen the quantum state extends over a region that includes the two slits. In principle this distance could be as large as one pleases.

The spatial extension of the wave function of the two protons A and B in d'Espagnat's example is to be understood as follows. The wave function contains correlations between the spins of A and B: when the spin of A is up, then B is down, and vice versa. This is the case whatever the distance is between A and B. A state with such correlations is called a singlet state. It has the remarkable property that it is one and the same quantum state, no matter in what direction the "up" and "down" are pointing. This surprising result is an aspect of the fact that the spin components are meaningful only in one direction at a time. Whenever a measurement is made on A, the spin of B is in the opposite direction in a singlet state, no matter what direction was chosen. Once I know that B has its spin in the opposite direction I can predict the probabilities of any spin measurement on B, even if B is distant from A.

This situation has nothing to do with any propagation of signals faster than light. The experimental setup discussed in d'Espagnat's article, or any other combination of measurements made on an extended quantum state, can never be used for the transmission of signals.

Quantum mechanics presents us with a much richer reality than we are accustomed to encountering in macroscopic physics. That is why it succeeded in describing what we actually observe in the atomic realm. In particular when the quantum state extends over macroscopic distances, as it does in the experiment described by d'Espagnat and for that matter in the phenomena of superconductivity (the Josephson effect), we encounter unexpected and puzzling correlations between measurements at different locations.

VICTOR F. WEISSKOPF

Massachusetts Institute of Technology
Cambridge

Sirs:

First of all I disagree with Professor Weisskopf when he states that the article under discussion is "based on a rather narrow definition of reality, namely the applicability of concepts we use in dealing with macroscopic objects, such as position, velocity or angular momentum." The article is definitely not based on any such a priori assumption. In fact, it is based on no a priori assumption whatsoever since it is constructed as a theorem, more precisely as a proof *a contrario*. The essential purpose is to show that a set of three, and only three, very general hypotheses (or premises),

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namely realism, the free use of induction and Einstein separability, have consequences that are contrary both to the predictions of the quantum rules *and* to observed facts, so that at least one of the premises must be wrong. Clearly when a mathematician develops a proof showing that an assumption *a* has a false consequence *b* (and must therefore be rejected), he should not be criticized for having considered, for the sake of the proof, the possibility that *a*, or some proposition deduced from *a*, could have been right!

Admittedly the validity of any such *a contrario* proof depends on the absence in it of supplementary implicit assumptions (whose falsity could then be responsible for the falsity of the conclusion). Now, it would be preposterous for me to claim certitude on that point of exhaustiveness. Nevertheless, I maintain that the various items cursorily noted by Weisskopf do not constitute such supplementary assumptions. For example, it is irrelevant to the proof that observation should "in many cases obliterate the conditions of the [quantum] states' existence." The proof is constructed in such a way as to guarantee that irrelevance (provided of course that the premises are assumed). Similarly, my statement that the spin of a proton of a singlet-state pair has several well-defined components is not a supplementary assumption; it is derived from the premises. (The key point is the definition of "property A^+" in the last paragraph on page 166.)

At this stage Weisskopf directs to me a second criticism. Without having recourse to experiment I should have known a priori that the statement just discussed above must be wrong, since it contradicts the uncertainty relations. I cannot accept that second criticism either. In my opinion it is based on an uncritical identification of some elements of the mathematical formalism (here the "quantum states") with elements of objective independent reality. And therefore it misses the main point underlying our recent investigations, which is that in view of the rather well-known difficulties entailed by every such a priori commitment it is interesting to avoid all such commitments wherever possible. Then, however, we must take into account the nonexistence of any correct proof that the uncertainty relations do not just refer to some unavoidable ignorance of some finer physical details, irrelevant for predictions. Hence in order to test the premises we must develop the argument further and ultimately let experiment decide for us. Since experiment is possible, any other attitude would, I think, carry with it a slight flavor of dogmatism.

As regards nonseparability both my article and Weisskopf's letter stress that it is well known in quantum mechanics. But when Weisskopf argues from this that the article says nothing new, he again overlooks the fact that up to the time of John S. Bell's work quantum nonseparability could logically be viewed as a mere feature of the formalism, not as a property of independent reality. In this respect the reported experiments do bring new knowledge, and it is knowledge that I think is philosophically quite important.

Now let me add a few more words about Weisskopf's own ideas, as summarized by the sentence "The ideas of quantum mechanics do not contain any reasons whatsoever for giving up the concept of a reality that is independent of our mind." That pronouncement is explicit. But, as I said, it is far from reflecting the real problem in its intricacy. If it did, how could we understand, for example, Heisenberg's statements that modern atomic physics "cannot deal any more with any Nature-in-itself" and "is a mere link in the infinite chain of the dialogues between Man and Nature"? The mere existence of these sentences should, I think, serve as a signal, warning us against the dangers of epistemological oversimplification. As Weisskopf himself puts it, we should not lightly disregard Heisenberg's signals. Indeed, an objective fact concerning quantum mechanics is the wide span of diverging views entertained, even among leading physicists, regarding the problem of its foundations in reality. The work described in my article should serve for isolating—and for solving—a special part of that problem. And considering the subtlety of the latter I do wonder whether, after all, it is not Weisskopf's forthright pronouncement rather than my own article (even with its cryptic subtitle) that is the more in danger of giving the reader a "distorted impression" of the essence of quantum mechanics.

Another objective fact, however, fortunately exists concerning quantum mechanics. It is that its rules of calculation are completely well defined. This is true even to the extent that they can form the basis of an objectivity of a new kind: a man-centered objectivity (see Heisenberg's sentences again) that may well suffice for the building up of the entire body of positivist science. And in that connection I should not like to end this response without stressing the debt all the physicists of my generation have toward the small body of men that includes Professor Weisskopf, for the very reason that their examples brilliantly showed us the almost incredible efficiency and fruitfulness of the new species of man-centered objectivity.

BERNARD D'ESPAGNAT

Laboratory of Theoretical Physics
and Elementary Particles
University of Paris-South
Orsay, France

EXPLODING THREE MILE ISLAND.

Think back. It hasn't been that long ago.

Pennsylvania looked like it might be blown off the map any minute, turned into a radioactive no-man's-land forever. "Permanently uninhabitable" was the way they said it in the movie, *The China Syndrome.*

That's the trouble. A lot of people said a lot of things. And a lot of it just wasn't true. Not even close.

Take the hydrogen bubble that made all the headlines. Bubble, nothing. The implication was time bomb, ticking away. And that would've frightened anybody who didn't have a degree in chemistry.

The fact is, that bubble couldn't explode. Not by any stretch of the imagination.

To understand why, you have to understand how the hydrogen got there in the first place. And that takes some understanding of how the reactor at Three Mile Island was designed to work.

It's the pressurized-water type, meaning the fuel core was cooled by keeping it submerged in water. H_2O. Hydrogen and oxygen. Heated by the core to more than 550 degrees, well beyond the boiling point.

What kept it from boiling was pressure, approximately 2,000 pounds worth. But on March 28th, last year, a relief valve on the pressurizer stuck open, the pressure dropped, and the water—the H_2O—inside the reactor boiled into steam.

When that happened, the zirconium-alloy tubes housing the fuel underwent a chemical reaction. A kind of accelerated rusting that combined the zirconium from the tubes with oxygen from the water to form zirconium oxide.

That's important, because with all the oxygen used up by the chemical reaction, the only part of the water left was hydrogen. The bubble. And what nobody bothered to tell you at the time was that without oxygen, hydrogen can't explode.

On May 1st, more than a month later, the Nuclear Regulatory Commission admitted the scare was all a mistake. Roger Mattson, Director of its Systems Safety Division, told a congressional committee there "never was any danger of a hydrogen explosion in that bubble."

That never made headlines.

And more than likely, neither will the fact that even if there had been a meltdown, it wouldn't have spelled disaster for Pennsylvania. It couldn't have.

First of all, the fuel core in the reactor vessel was surrounded by a containment building. Not just any building, an immense fortress with an enormously thick floor. Eleven feet of solid concrete reinforced with steel.

Second, for a molten mass to eat through it, that concrete-and-steel floor couldn't be covered with water. But water is what's used to cool the core. And when the relief valve on the pressurizer stuck open, sending several hundred thousand gallons shooting out, the law of gravity gave it only one place to go.

Down to the floor, right under the reactor vessel. Right in the path a molten mass would take.

That's the fallacy of the meltdown theory. In spite of the overwhelming odds against it, if all systems failed, if the entire core melted, if it got through the foot-thick steel reactor vessel in one piece and dropped to the floor below, it would've been stopped right there. Cooled by an ocean of water inside the containment building, not 20 feet from where the meltdown started.

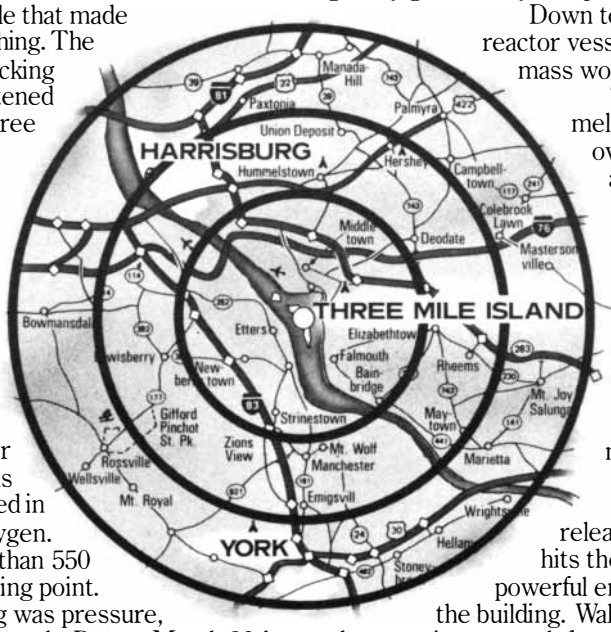
As for any sudden burst of steam pressure that might be released when the molten mass hits the water, it wouldn't be nearly powerful enough to rupture the walls of the building. Walls capable of withstanding almost twice as much force.

In other words, there was no way for significant radioactivity to reach the atmosphere outside.

The point of it all is that Three Mile Island and nuclear power itself deserve a fairer shake. A second look minus the hysteria, the hyperbole, the half-truths, and the untruths. They deserve a close, careful reading of the facts.

True, we've experienced the worst accident in the 22 years America has been using nuclear energy to produce electricity. But it wasn't the apocalypse. No one died. And except for the stress of being scared stiff, no one was injured. Despite the equipment failures and failures in judgment, despite everything that went wrong, the safety systems worked.

What really exploded were myths.



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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MAY, 1930: "In addition to flying to the South Pole the recently concluded Byrd expedition to Antarctica discovered and named the Rockefeller Mountains, Marie Byrd Land, the Charles Bob Mountains, another new mountain range on the polar flight, Barrier Inlet and a vast coastal range. The geological party gathered much scientific data and erased Amundsen's supposed Carmen Land from the map of Antarctica."

"For many years astronomers have dreamed of photographic plates that would be sensitive not only to red light but also to the slower infra-red vibrations the eye cannot see. Help has come from an unexpected quarter. Ordinary blue sky reflects a great deal of the shorter waves of sunlight but very little of the longer waves. Therefore if a landscape photograph is taken through a screen that transmits only deep red and infra-red light, the sky looks black on it. With the plates available until recently this demanded an exposure of minutes. Meanwhile the producers of moving pictures had been struggling with the problems of night scenes. They had succeeded only with the use of powerful and expensive floodlights. The infra-red landscapes, however, showed just the combination of dark sky and brightly lighted foreground they wanted. This justified the cost of further investigation, and a new dye, 'neocyanine,' was discovered by the chemists of the Eastman Kodak Company that makes it possible for the producers to photograph their night scenes in broad daylight. With the aid of these new neocyanine plates Harold D. Babcock of the Mount Wilson Observatory has photographed the solar spectrum out to about 11,500 angstrom units, some 2,000 angstrom units farther than the previous limit. He has measured many hundreds of spectral lines in the new region."

"Last Christmas Day marked the beginning of a new epoch in the international exchange of radio programs. A week before Christmas the National Broadcasting Company announced that it would attempt to rebroadcast special programs originating in England, Holland and Germany and that American programs would be sent on short waves to those countries. Christmas Day came and with it came three programs from abroad. The reception was better than even the most optimistic had expected. Of the special equipment used in this international exchange of programs little can be written. Much of it is still being improved, and construction details are still closely guarded secrets. Although engineers have known for a long time that static can no more be eliminated than snow or rain, they have learned much about shielding the delicate signals from atmospheric disturbances. Standard antennas do not give the best results in the reception of short-wave signals and the result has been the development of a new type of antenna, covering acres of ground and resembling a huge spiderweb."

"In spite of the fortune he has accumulated, Colonel Lindbergh remains as busily at work as ever, rendering consulting service to air transport companies. He has just bought, paying more than $17,000, the fastest two-seater sport plane ever built, the Lockheed Sirius. The plane is the last word in streamlining. The wings are internally braced, without the slightest exposed bracing. The engine cowling reduces head resistance yet allows perfect cooling. The wheels are almost entirely enclosed in special streamline housings, commonly termed 'pants.' A Pratt and Whitney Wasp engine is employed, developing 425 horsepower at 2,000 revolutions per minute. The two cockpits, which Colonel and Mrs. Lindbergh will occupy so often, are positioned well to the rear of the fuselage in order to give maximum protection in a crash."

MAY, 1880: "The total number of immigrants who arrived in New York last year was 175,589, which was much in excess of preceding years, being 50,723 more than in 1878, which exceeded 1877 by 20,811. The new arrivals are chiefly Germans. Since the Commission on Emigration was organized in 1847, Germany and Ireland have sent in about equal numbers, the total figures to the close of 1879 being for Germany 2,195,398 and for Ireland 2,042,046. Curiously the number of immigrants registered as seeking employment is smaller than it has ever been. Nearly all have definite plans for the future. They have money and friends, and they usually go west to situations procured in advance by their countrymen resident here. The demands for immigrant labor are mostly for Germans, Swedes and Scotch, but among these nationalities scarcely one in a hundred stops in New York to seek employment."

"Since the conclusion of the Treaty of Tientsin in 1858 the quantity of opium annually imported into China from India has increased to 90,000 chests. In 1875 as many as 85,454 chests, worth £10,000,000, were brought into the Chinese market, while the consumption of the drug for medicinal purposes in Great Britain in the same year was only 165 chests. The progressive growth of the trade during the past 80 years is thus shown: in 1800, about 5,000 chests; in 1825, 12,000; in 1850, 50,000, and in 1875 more than 85,000. Among the most striking effects caused by the extension of the poppy plantations in India are the diminution of the quantity of land available for other crops and the consequent curtailment of the production of food. Quite recently 100,000 acres of the richest agricultural plains in Central India, which used to produce corn, sugar and indigo, has been turned to opium culture. The acreage devoted to that purpose in India to-day is estimated at 1,033,000."

"The railroad tunnel under the Hudson River, which has been a conception of engineers and the talk of speculators for many years, is at last fairly under way. The commencement of the work was made by sinking a perpendicular shaft or well, 30 feet in diameter by 60 feet deep, at a distance of 100 feet from the water in Jersey City. The work has been carried forward about 150 feet from the shaft, or a distance of some 50 feet under the water. The width of the river on the line of the tunnel is 5,500 feet, and the terminus on the New Jersey shore will be about half a mile from the water. The terminus on the New York side has not yet been fully fixed upon. The great railway tunnel under the Thames at London, 1,600 feet long, is justly regarded as one of the most remarkable engineering works ever undertaken, but the Hudson River tunnel puts it far in the shade. It will establish a new line of unbroken communication between the East and the West."

"Salicylic acid, the manufacture of which on a large scale has only been rendered possible since 1874 by the patented method of Professor Hermann Kolbe, is the most important antiseptic, antizymotic and antipyretic ever discovered. It is a white, dry, crystalline powder, devoid of smell or taste, and has no detrimental effect whatever on the animal system. Experiments made by the most eminent physicians and surgeons have been so successful that both the acid and its sodium salt are universally recognized as valuable acquisitions in medicine. The scientific papers in all countries have been full of the most favorable reports concerning the immense success obtained in using salicylic acid in treating all cases of gout, neuralgia, acute rheumatism, fevers of all kinds, typhus, cancer, diseases of the throat and stomach, diabetes and other intestinal complaints."

THE AUTHORS

ELI GINZBERG ("Youth Unemployment") is A. Barton Hepburn Professor of Economics at the Columbia University Graduate School of Business and director of the Conservation of Human Resources Project at the university. He has had a long association with Columbia, having received his bachelor's degree there in 1931, his master's degree in 1932 and his Ph.D. (in economics) in 1934. He has also served in numerous capacities as a consultant to Government officials and agencies, currently as chairman of the National Commission for Employment Policy. His professional interests include the economic problems of women and minority groups, metropolitan economic problems, the economics of developing countries, medical economics and the economy of Israel. Ginzberg wishes to express his appreciation to Anna B. Dutka for her help in preparing the data used in his article.

JURI MATISOO ("The Superconducting Computer") is the engineering manager for the Josephson Computer Technology program at the Thomas J. Watson Research Center of the International Business Machines Corporation. He began working for IBM on a part-time basis while he was an undergraduate at the Massachusetts Institute of Technology, from which he obtained his bachelor's and master's degrees in 1959 and 1960 respectively. After a year in industry he enrolled at the University of Minnesota for further graduate study, receiving his Ph.D. in 1964. That year he began working full time for IBM and became interested in the Josephson effect, which had recently been discovered. Recognizing the potential of the effect in computers, he conceived computer devices and circuits based on it. In 1978 he was the recipient of the Jack A. Morton Award of the Institute of Electrical and Electronics Engineers (IEEE), which is given for outstanding contributions in the field of solid-state devices; his award was for "pioneering the Josephson computer technology."

DANIEL M. GREENBERGER and ALBERT W. OVERHAUSER ("The Role of Gravity in Quantum Theory") are respectively professor of physics at the City College of the City University of New York (currently on leave as a visiting professor at the Massachusetts Institute of Technology) and Stuart Professor of Physics at Purdue University. Greenberger was graduated from M.I.T. in 1954 and obtained his Ph.D. from the University of Illinois in 1958. He has served on the faculty of Ohio State University and the University of California at Berkeley and has been a visiting member of the faculty at the University of Oxford and the University of Washington. Overhauser received his A.B. in 1948 and his Ph.D. (in physics) in 1951 from the University of California at Berkeley. After two years of postdoctoral work at the University of Illinois he was for several years on the faculty of Cornell University. In 1958 he joined the staff of the scientific laboratories of the Ford Motor Company, where he eventually became director of the physical sciences laboratory. He joined the Purdue faculty in 1973.

PIERRE MORELL and WILLIAM T. NORTON ("Myelin") are respectively professor of biochemistry at the University of North Carolina School of Medicine and professor of both neurology (neurochemistry) and neuroscience at the Albert Einstein College of Medicine in New York. Morell followed a well-traveled path among American scientists, graduating from the Bronx High School of Science and Columbia University. He obtained his Ph.D. in 1968 from the Albert Einstein College of Medicine. "My interest in neurochemistry," he writes, "was stimulated by postdoctoral training at the University of Michigan and later through interactions with the faculty of the department of neurology at Einstein, to which I had returned for my first faculty position." Morell went to the University of North Carolina in 1972. Norton, born and raised in Maine, was graduated from Bowdoin College in 1950 and took his Ph.D. (in organic chemistry) from Princeton University. He writes that after a period of work as an industrial chemist studying high polymers he looked for a field that "promised more significance and stimulation" and turned to neurochemistry, joining the Albert Einstein College of Medicine two years after it was founded.

R. K. O'NIONS, P. J. HAMILTON and NORMAN M. EVENSEN ("The Chemical Evolution of the Earth's Mantle") established their working association at the Lamont-Doherty Geological Observatory of Columbia University. O'Nions and Hamilton are now at the University of Cambridge, where O'Nions is Royal Society Research Professor and Hamilton is research associate in the department of mineralogy and petrology; Evensen is assistant professor of geology at the University of Toronto. O'Nions did his undergraduate work at the University of Nottingham and obtained his Ph.D. (in geochemistry) from the University of Alberta in 1969. He taught at the University of Oxford until 1975, when he began a four-year association with Lamont-Doherty. Hamilton was graduated from King's College of the University of London in 1972 and received his D.Phil. from Oxford in 1975. He was at Lamont-Doherty from then until this year. Evensen's degrees are from the University of Minnesota. He was at Lamont-Doherty from 1974 until this year.

RALPH O. ERICKSON and WENDY KUHN SILK ("The Kinematics of Plant Growth") are respectively professor of botany at the University of Pennsylvania and assistant professor of water science at the University of California at Davis. Erickson earned his bachelor's degree at Gustavus Adolphus College in 1935 and his master's degree and Ph.D. from Washington University in 1941 and 1944 respectively. He taught at the University of Rochester for three years before joining the Pennsylvania faculty in 1947. Silk was graduated from Harvard College in 1968, began her graduate work at the University of Pennsylvania, completed it at the University of California at Berkeley, from which she obtained her Ph.D. (in botany), and returned to Pennsylvania for a period of postdoctoral work.

BORISLAV JOVANOVIĆ ("The Origins of Copper Mining in Europe") is a scientific counselor of the Institute of Archaeology in Belgrade. His degrees are from the University of Belgrade: a master's in 1955 and a Ph.D. in 1964. In addition to writing a number of monographs on Yugoslavian archaeology he has directed archaeological excavations at many sites. He is now collaborating on the preparation of a plan for protecting the archaeological monuments in the region of the Djerdap II power station, on the Danube between Yugoslavia and Romania. Jovanović writes: "As the Danube has always been and still is a most important line of communication in Europe, these excavations will yield, like the previous ones at Djerdap I, very interesting and new results pertaining to the cultural history of southeastern Europe."

IRVING M. KLOTZ ("The N-Ray Affair") is Morrison Professor of Chemistry at Northwestern University and also teaches a freshman seminar in English composition there. He has been at Northwestern since 1940, the year he received his Ph.D. from the University of Chicago. "My central researches of the past few decades," he writes, "revolve around questions of molecular structure and the functional behavior of macromolecules of biological importance. These investigations are directed primarily toward uncovering general rules of structure and behavior but occasionally focus on a specific practical objective; for example, we are trying to design molecules that might alleviate sickle-cell anemia."

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MATHEMATICAL GAMES

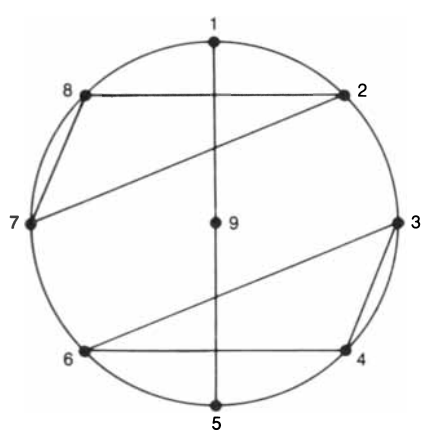
What unifies dinner guests, strolling schoolgirls and handcuffed prisoners?

by Martin Gardner

A woman plans to invite 15 friends to dinner. For 35 days she wants to have dinner with exactly three friends a day, and she wants to arrange the triplets so that each pair of friends will come only once. Is this arrangement possible?

That question and others like it, which belong to a vast area of combinatorics called block-design theory, were investigated intensively in the 19th century chiefly as recreational problems. Later they turned out to have an important role in statistics, particularly in the design of scientific experiments. A small branch of block-design theory deals with Steiner triple systems, of which the dinner-guest problem is a simple example. Jakob Steiner, a Swiss geometer, pioneered the study of these systems in the 19th century.

In general a Steiner triple system is an arrangement of n objects in triplets such that each pair of objects appears in a triplet once and only once. It is easy to show that the number of pairs is $\frac{1}{2}n(n-1)$ and that the number of required triplets is one-third the number of pairs, or $\frac{1}{6}n(n-1)$. Of course, a Steiner triple system is possible only when both of these numbers are integers. That happens when n is congruent to 1 or 3 modulo 6, namely, there is a remainder of 1 or 3 when n is divided by 6. Therefore the sequence of possible values for n is 3, 7, 9, 13, 15, 19, 21 and so on.



Disk for solving Kirkman's schoolgirls, n = *9*

With only three guests the dinner problem has a trivial solution: all of them come on the same day. Since Steiner triplets are not ordered, the solution is of course unique. There is also a unique solution for seven guests: (1,2,4), (2,3,5), (3,4,6), (4,5,7), (5,6,1), (6,7,2) and (7,1,3). The order of the triplets and the order of the numbers in each triplet can be altered any way you want without changing the basic pattern. In addition, the numbers can also be exchanged. To understand this point think of each guest as wearing a button with a number painted on it. If two or more guests exchange buttons as they please, the new combination is considered to be the same as the old one.

Similarly, for nine guests there is a unique solution, for 13 guests there are two solutions and for 15 guests it has long been known there are 80 basic solutions. For values of n greater than 15 the number of distinct solutions is not known, although it has been proved there is a solution for every value of n. For $n = 19$ there are hundreds of thousands of solutions.

Let us now complicate the Steiner triple systems a bit to make them more interesting. Suppose the woman decides to invite all 15 friends on each of seven days, seating them three to a table at five tables. She wants each pair of friends to be together at a table only once.

Our new problem is equivalent to one of the most famous puzzles in the history of combinatorial mathematics: Kirkman's schoolgirl problem, named for the Reverend Thomas Penyngton Kirkman, a 19th-century amateur British mathematician who was rector of the church at Croft in Lancashire for more than 50 years. Although he was entirely self-taught in mathematics, his discoveries were so original and diverse that he was elected to the Royal Society. In addition to combinatorics he did significant work on knots, finite groups and quaternions. There is a well-known configuration in projective geometry called Pascal's mystic hexagram (six points on a conic curve joined in all possible ways by straight lines) in which certain intersections are known as Kirkman points.

Kirkman was notorious for his biting sarcasm, which he frequently directed at the philosophy of Herbert Spencer. His parody of Spencer's definition of evolution was often quoted: "A change from a nohowish untalkaboutable all-likeness, to a somehowish and in-general-talkaboutable not-all-likeness, by continuous somethingelseifications and sticktogetherations."

Kirkman first published his schoolgirl problem in 1847 in a British mathematics journal, and it appeared again in *The Lady's and Gentleman's Diary for the Year 1850.* Here is how he presented it. Every day of the week a teacher takes 15 schoolgirls on a walk. During the walk the girls are grouped in triplets. Can the teacher construct the triplets so that after the seven walks each pair of girls has walked in the same triplet once and only once?

Any solution to this problem is of course a Steiner triple system, but of the 80 basic solutions for $n = 15$ only seven are basic solutions to the schoolgirl problem. Kirkman designs is the name given to Steiner triple systems with the extra requirement that the triplets be grouped so that each group exhausts all the objects.

Again the number of pairs of girls is $\frac{1}{2}n(n-1)$ and the number of days required for the walks is $\frac{1}{2}(n-1)$. These values are integers only when n is an odd multiple of 3. Thus the sequence of possible values is 3, 9, 15, 21 and so on, or the sequence for the Steiner triple systems with every other number left out. Does every value in the sequence have a solution? Since the time Kirkman raised the question a host of papers have been written on the problem, including many by eminent mathematicians. The case of $n = 3$ is still trivial. The three girls simply go for a walk. The case of nine girls in four days has a unique solution:

123	147	159	168
456	258	267	249
789	369	348	357

Like the Steiner triple systems, the numbers in a triplet are not ordered, and so it does not matter how the numbers are permuted, how the triplets are arranged within each group or how the digits are exchanged with each other. All variations obtained by these permutations are considered to be the same solution.

There are many novel methods, including geometric ones, for constructing Kirkman designs. One of them would have delighted Ramón Lull, the 13th-

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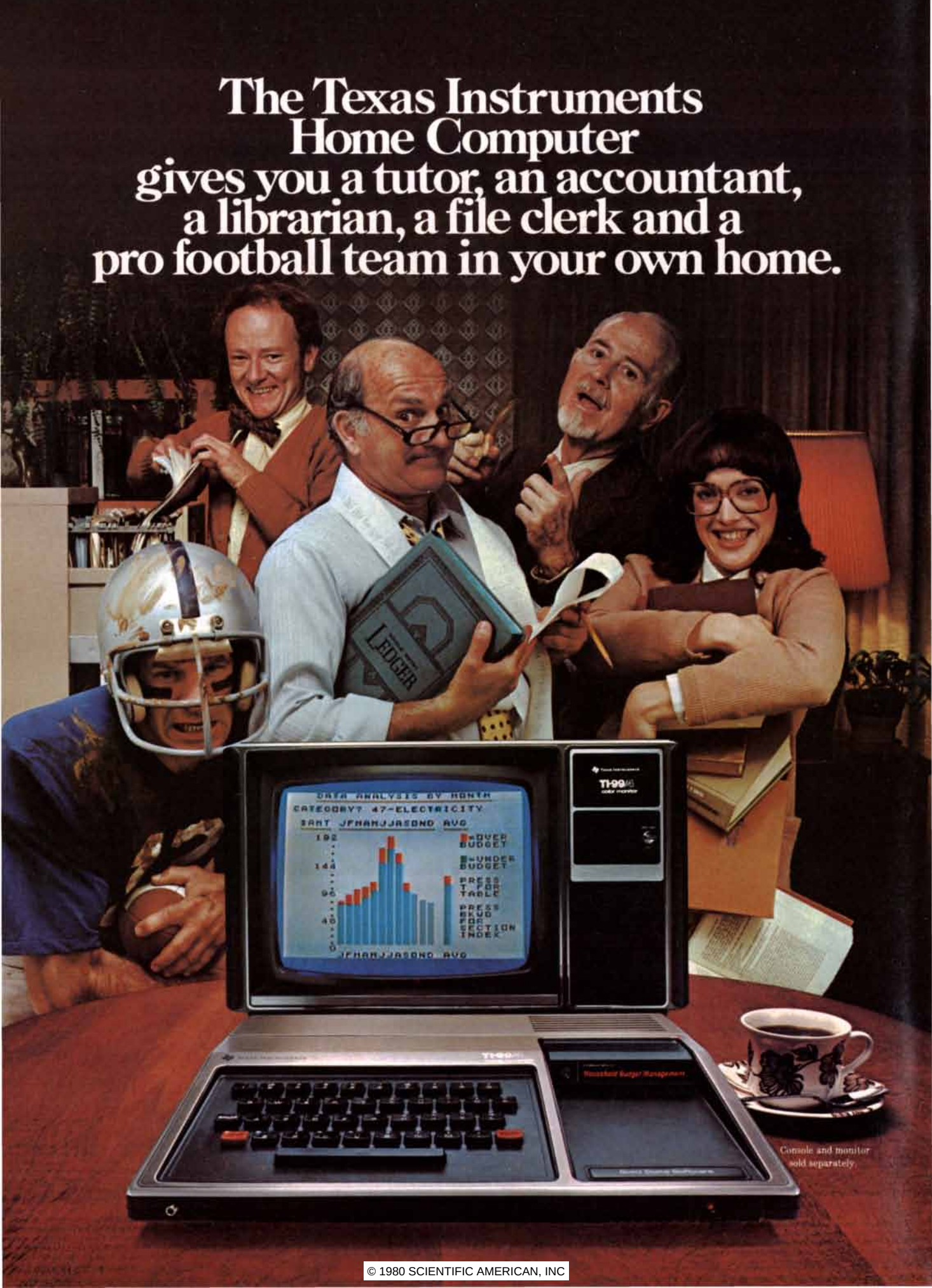

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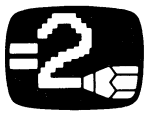

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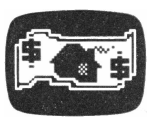
HOME FINANCE



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century Spanish theologian whose *Ars magna* explored combinations of symbols with the aid of rotating concentric disks. To find a solution for $n = 9$ draw a circle and write the digits 1 through 8 around it equally spaced. A cardboard disk of the same size is fastened to the circle with a pin through both centers. Label the center of the disk 9. On the disk draw a diameter and two scalene triangles as shown in the illustration on page 16.

Now rotate the circle in either direction one step at a time to four different positions. (The fifth step brings the pattern back to what it was originally.) At each step copy down the triplet indicated by the ends and the center of the straight line and the two triplets indicated by the corners of the two triangles. The three triplets found at each of the disk's four positions give the triplets for each of the four days. This solution seems to be different from the design given above for the schoolgirl problem, but by substituting 2 for 5, 3 for 7, 4 for 9, 5 for 3, 6 for 8, 7 for 6, 8 for 4, and 9 for 2 (and leaving 1 the same) you get the identical design. The only other way to put triangles on the disk to generate a solution is to draw the mirror image of the pattern in the illustration. This procedure, however, will not give rise to a new design.

Since 1922 the case of $n = 15$ has been known to have seven basic solutions. They can be generated by different patterns of triangles, with or without a diameter line. One pattern of five triangles is shown in the illustration below. In this case the disk must be rotated two units at a time to seven different positions. At each position the corners of each triangle provide one of the five triplets for that day.

It should be noted that no two triangles on a disk can be congruent. If they were that way, they would duplicate triplets in the overall design. The classic work on Kirkman designs is Chapter 10 of the 11th edition of W. W. Rouse Ball's *Mathematical Recreations & Essays,* revised by H. S. M. Coxeter. The same chapter in the 12th edition of the book (University of Toronto Press, 1974), completely rewritten by Coxeter, is also valuable. The new chapter replaces the early history of the designs with a discussion of how they relate to topics such as affine and projective geometry, Hadamard matrixes, error-correcting codes, Latin squares and higher-dimensional geometry.

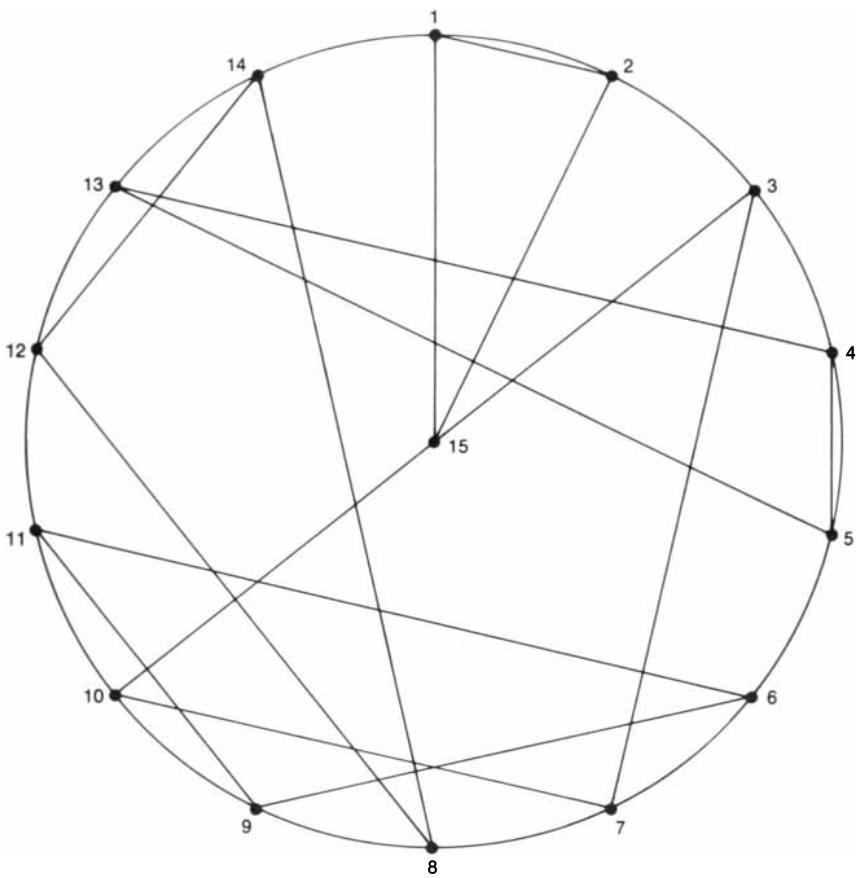
Is there a Kirkman design for every possible value of *n?* Surprisingly this question went unanswered until 1970, when D. K. Ray-Chaudhuri and Richard M. Wilson of Ohio State University proved that the answer is yes. The number of solutions, however, remains unknown for values of *n* greater than 20. The proof is presented in "Solution of Kirkman's Schoolgirl Problem" in *Combinatorics* (*Proceedings of Symposia in Pure Mathematics,* Vol. 19, pages 187–203; 1971).

Kirkman designs have many practical uses. Here is a typical way to apply the $n = 9$ design to a biological experiment. Suppose an investigator wants to study the effect of nine environments on a certain animal. There are four species of the animal, and any individual animal can be affected differently depending on whether it is young, fully grown or aged. Each species is randomly assigned to one of four groups. Within each group are three triplets, each of which includes a randomly picked animal of each age category. Every animal is now assigned to one of the nine environments according to the pattern of nine numbers in its group. This design makes possible an extremely simple way of statistically analyzing the results of the experiment in order to determine what effect the environment has regardless of differences in age and species.

I described above how Kirkman introduced an additional condition that transformed Steiner triple systems into a new kind of block-design problem. In 1917 the British puzzle genius Henry Ernest Dudeney imposed a novel constraint on Kirkman designs that gave rise to still another block-design problem (see Problem 272 of Dudeney's *Amusements in Mathematics* and Problem 287 of his posthumous work *Puzzles and Curious Problems*).

"Once upon a time," begins the second story line of Dudeney's puzzle, "there were nine prisoners of particularly dangerous character who had to be carefully watched. Every week day they were taken out for exercise, handcuffed together, as shown in the sketch made by one of their guards [*see illustration on page 22*]. On no day in any one week were the same two men to be handcuffed together. It will be seen how they were sent out on Monday. Can you arrange the nine men in triplets for the remaining five days? It will be seen that No. 1 cannot again be handcuffed to No. 2 (on either side), nor No. 2 with No. 3, but, of course, No. 1 and No. 3 can be put together. Therefore it is quite a different problem from the old one of the Fifteen Schoolgirls, and it will be found to be a fascinating teaser and amply repay for the leisure time spent on its solution."

Dudeney gave a solution without explaining how to reach it and other solutions like it. They can nonetheless be happily found by a Lullian technique with two wheels. A sample pair are shown in the top illustration on page 24. Each disk is rotated, say clockwise, three steps at a time. At each step a triplet is



Disk for solving Kirkman's schoolgirls, **n** *= 15*

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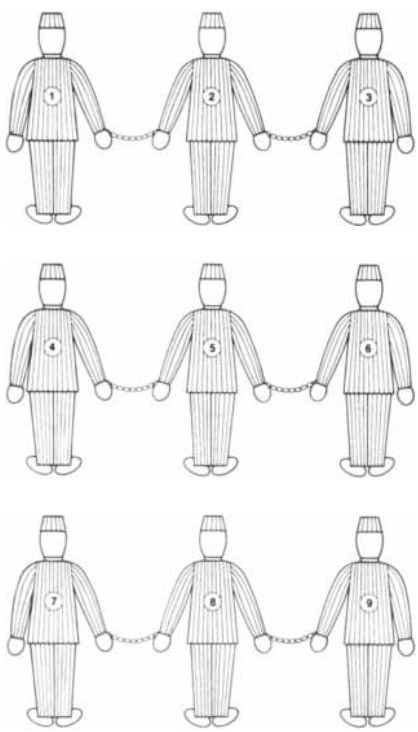
generated by the corners of the three triangles. In this case each triplet must have at its center the number indicated by the corner with a spot in it.

Each disk generates the three groups shown below it. In both sets the groups are cyclic in the sense that if you add 3 (modulo 7) to every number in the first group, you get the second group. Similarly, the second group generates the third one, which in turn returns you to the first one. The solution does not start with the pattern given by Dudeney for the first day, although it is easy to exchange digits to obtain that pattern.

After Dudeney answered the puzzle he teased: "If the reader wants a hard puzzle to keep him engrossed during the winter months, let him try to arrange twenty-one prisoners so that they can all walk out, similarly handcuffed in triplets, on fifteen days without any two men being handcuffed together more than once. In case he should come to the opinion that the task is impossible, we will add that we have written out a perfect solution. But it is a hard nut!"

It is a hard nut indeed. As far as I know the first published solution is in Pavol Hell and Alexander Rosa's "Graph Decompositions, Handcuffed Prisoners and Balanced *P*-Designs" in *Discrete Mathematics* (Vol. 2, No. 3, pages 229–252; June, 1972).

Before I give the solution I should like to make a few general remarks about the handcuffed-prisoner problem. The number of pairs of prisoners is $\frac{1}{2}n(n-1)$, as it was with Steiner triple systems and Kirkman designs, although the new restraint (handcuffs!) lengthens the required number of days to $\frac{3}{4}(n-1)$. There is a solution only when this expression is an integer, which is the case when n has a value in a sequence consisting of exactly half of the possible values for a Kirkman design, namely the sequence 9, 21, 33, 45, 57, 69, 81, 93 and so on, in which the difference between each adjacent pair of integers is 12.



Problem of the handcuffed prisoners, **n** = *9*

In 1971 Charlotte Huang and Rosa published a classification of 334 basic solutions for $n = 9$. When Dame Kathleen Ollerenshaw and the cosmologist Hermann Bondi checked each of the solutions, however, they found two duplications among the 334. The actual number of solutions is now thought to be 332. For all values of n greater than 9 the number of solutions is not known. For $n = 21$ Rosa thinks the number of solutions is in the millions. Hell and Rosa have proved that an infinite number of n's have solutions, and they have shown how to find cyclic solutions for all n's less than 100 with the exception of 57, 69 and 93. Wilson (who had helped to crack the Kirkman schoolgirl problem) has demonstrated by work not yet published that all values of n have a solution.

The bottom illustration on page 24 shows a cyclic solution found by Hell and Rosa for $n = 21$. The first seven days form a cyclic set that can be generated by a disk with seven triangles whose corners correspond to the triplets heading each day's design. The disk is rotated three steps at a time. A second disk with seven triangles similarly generates the next seven days, and the 15th day has the design shown at the right in the illustration. In both cyclic sets a day's design can be changed to the next day's by adding 3 (modulo 21) to each number, and doing the same to the last day's design brings back the pattern of the first day. Hell and Rosa give similar cyclic solutions for $n = 33$ and $n = 45$.

Both the schoolgirl problem and the prisoner problem can be generalized to quartets, quintets, sextets and so on. Such generalization leads to deep combinatorial enigmas, many of which are far from answered. Hundreds of related problems appear in puzzle books, often with story lines about seating arrangements, game tournaments, committee memberships and other combinatorial schemes. For example, I am often asked how to arrange n members of a bridge club (n must be a multiple of 4) so that they can meet daily for $n-1$ days at $n/4$ tables such that each player is the partner of every other player exactly once and the opponent of every other player exactly twice.

The bridge problem seems quite simple, but actually it is so thorny that it was not completely solved until a few years ago. The fullest analysis can be found in "Whist Tournaments," an article by Ronald D. Baker of the University of Delaware. (The article appeared in *Proceedings of the Sixth Southeastern Conference on Combinatorics, Graph Theory and Computing,* published in 1975 by Utilitas Mathematica, Winnipeg, as Volume 14 of the series *Congressus Numerantium.*) Baker shows how to find solutions for all values of n except 132, 152 and 264. Since then the Israeli mathematician Haim Hanani has cracked the case of $n = 132$, and Baker and Wilson have solved the cases of $n = 152$ and $n = 264$. Baker and Wilson will soon publish a detailed analysis of the three cases.

For many values of n solutions are generated by disks that rotate one step at a time. The illustration on page 28 shows disks for $n = 4$ and $n = 8$. The technique for generating the solutions is straightforward. A line is drawn from *1* (the disk's center) to *2*. Another line is drawn to connect two other numbers. The end points of each line are bridge partners, and the pairs of partners are opponents at the same table. If there is a second table, two more pairs of numbers are joined with colored lines to indicate the seating arrangement for the table. More colors are introduced for additional tables.

The arrangement of such lines generates a cyclic solution if and only if two conditions are met. First, no two lines are the same length (as length is measured by the number of units a line spans on the circumference). Except for the radius line the lengths will necessarily be consecutive integers starting with 1 and ending with $\frac{1}{2}n - 1$. Second, if all the opponents at each table are connected by lines (which are broken in the illustration), each length will appear on the disk only twice.

The lines are positioned chiefly by trial and error. No known procedure guarantees a correct pattern for all values of n. Once a pattern is found it indicates the seating arrangement for the first day. Rotating the disk generates the arrangements for the remaining days. Every column of the final design is cyclic, so that once the seating arrangement for the first day is determined a seating chart for the other days can be rapidly completed without having to turn the disk. The unpublished solutions for $n = 132$, $n = 152$ and $n = 264$ are not cyclic, although it may be possible to put them in a cyclic form by permuting the numbers. According to Baker, all values of n may have cyclic solutions, although no general algorithm is known for finding them.

Now for a pleasant problem to be answered next month: Can you design a disk for 12 bridge players that will generate a cyclic tournament meeting all the desired conditions?

In giving the problem about the train in my column for December I should not have had the train make stops along the 500-mile track. Henry S. Warren, Jr.,

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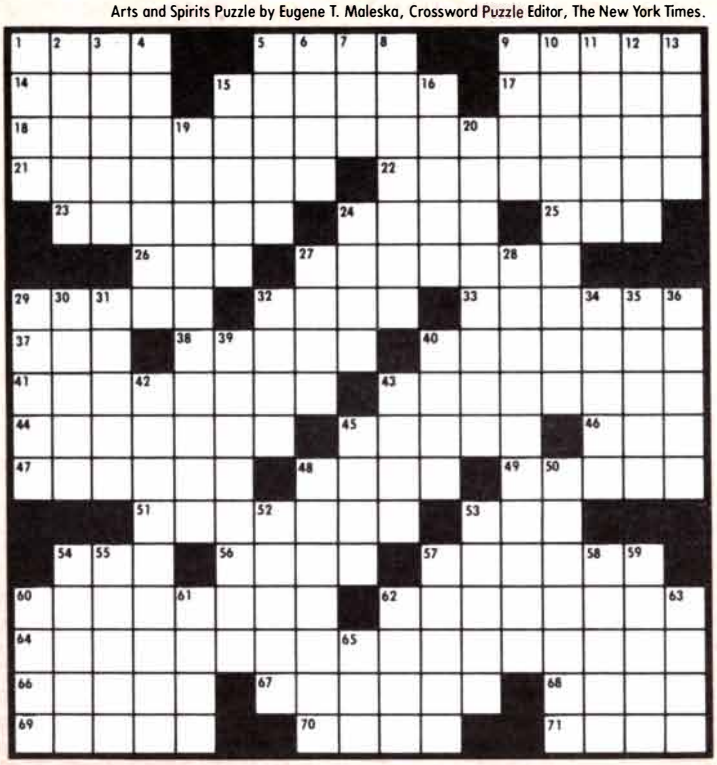

ACROSS

1 Carpenter's file
5 Game with 32 cards
9 Plowed land
14 Nanking nana
15 Audient
17 Noted Finnish philosopher: 1835-1924
18 Start of a poem by Burns
21 Too young to be served liquor
22 "--- tavern..."
23 Rubbernecking
24 Make sound
25 Q-U connection
26 "--- for the road"
27 Composer of "The Red Mill"
29 Middle East weight unit
32 Walleyed pike
33 Matador's lure
37 Raggedy doll
38 Philippine trees: Var.
40 Round Table town
41 China
43 Equipment for Mr. America
44 He has no deity or piety
45 Japanese lyric
46 Seine sight
47 Yucatecs
48 Undiluted
49 "And every --- queen": Kingsley
51 Goes
53 What an R.N. gives
54 Watering place
56 Birds called wahoos
57 Secular
60 Part of an atom
62 Painted the town red
64 Dos Passos novel
66 Famed Austrian contralto: 1803-77
67 Eiffel Tower levels
68 Douglas Hyde was its first president
69 German sculptor-painter: 1440-1533
70 Argus multiple features
71 Ocular ailment

DOWN

1 Stew, in Siena
2 Mohammed's mother
3 White --- National Monument, N.M.
4 One that may set the world on fire
5 Flock of herons
6 Danny, Sammy or Stubby
7 Estuary
8 Reeling
9 "Kilt him --- when he was three"
10 Church of Scotland clergyman: 1804-68
11 He spawned Hitler
12 "When thou --- this terrible thing": Isa.64.3
13 Author Seton
15 Viscount Templewood
16 Therapy center, to a G.I.
19 Battle site: Sept. 11, 1777
20 Skier's turn
24 Linen marking
27 Darner's target
28 Uproar; fracas
29 Palindromic title
30 Loos or Louise
31 Not bashful
32 Gossip's interest
34 --- Bell (Emily Bronte)
35 End of a Hemingway title
36 Flummoxed
39 Foreign visitor's need
40 Item to go with ale
42 Vexatious situations
43 Man from 40 Across
45 Shebangs
48 Turn the palm downward or backward
50 Impeaches
52 Make --- of (record)
53 Gogol's "--- Bulba"
54 Distort a report
55 Hungarian coin: 1925-46
57 Roman tutelary gods
58 --- as a fiddle
59 Suspicious
60 Australian avifauna
61 Grog quaffers
62 Drayman's charge: Abbr.
63 Scotch for grief
65 Aye neutralizer

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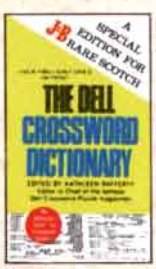

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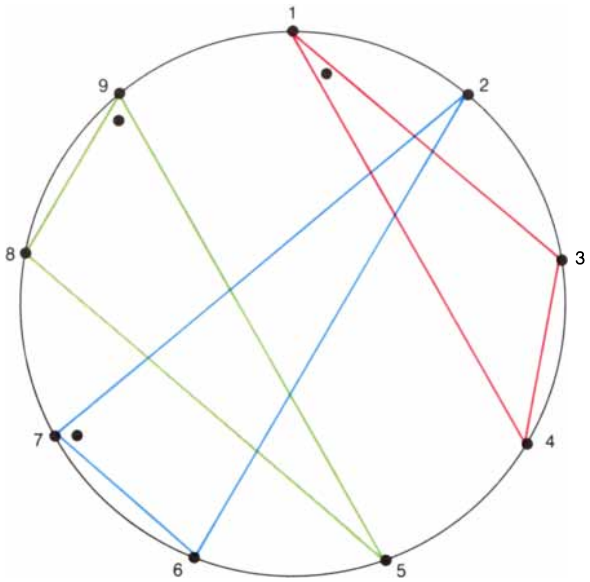

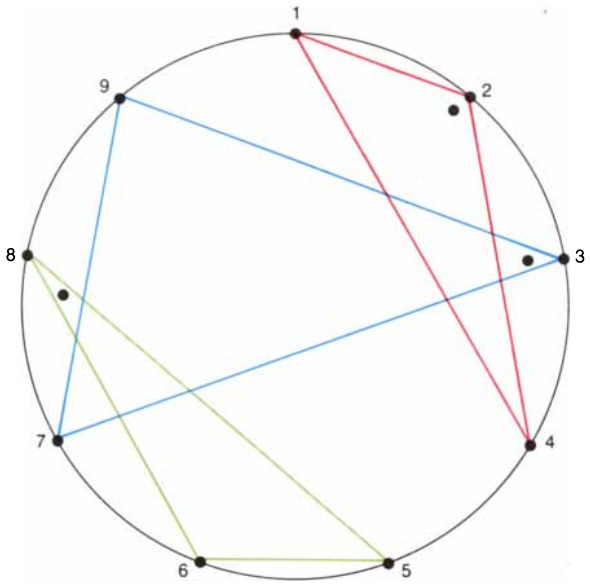

	1st DAY	2nd DAY	3rd DAY
RED	4 1 3	7 4 6	1 7 9
BLUE	2 7 6	5 1 9	8 4 3
GREEN	5 9 8	8 3 2	2 6 5

	4th DAY	5th DAY	6th DAY
RED	1 2 4	4 5 7	7 8 1
BLUE	7 3 9	1 6 3	4 9 6
GREEN	5 8 6	8 2 9	2 5 3

A solution to the handcuffed prisoners, **n** *= 9*

was the first of many readers to point out that if stops are made, the time it takes the train to traverse any 50-mile segment is not a continuous function of the segment's position as it moves from one end of the track to the other.

If instead of sliding a 50-mile segment you slide a one-hour time segment in the time direction along a space-time graph, then you can indeed show that there must be at least one hour in which the train moved only 50 miles even when stops and backing up are allowed. It is not possible to say, however, that there is always a 50-mile stretch traversed in just one hour.

To clarify this point, assume that the train went a steady 100 miles per hour except for one five-hour stop in the middle of the journey. After it had gone the last 50 miles in 30 minutes before coming to a stop the engineer could look at his watch and when 30 minutes had passed with the train standing still, he could truthfully say that in the past hour the train had gone 50 miles. Yet only in a Pickwickian sense can one say the train traveled that 50 miles at an average speed of 50 miles per hour, because a split second later the average speed for the same segment is reduced and continues to decrease until the train moves again.

In my March note about the ill-fated "impossible problem" I promised another report. Many readers wrote computer programs showing that as the upper bound for the two numbers is raised above 100, new solutions continually

1	2	3	4	5	6	7
1 8 18	4 11 21	7 14 3	10 17 6	13 20 9	16 2 12	19 5 15
2 4 20	5 7 2	8 10 5	11 13 8	14 16 11	17 19 14	20 1 17
3 7 15	6 10 18	9 13 21	12 16 3	15 19 6	18 1 9	21 4 12
10 11 6	13 14 9	16 17 12	19 20 15	1 2 18	4 5 21	7 8 3
5 16 21	8 19 3	11 1 6	14 4 9	17 7 12	20 10 15	2 13 18
19 9 17	1 12 20	4 15 2	7 18 5	10 21 8	13 3 11	16 6 14
13 12 14	16 15 17	19 18 20	1 21 2	4 3 5	7 6 8	10 9 11

8	9	10	11	12	13	14	15
1 4 19	4 7 1	7 10 4	10 13 7	13 16 10	16 19 13	19 1 16	1 3 2
7 16 9	10 19 12	13 1 15	16 4 18	19 7 21	1 10 3	4 13 6	4 6 5
10 2 6	13 5 9	16 8 12	19 11 15	1 14 18	4 17 21	7 20 3	7 9 8
13 17 8	16 20 11	19 2 14	1 5 17	4 8 20	7 11 2	10 14 5	10 12 11
11 14 20	14 17 2	17 20 5	20 2 8	2 5 11	5 8 14	8 11 17	13 15 14
5 12 21	8 15 3	11 18 6	14 21 9	17 3 12	20 6 15	2 9 18	16 18 17
3 18 15	6 21 18	9 3 21	12 6 3	15 9 6	18 12 9	21 15 12	19 21 20

A solution to the handcuffed prisoners, **n** *= 21*

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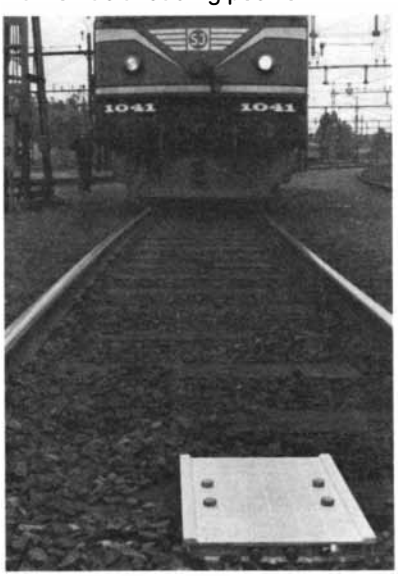

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appear. The next number pair is 4 and 61. It is not the case, therefore, that 4 and 13 is a unique answer regardless of the height of the bound.

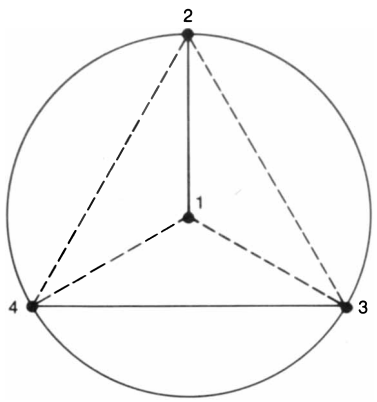
A program by David Pearson of Dartmouth College identified 78 pairs that solve the problem when the sum of the two numbers is less than 2,000 and the bound is sufficiently high. In all cases the smaller of the two numbers is a power of 2 and in all but five cases the larger number is a prime. It is conjectured that the smaller number is always a power of 2, although I have seen no proof of this. Moreover, it has not been established that without an upper bound the number of solution pairs is infinite.

A correspondent in Amsterdam, Robert W. van der Waall, sent me a copy of the problem as Hans Freudenthal presented it in the Dutch mathematics magazine *Nieuw Archief Voor Wiskunde* (Series 3, Vol. 17, page 152, 1969, and Vol. 18, pages 102–106, 1970). I know of no earlier reference.

In my column for last June I discussed the problem of putting n superqueens (a superqueen is a chess piece that combines the moves of a queen and a knight) on an n^2 board so that no two pieces attack each other. For values of n greater than 9 it has been shown that solutions must exist for all n's that are not of the form $(12k + 8)$ or $(12k + 9)$, where k is an integer. In other words, solutions have not been shown to exist for values of n in the sequence 20, 21, 32, 33, 44, 45, 56, 57 and so on. Readers too numerous to mention have sent solutions for the first six of these values. J. Reineke and P. Päppinghaus of the University of Hannover sent solutions for all n's through 69, leaving 80 as the lowest unsolved case.

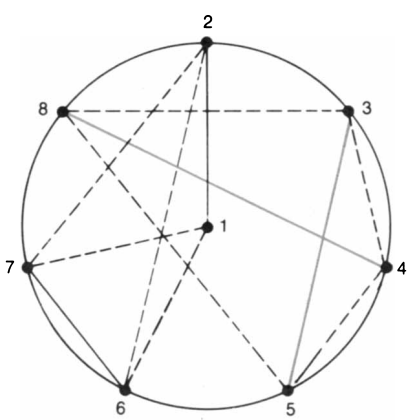
Many readers of my January column on checkers sent a second solution to the problem of how one black king can draw against two white kings in a position in which White is the first to move. I should have added "and not immediately lose a king." Without this proviso there are two trivial solutions other than the one I gave in February. One solution takes the form of White on 10 and 19 and Black on 15 between the two kings. The other solution has White on, say, 30 and 21 and Black on 22.

John Harris worked on the checker task of transferring the black and white sides in a legal game with a minimum number of moves. He lowered the record I gave from 172 moves to 160. Harris, by the way, should have been credited with the other task I mentioned: exchanging sides so that at the finish all 24 checkers are kings. His record of 180 moves (90 moves for each side) remains unbroken.



$n = 4$

DAYS	TABLE 1	
1	12	34
2	13	42
3	14	23



$n = 8$

DAYS	TABLE 1		TABLE 2	
1	12	67	35	48
2	13	78	46	52
3	14	82	57	63
4	15	23	68	74
5	16	34	72	85
6	17	45	83	26
7	18	56	24	37

Bridge tournament designs for* n = *4 and* n = *8

Extended Lifespan

JS&A was destined for failure when we introduced our first electronic blood pressure unit. But then a miracle happened.

Model 310

Model 410

Advertisements were starting to appear everywhere. JS&A had just introduced the world's first home electronic blood pressure unit in a massive national advertising campaign.

But something was strange. JS&A often tests its products in its catalog first before they are nationally advertised. If they sell well, we then start a national magazine advertising campaign. The blood pressure unit sold well in our catalog, but for some strange reason, it wasn't selling well in magazines.

SHOCKING DISCOVERY

And then we found the answer. A few months earlier after our blood pressure unit appeared in our catalog, our computer manager (let us call him Ralph to protect his identity) handed us a computer printout of the catalog sales results.

Scanning the results, we discovered that the blood pressure unit was the best-selling product in our catalog–far exceeding every other product by five times.

The results were so positive that we immediately placed hundreds of thousands of dollars in an advertising campaign launched in early 1978.

Just as the advertisements were starting to appear, Ralph walked into our president's office with some startling news. "There's been a mistake," Ralph said. "The computer printout was wrong. The blood pressure unit is actually our worst selling product but a computer error gave us the wrong information."

And so our president sat back and watched JS&A advertisements appearing everywhere, knowing full well that the campaign would cost his company almost the price of a new computer.

Then came the miracle. As if by plan, the American Medical Association came out with an advertising campaign urging consumers to take their blood pressure regularly to combat hypertension or high blood pressure. Ads appeared everywhere.

The campaign revealed that there may be as many as 25 million Americans who have high blood pressure and don't know it. Simply by taking their own blood pressure and discovering hypertension early enough, Americans could be saving their lives and reducing the chances of heart attacks. Suddenly our campaign started to sell blood pressure units by the thousands.

AWARD RECEIVED

This year JS&A's president received the Extended Lifespan award for "pioneering in the distribution of home health electronic devices" by the Committee for an Extended Lifespan. In accepting the award, our president made it very clear that the award was earned as a result of a computer error and not as a result of his brilliance.

This story is painfully true. And although it may be a slight embarrassment to us, there is one aspect that is not. JS&A was indeed the company that pioneered the electronic blood pressure units and has always selected the very best units available to offer at the very lowest prices possible.

NEWEST UNIT

Our newest unit shown above is another example. The model 310 sells for only **$69.95** plus $2.50 for postage and handling (Illinois residents, please add 6% sales tax.) You simply wrap the velcro cuff around your arm (you can even keep your shirt on) and inflate the cuff. Both an audible tone and a visible red light will indicate your systolic and diastolic readings. The system is extremely accurate, comes with a self-bleeding air valve and can be stored in a convenient carrying case that comes with each unit.

The deluxe model 410 functions similar to the first system except that the readings are displayed in digits, and the unit also displays your pulse reading. It sells for **$139.95** plus $2.50 per unit for postage, insurance and handling. If for any reason you are not completely satisfied with either unit, you may return it within 30 days for a prompt and courteous refund including your $2.50 postage and handling. To order either unit, credit card buyers may call our toll-free number, or you may send your check or money order to the address below.

Both units use solid-state components, come complete with instructions and a one-year limited warranty, and should give you years of trouble-free service. If service should be required, we maintain a service-by-mail center as close as your mailbox. JS&A is America's largest single source of space-age products–further assurance that your modest investment is well protected.

If you are concerned about your blood pressure or know somebody who is concerned about monitoring his or hers, we recommend JS&A's latest units.

Incidentally, Ralph left JS&A on his own accord and bought a farm in another state. There were no hard feelings when he left. How could there be? Order your blood pressure unit at no obligation, today.

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BOOKS

Origins in astronomy, picture messages from schizophrenics and the beauty of Antarctica

by Philip Morrison

A SOURCE BOOK IN ASTRONOMY AND ASTROPHYSICS, 1900–1975, edited by Kenneth R. Lang and Owen Gingerich. Harvard University Press ($50). THE SKY EXPLORED: CELESTIAL CARTOGRAPHY 1500–1800, by Deborah J. Warner. Alan R. Liss, Inc., 150 Fifth Avenue, New York, N.Y. 10011 ($70). Ancient astronomy was a matter of cosmic cycles; the astronomy of the founders of modern science studied the orbital clockwork, everywhere ruled by the laws of Newton, and marveled at the new cosmography of telescope-magnified skies. A deeper look into the economy of the universe waited both on the maturity of the physics of light and of its atomic emitters, and on the new technologies flowing from laboratory and shop. The modern view might be dated to the spectroscope, perhaps even more aptly to the rise of the patient photographic plate, whose integrations have shown us most of what glows so faintly over the cosmic distances.

For a generation there have appeared related source books; *A Source Book in Astronomy and Astrophysics* is the latest in a coherent series under the general editorship of Edward H. Madden of the State University of New York at Buffalo. These gather up classical texts that have "shaped the structure of the various sciences," assembled by discipline and period, each volume chosen, Englished and annotated by knowing specialists. This bulky book is the latest, both of its editors men of research experience in modern astrophysics. Lang is a young theorist at Tufts University who has already published a wide-ranging compendium of astrophysical theory and Gingerich is a well-known astronomical historian at the Harvard College Observatory. They have selected about 160 publications (all but a handful are papers from scientific journals; a few come from books or more popular periodicals) within 132 specific topics over the entire field of the title, from the earth and the moon to the horizons of the cosmos.

The articles are shortened, the cuts generally bridged with helpful editorial constructions. All the matter is newly set; there are no facsimiles, although many figures are from the originals, with new captions. Useful glosses place each topic in context, generally right to the point. (The editors are a bit optimistic about our current understanding of cosmic-ray origins and of cosmology.) They have added a few welcome figures from sources not included, to enrich more than 900 rather heavy and often mathematical pages with a variety of fine photographs. The papers are presented by topic, in chronological order within each narrow subject, a good general compromise in such a rich treasury. It holds everything from A. A. Michelson's star interferometry to the famous Holmdel, N.J., microwave horn, and the theorists' growing nets over the whole.

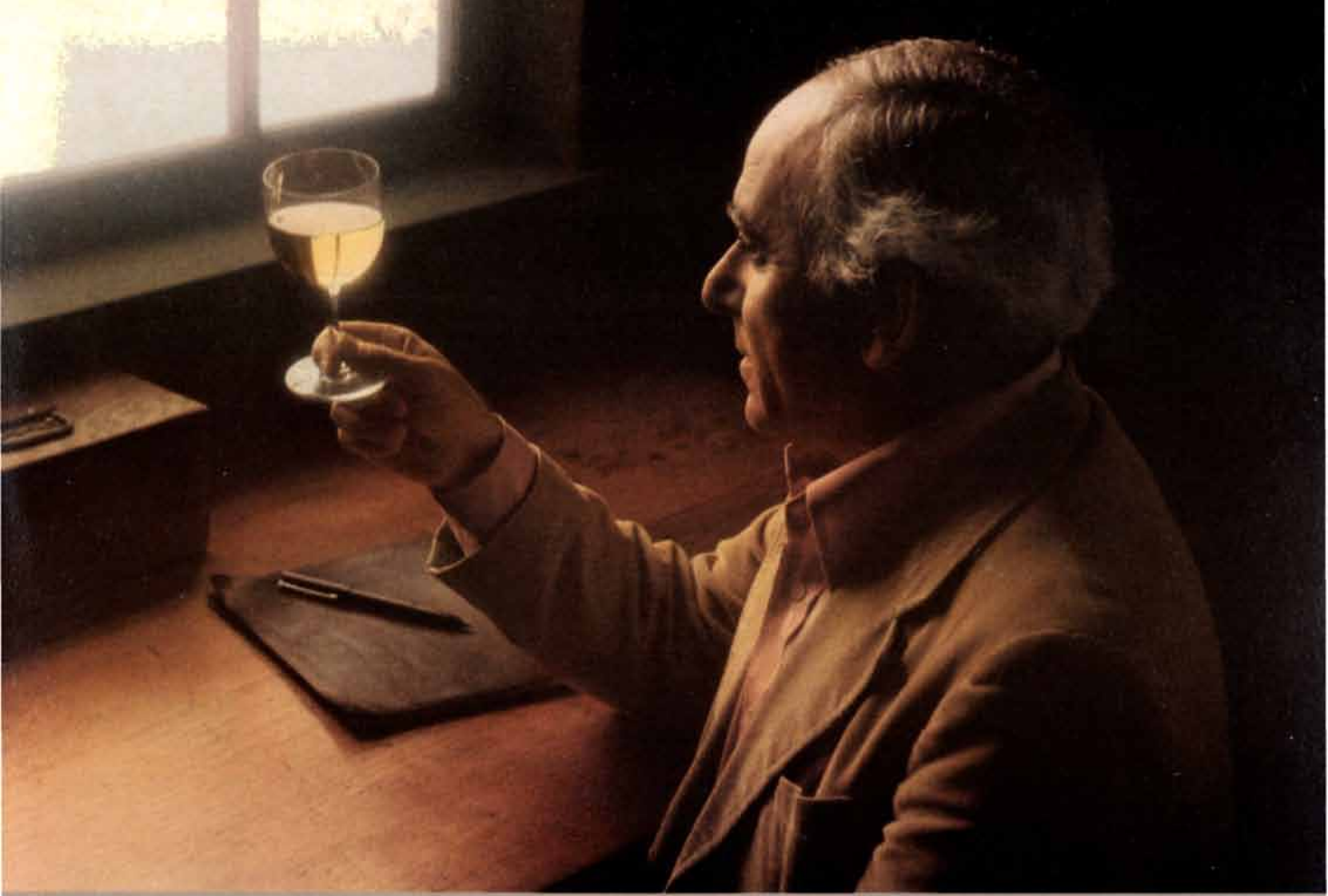
The selection is catholic, including many less widely known papers as well as the most famous but excluding catalogues as a category (a debatable decision; a sample page or two each from half a dozen important catalogues could have been of high interest). It generally steers away from review papers toward original work. There is no insistence on absolute priorities; we read the first clear and influential paper rather than the earliest obscure hint the literature affords. The indexes are rich; the book should engross many a student and give pleasure to the browsing general reader, less, of course, for a single session than as a steady companion.

Let a handful of items here stand for the rest. Viktor Franz Hess, a keen balloonist, set out from the Prater in old Vienna in a hydrogen balloon with his ionization chambers to see how much charge leaked at high altitude. He made seven flights in the summer of 1912, the last and highest launched "from Aussig on the Elbe." He returned with a firm conclusion: up there at five kilometers "a radiation of great penetrating power" came in from above. Cosmic rays, not emanating in straight lines from the sun, had been found. Electronics of a sort entered the telescope dome with the thermocouple and the bolometer, but the first novel result came in 1910 from a selenium photoresistive cell, not very sensitive but more accurate over short times than the photographic plates of the day, carefully nursed in an ice pack and artfully used by Joel Stebbins to disclose the little second dip in the light of eclipsing Algol.

It is striking to read how skeptical was the late Cecilia Payne (her 1925 monograph is excerpted here, praised by Otto Struve as "the most brilliant Ph.D. thesis ever written in astronomy") that hydrogen and helium could in fact be the major atoms of the stars, as her own spectral studies indicated. It was not until the early 1930's that it became accepted that the two lightest atoms dominated the chemistry of the cosmos: the solar atmosphere and its chromosphere, the stellar interiors and the gaseous nebulas. The theme of magnetism becomes real first for George Ellery Hale in 1908, when he looked for polarized Zeeman lines in the light coming from the spinning vortexes he could see in his monochromatic images of sunspots. Lev Landau's paper in 1932 and the joint work of Walter Baade and Fritz Zwicky in 1934 both presage the neutron star, even if Landau shows great sympathy for the "beautiful idea of Professor Niels Bohr's" that energy conservation may break down when nuclei come in close contact! The entire story of the Crab Nebula is here, with the polarized-light photographs that bore out the bold predictions of Iosif Shklovskii that the bluish continuum light was the result of synchrotron emission.

On we read, past the discovery of pulsars to the proposals of Franco Pacini and Thomas Gold that neutron stars might be conspicuous generators, not the shy, dark, hidden spheres of the older theorists. The story of the island universes and of our present understanding of the realm of the galaxies is both fascinating and cautionary. From the time of Kant the philosophers had grasped the idea, with much luck and a little data. William Herschel embraced it happily, because he found that the better telescopes resolved most of the fuzzy patches into stars. The spectroscope, however, showed that at least the green nebulas consisted not of stars but of gas. It was given to E. P. Hubble to make the matter secure, but the paper by Heber Curtis of the Lick Observatory makes plain how strong the arguments were in 1919 (before the famous Shapley-Curtis debate) that the high recession speeds of the spiral nebulas, the strange absence of all such objects from the Milky Way and the very look of the stripes of occulting dark matter in some of the little edgewise spirals admitted of a unique interpretation.

There is a similar early confusion about the nature of celestial radio sources. As of 1946 they were surely small, relatively nearby and probably stellar. Did not strong Cygnus A vary within a matter of seconds? Those variations turned out to be local twinkling, and by 1958 Martin Ryle clearly ex-



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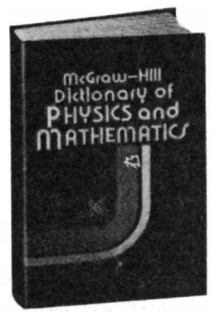

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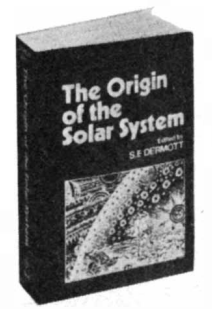

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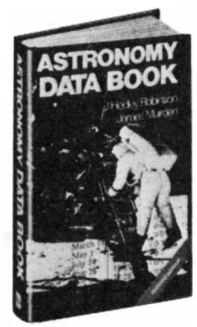

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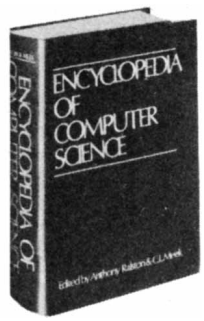

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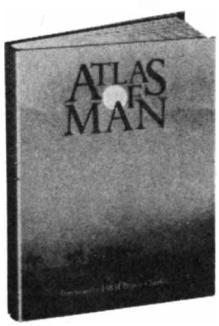

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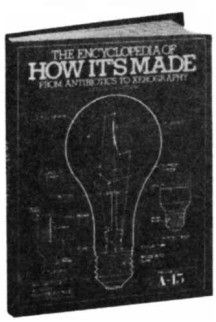

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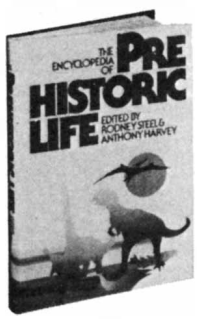

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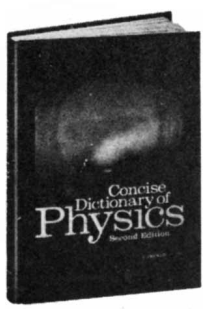

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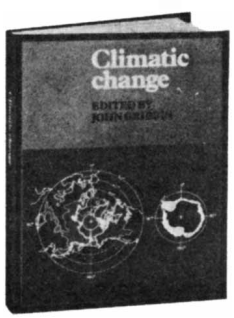

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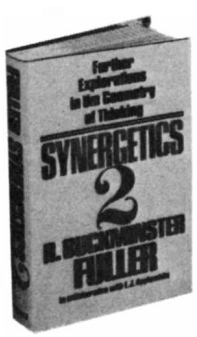

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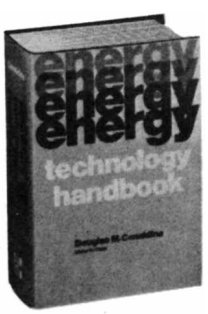

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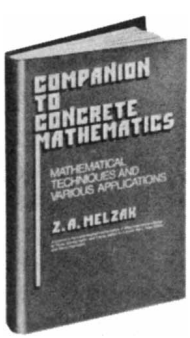

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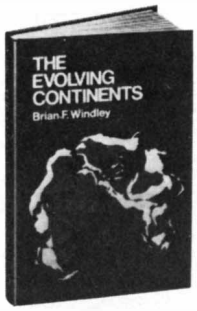

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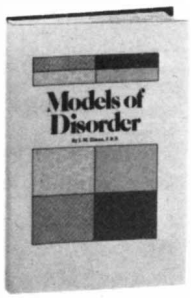

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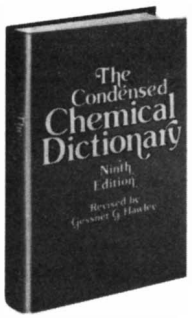

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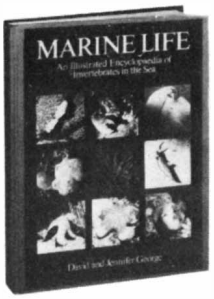

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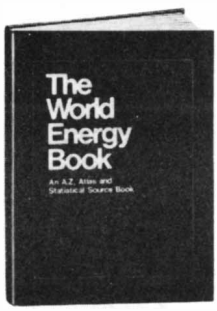

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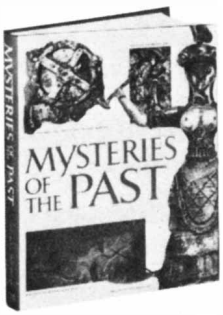

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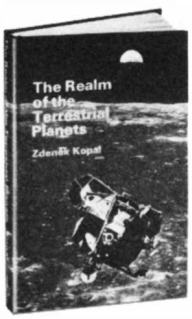

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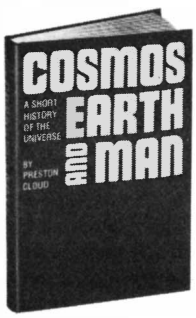

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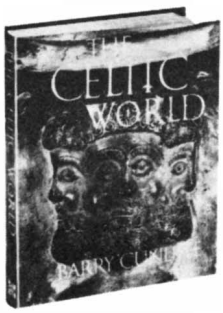

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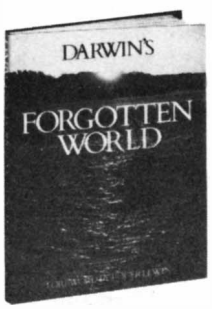

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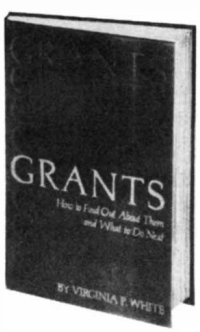

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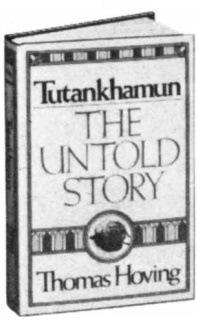

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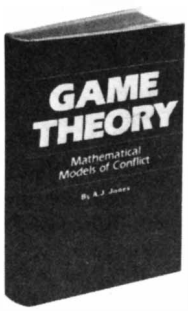

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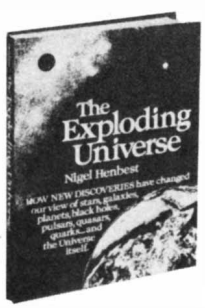

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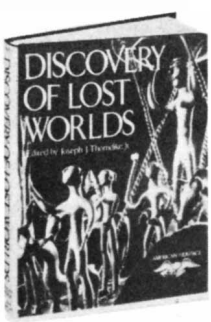

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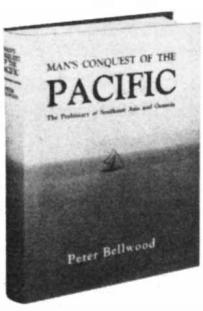

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Mozart flowing

Ultimately, the 450 SEL amounts to something more than the sum of its facts and figures. The Editor of *Car and Driver* put it into words.

"I sincerely wish," he wrote, "that everyone I love, anywhere in the world, could savor the experience of rushing down a country road in the middle of the night with Mozart flowing out of the speakers, and the three-pointed star, silhouetted against the headlights' path, leading the way. What a gift!"

Engineered like no other car in the world

plained how the radio sources had to be extragalactic objects of very high power. In 1951 a lively discussion with the heterodox Gold and Fred Hoyle had found Ryle dismissing that very view rather haughtily with "I think the theoreticians have misunderstood the experimental data." The first real quasar, 3C 48, was greeted as "the first case where strong radio emission originates from an optically observed star" by a coterie of Palomar and Cal Tech experts. It took a year or two before the quite unstarlike nature of the "quasi-stellar sources" was manifest.

There is some first-rate writing here, usually not in the most conventional contexts. In a complicated summary paper of 1975 Farouk El-Baz writes: "There are three basic theories of origin of the Moon. She is either Earth's wife, captured from some other orbit; daughter, fissioned directly from 'proto' Earth; or sister, accreted from the same binary system." The relationship is still not clear. A. S. Eddington spoke in a famous address of 1920 about the "analytical boring device" able to penetrate not the rocks of the earth but the gases of the sun. He spoke of nuclear energy as well, remarking that "what is possible in the Cavendish Laboratory may not be too difficult in the sun," and adding that the latent power might be used "for the well-being of the human race—or for its suicide."

Vesto Slipher tells of his spectroscopy of 25 faint spirals, requiring exposures of 20 to 40 hours each with the Lowell Observatory 24-inch refractor in the seasons after 1912. Baade writes of his famous deep exposures through browned-out Los Angeles skies, an opportunity born of World War II. Indeed, so was the leisure for Baade himself, an enemy alien not sought for wartime research, to push his techniques of guiding and plate sensitization to unheard-of limits. The digital world enters, with autocorrelations and fast Fourier transforms, with the radio molecular spectroscopy of 1963. Satellites are here too, of course: the early work of 1958 showing the Van Allen "banana" of magnetically trapped particles, Pioneers, *Copernicus,* X-ray satellites and the Venus and Moon visitors, forerunners of deep-space astronomy from 1975 to the century's end. Twentieth-century astronomy does not at all progress by revolution; generally the sovereignty of past theories is weak. Rather it expands into trackless forests to establish crude frontier order where no settlers had been.

Before the camera, certainly before the telescope, the visible sky was the cynosure of the learned. Man sought in the stars the count of works and days, and even portents of the future. Once printing came to Europe there grew up a tradition of flat maps of the sky, both of the stars seen there and of the figurative groupings long imposed on the random patterns. In a valuable work of reference, *The Sky Explored: Celestial Cartography 1500–1800,* Deborah Warner of the Smithsonian Institution has collected with learning and care three centuries of star maps, the work of Dürer and Kepler, Mercator and Thomas Young. Her catalogue includes nearly 200 such works, carefully annotated (although with a few editorial lapses) with bibliographical details, context and full contents. The handsome two-page spread of the Dürer woodcuts of 1515 allows us to realize how much we miss from the small size and low-contrast reproduction of most of the maps illustrated. This is a working index catalogue, not an artistic collection. The alphabetical arrangement fits that decision, although we lose by it a good deal of the historical sense a general reader might have won from examination of the works in chronological order.

Surely the volume will commend itself to librarians and collectors: it is a mine of otherwise obscure information. One can with some patience trace out the origins of the images of the constellations, which appear to mix an Islamic tradition direct from its Ptolemaic sources with a ruder, more mythological style, stemming from medieval manuscripts that offered illustrated versions of the long sky-myth classical poems of Aratus of Soli and Hyginus. The material is rich with implications and conclusions, from the coming of the southern stars and the Clouds of Magellan to the efforts, sometimes lastingly successful, to father new constellations, even in the skies Ptolemy had mapped. The sky maps turned detailed and matter-of-fact at the end of this period; Thomas Young himself proposed to catasterize his colleague Humphrey Davy's trough battery as "the Battery of Volta" in 1806. But even that modest group of only two fourth-magnitude stars came too late for any acceptance.

THE PAINTED MESSAGE, by Otto Billig and B. G. Burton-Bradley. Schenkman Publishing Company, Halsted Press Division, John Wiley & Sons ($19.50). In the deep green valleys and along the rugged rain-drenched ridges of the highlands of central New Guinea there are a couple of thousand little villages, a few dozen round and oval huts each, where the Melanesian subsistence farmers live out the intricate lives of their ancient cultures (there are hundreds of languages), diverse, isolated, egalitarian. ("The only specialist was the artist, who was always male.") The men plant yams and taros, the women gather the crop and tend the pigs; there is rigid separation by sex, even to living quarters. Across this densely settled but long unvisited land have swept gales of change, first in the coming of the gold miners only 40 or 50 years ago, then in the echo of nearby war, then with an earnest colonial administration, the cash crops of tobacco and coffee, the ministry of tireless missionaries (often arriving headlong by parachute) and now with the building of a new nation: Papua New Guinea.

B. G. Burton-Bradley is the director of Mental Health Services there. His organization operates centers of psychiatric care: one outside the capital city, Port Moresby on the Coral Sea, and one a couple of hundred miles inland, at Goroka under the high peak of Mount Wilhelm. The patients resident at Laloki outside Moresby include many from coastal and riverine peoples, still more diverse in culture, open perhaps twice as long ago to contact with the world outside. The psychotic men and women under treatment show basic symptoms of schizophrenia similar to those of patients in developed countries, but "throughout this book we have used the less specific label of *personality disintegration* to describe the mental state of our patients." The volume does not rest on tricky diagnostic detail; the patients show patterns of behavior that deviate from what the patient's own cultural group considers normal and "are recognized as pathological by his peers." The patients from the rural areas were usually hospitalized for the physical protection of their fellow villagers; the patients from the larger towns were more often hospitalized for treatment.

Otto Billig, the other author, is clinical professor of psychiatry at the Vanderbilt University School of Medicine. Since his student days he has been caught by the evident importance of the graphic productions, usually in crayon or paint on paper, made by many schizophrenic patients in his own long experience. He went to New Guinea to find similar patients, drawn in some numbers from a large population, who could be said to be as culturally distinct as possible from the patients he knew. In this touching, thoughtful, richly illustrated volume the two psychiatrists have tried to sum up their findings based on that remarkable comparison. About 150 New Guinea patients were encountered, and a score of those cases are reviewed in some detail, with sequences of illustrations.

Rich lands and poor the sad progression is the same. Strange ideas lead to incoherent, purposeless speech. A deep need for human relationships may be concealed by a superficial crust of preoccupation, even detachment, that can suddenly shatter into anger or despair. Delusions may begin in a half-acceptable magical or religious guise and then progress into behavior so unusual that it is widely perceived as being bizarre.

A farmer in the New Guinea highlands had been a youth when the first

outside contact came. He lived inconspicuously in the village until his wife died. The Australian patrol officer saw a marked change in the man. His speech became vague, difficult, inconsistent. He left his lonely hut to wander with bow and arrow, although carrying a weapon was customary only in time of war. He grew no more food; he stole from the gardens and killed neighbors' pigs. When he encountered a woman working in a garden he had entered for food, he killed her. He killed a man from whom he had stolen some nuts, making the accusation that the dead man had stolen the nuts from him. In another time the villagers might then have killed him or driven him into the forest, but instead the patrol took him off. He sat alone and indifferent in the dayroom at the hospital, evasive under questioning, without insight into the reason for his plight. A few weeks of chemotherapy brought an improvement; he was discharged after a couple of years, but he immediately relapsed and was returned. In the hospital he took a vigorous part in art therapy; his output "is remarkable in its variety and quantity." His first watercolor is a spotty sheet of mandalas, zigzags and enclosed forms, a prototype of incoherence. Step by step his work came to resemble the ranks of triangles and crosshatchings that are the traditional decorations of his own culture. Tentative humanoid figures appear, hidden under the pattern. His last watercolors show lizards in the traditional pose, although elongated beyond the already lengthened norm. "Most of the patient's graphics find their basis in the cultural patterns of traditional art. Only a few of his watercolors, painted at the height of his psychotic disintegration, lack culture-bound designs; the structure of these watercolors is found universally in drawings by highly disintegrated psychotics."

Three famous artists, Vincent van Gogh, Giorgio de Chirico and Edvard Munch, suffered periods of clear psychotic disintegration; two of them were hospitalized. Sequences of their works are shown here; they have some affinities with the pictures made by other patients. The working artists, however, had a coherence, diminished but still strong, that gives their work meaning to us. Munch in particular managed to convey the human quality of his emotional state with remarkable eloquence. "The mentally ill patient is solipsistic and expresses his own inner feelings; the artist's work ... evokes significant reactions in his audience," even to his own inner conflict.

It is a more than visual space these pictures reflect; a rich multidimensionality replaces the powerful one-dimensional mapping by language that seems to be lost to the ill. Everyone internalizes some sense of space, based deep in the past on gravity, light and air and rooted universally in all cultures. Out of these elements is built up complex human behavior, social, maturing, intricately structured. As words come to fail the mind, deeper (earlier?) mappings can be called up. Layer by layer the coherence of the inner world is unwrapped, to end in those papers spotted with their floating inchoate designs. John Donne felt something like it in the new Copernican world, when only a public cosmology had been struck down: "'Tis all in peeces, all cohaerence gone; / All just supply, and all Relation: / Prince, Subject, Father, Sonne, are things forgot."

Like most psychiatric theorists, these observers extend their reflections very far indeed, with interesting chapters on magic, on the psychology of space and its ontological development, on the general and the artistic history of Europe. Tables of parallels are as close as this discipline can come to tests of theory; there are no counts, no statistical samples. There is, however, a good deal of mature knowledge and impressive argument. More than that, in this volume we enter directly the mentality of these our fellows, through their own symbolic handiwork. We vault with the eye the high barrier of the loss of language. "I can't say what I want to say.... There is too much." Consider that the words of the New Guinea patients had to traverse the slippery slopes of double translation, first from the place language to Neo-Melanesian pidgin, then from pidgin to the English text. In the sheer sweep of the clinical data, above all in the vivid directness of the painted message, this fine volume opens a wide door into the world of psychosis, and by contrast and affinity into the mind itself.

ANTARCTICA: NO SINGLE COUNTRY, NO SINGLE SEA, by Creina Bond and Roy Siegfried. Photography by Peter Johnson. Mayflower Books ($27.50). An American is likely to think of Cape Horn as fit gate to the Antarctic; its frightening rollers and howling winds seem to point the way to the icy shores of the Southern Ocean. We forget that the well-kept vineyards of Cape Town, where the summer sun is as high and hot as it is in the Carolinas, equally frame a port of departure for that Antarctic Circle beyond which the ice cap lies. No land lies south of that Cape before the Antarctic, only "the roaring forties, the filthy fifties and the screaming sixties" and then the great floats of pack ice come July.

This unusually beautiful book is a South African view of the isolated continent. Its focus is not the high ice, nor the aircraft and the geophysical stations that mark the plateau, but the ocean and its shores of rock and ice, the ships that have braved the waves, the cold, lonely volcanic islands dotting it here and

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there, and the life, from euphausid krill to wandering albatross and great blue whale, whose home it is. It is a work of the 1970's; the brilliant photographer whose large and well-reproduced photographs are the core of the volume has been to the Antarctic five times during the decade. In the context of his photographs a conservation journalist, Creina Bond, and a University of Cape Town naturalist, Roy Siegfreid, have presented an account of the history of the exploration and of the ecology of that world. The level is entirely popular, but they have used the classical historical sources—the pages of Shackleton, Scott, Apsley-Garrard—so well, and they offer such an up-to-date account of the geographical and biological truth and the political realities around that Southern Ocean, that the general reader will find it fresh and full of interest.

The extraordinarily fine photographs show both the icy world, cobalt blue and sun rosy more often than ice-blink white, and the rocky world of the dark shores. Three or four of the dozen brief chapters are of particular interest, both to the eye and to the mind. A couple treat of the islands. Here is Deception Island, whose sulfur-colored crater lake and sea-flooded caldera with its broken rim once gave safe harbor to busy whaling factories. Arctic reindeer now roam free along the talus slopes of South Georgia; 11 animals were brought there by Norwegian whalers before World War I. Beaufort Island is shown, a peak rising sheer from the cold seas, perhaps never climbed. The wandering albatross is celebrated in an interesting chapter. The story of the great bird, flying steadily up the prevailing wind, to return after a few years to its breeding islands from around the world, is well told and sharply pictured. Such a bird may voyage afar for 50 years; it seems likely that the staunchest and most enduring of the species may have circled the earth scores of times, rivaled among members of our species only by some airplane pilots and by the astronauts in orbit, logging five million miles aloft.

The chief concerns of the authors are the three great ocean resources. The marine animals, first the seals and then the big whales, have been exploited beyond the danger point. Second is the icebergs. Big and small, they show here vividly. Icebergs towed northward may offer a resource of fresh water, even of free energy, exploitable before the turn of the millennium, "one of the few Antarctic developments that might possibly take place without raising problems of original ownership." Finally there are the krill, the unappetizing luminous "supershrimp" whose mass fishery is one active if uncertain goal of the fishing nations. Two shots are memorable: a cast-up euphausid, cooked pink by volcanic warm waters, lying on the dark shingle,

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and the glowing big-eyed animals in life. *Pasta Okean,* a pink coagulated krill paste, is now in Russian marketplaces; the Norwegians feed frozen krill to livestock. The prospect of a truly giant fishery waits prudently—one hopes—on a better understanding of the life cycle of the multitudinous swarms, well caught only by the whales, now so few.

Since 1978 a new Convention on the Living Resources of the Southern Ocean has been under negotiation among the dozen nations that had earlier preserved the ice cap as an international laboratory, freely open to all countries that can afford research. Can they produce "a second miracle—a convention that will conserve krill," recognizing and being recognized by all the nations that might fish for the food of the blue whale? The blues have been worse than decimated; down to one where once swam 30, finally under full protection at least on paper, they may yet survive the shortsightedness of us hunters. During the southern summer of 1978–79 only three factory ships, Russian and Japanese, pursued whales there; "they had to work hard for every whale they caught." With helicopter and sonar they searched out mainly the minke whale, "once considered too small to hunt." There is still hope; perhaps the air view here of two blue whales, so freed of scale that they might be trout curving in some mountain stream, is a good omen at last.

ELECTRONIC INVENTIONS AND DISCOVERIES, by G. W. A. Dummer. Pergamon Press ($39). A genuine prophet, this British author gave his Washington audience in 1952 a "peep into the future." Said he: "With the advent of the transistor, it seems now possible to envisage electronic equipment in a solid block with no connecting wires. The block may consist of layers of insulating, conducting, rectifying and amplifying materials." That future has arrived, more or less as he saw it. Dummer, himself an innovator of no small importance (he was in 1940 co-inventor of the all but universal radar display that shows direction and range directly in polar plot on its screen), has turned to history. In this revised second edition he offers us a chronology of 450 inventions in electronics, giving to each a paragraph or two, with sources.

The entries span the years from Pascal's mechanical computer of 1642 to the two-inch-screen portable television set of 1977. Only Western Europe and the U.S. are covered in any systematic way; indeed, there can hardly be any well-defined criterion for inclusion on the list. We depend on the judgment of this acute observer. He starts slowly, with the Leyden jar and the Wheatstone bridge nearly a century apart. The oldtimers give way to W. K. Röntgen and Ernest Rutherford, J. J. Thomson and Ferdinand Braun. (Braun built his first cathode-ray oscilloscope at the University of Strasbourg in 1897; how he would be impressed by the multiplication of Braun tubes, now a population of nearly half a billion worldwide!)

Thermal noise, spinning-disk television and the first commercial shortwave station (Hilversum "on 26 meters . . . loud and clear") mark 1925. Vacuum begins to leak away as computers rise and solidify in the postwar world. It has been 20 years since the integrated-circuit patent; the art explodes into the giant industry of today and tomorrow. There is a twinge of nostalgia in learning that the familiar multipin dual-in-line integrated-circuit package was first put out by Bryant Rogers at Fairchild in 1964; it looked just as it does today, like a bug with 16 stiff legs. The microcomputer was introduced by Intel in 1972, the same year as the first video game, Magnavox' silent Odyssey, the CAT scanner from E.M.I. and the first substantial semiconductor memory.

A few old inventions are genuinely surprising. An English inventor, Dancer (no first name is given us), produced in 1839 tiny daguerreotypes of documents, images only an eighth of an inch on a side. The concept of the microfilm library was already several years old. The first relays, used of course in telegraphy, date from about the same year. The patent was taken out first by Edward Davy in 1838 and then by Samuel F. B. Morse in 1840; Davy had contested a patent granted Cooke and Wheatstone in 1837. Valdemar Poulsen of Denmark invented magnetic recording in 1898; he used steel wire and tape as the recording mediums. The first printed-circuit patent was issued to P. Eisler in the United Kingdom in 1943; there were precedents around the wartime proximity-fuze development both in the U.K. and in the U.S. The bold proposal to put a radar system into each antiaircraft shell was that of an Englishman, W. S. Butement. ("The Americans performed the prodigy of making 150,000,000 of the special valves for these fuzes.")

Dummer offers a variety of aids to the use of his long chronology: lists by category, by inventor and so on. There are interesting graphs, maps, occasional period diagrams and photographs. One might complain a little about a padding of the list with more than 60 satellites after 1957; Arthur C. Clarke's concept, *Sputnik 1* and *Sputnik 2,* and maybe *Echo 1* and the Intelsats, but *Tacsat 1* and *AZUR?* A more serious complaint can be lodged about references; most of the sources given are secondary review articles and the like, so that a curious reader will have a tedious path to follow to any beginning. The work is nonetheless a pleasure for the browser and is bound to become a mainstay in the trade.

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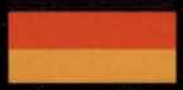

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26 EPA EST. MPG **38** HWY EST. MPG

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— *Criterium*

Great Britain 1978
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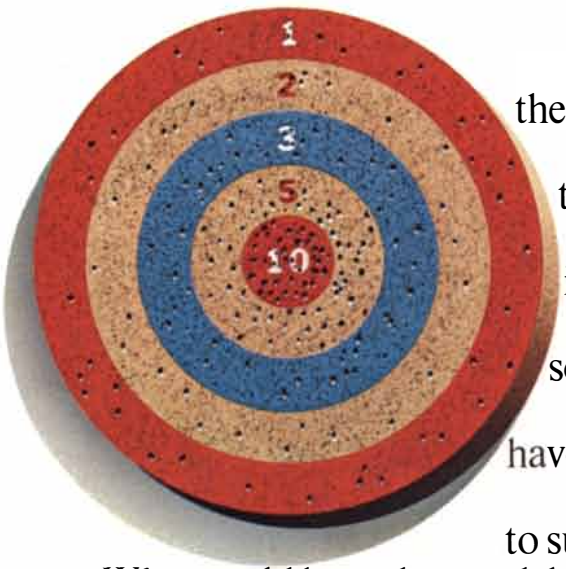

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Established 1845 SCIENTIFIC AMERICAN May 1980 Volume 242 Number 5

Youth Unemployment

Getting work has been increasingly difficult for young Americans ever since the 1950's. Among nonwhites more than a third of the teenagers and a fifth of the young adults are currently unemployed

by Eli Ginzberg

Ten years ago I served on a task force studying the problem of unemployment among young black Americans. We came to the conclusion that the dimensions and effects of black youth unemployment constituted not merely a serious problem but a real crisis. A decade later the crisis persists. A social and economic crisis of 10 years' duration must surely be considered a catastrophe.

It will come as no surprise that unemployment weighs most heavily on blacks. For young white people the statistics are less alarming: the unemployment rates are lower. Even for young whites, however, the rates are substantially higher than they are for adults. To want work and be unable to find it is painful at any age, but youth unemployment has particular effects, both on the individual and on society. A lengthy period of frustration and enforced idleness when a person first enters the labor force can disable him or her, psychologically and in terms of experience, for later employment, with the result that large numbers of Americans fail to function effectively in the economy.

Youth unemployment is nonetheless one of those many national problems with respect to which presumably well-qualified experts disagree, both about what the facts and figures mean and about the solution. Pessimists point out that unemployment among teenagers

UNEMPLOYMENT INSURANCE is just one of the high costs of youth unemployment. The scene is a typical unemployment-insurance line, this one in New York. Other social costs of youth unemployment are alienation, violent crime and long-term job disability.

(from 16 through 19 years old) rose from 11 percent in 1955 to more than 16 percent in 1978, or from three times the rate for adults (25 years old and over) to more than four times that rate. Alarmists emphasize the skyrocketing unemployment rate among nonwhite teenagers, which is now more than 40 percent for 16- and 17-year-olds. Yet there are optimists who refuse to be disturbed by the statistics. Some experts who acknowledge that youth unemployment is high and has risen sharply nonetheless think there is no need to be alarmed since so much of the reported unemployment is "voluntary," by which they mean that many young workers are quick to quit their jobs simply because they do not like the work or the boss or expect to find something better. Many experts believe youth unemployment is cured in time as teenagers become adults. The pessimists retaliate by pointing out that the official unemployment figures are surely understated: they do not include the many youngsters who are not actively looking for a job, in many cases simply because they are convinced they could not find one.

How is one to decide which group is right? At the human level, at least, it seems to me the answer is clear. When a few years ago a distinguished economist emphasized the curative qualities of time, I pointed out that for some young people his cure would not work: they would be dead as the result of homicide on the streets or would have been imprisoned and thereby scarred for life. To evaluate the problem more coolly, as a broad social and economic issue, it is necessary to look closely at what has happened in the past 25 years to unemployment rates for teenagers and young adults (from 20 through 24 years old).

The most important findings to be extracted from the statistics for selected nonrecession years point to an absolute and relative increase in all teenagers' unemployment and to modest increases among young adults. As far as young white men are concerned, once one disregards the 16- and 17-year-olds (the overwhelming proportion of whom are still in school) one cannot find any significant increases, although the unemployment rate is much worse than the rate for men 25 years old and over. Young white women between the ages of 18 and 24, on the other hand, did experience a significant rise in their unemployment rate. And among young blacks, both men and women, the unemployment rate almost doubled and in some cases almost tripled.

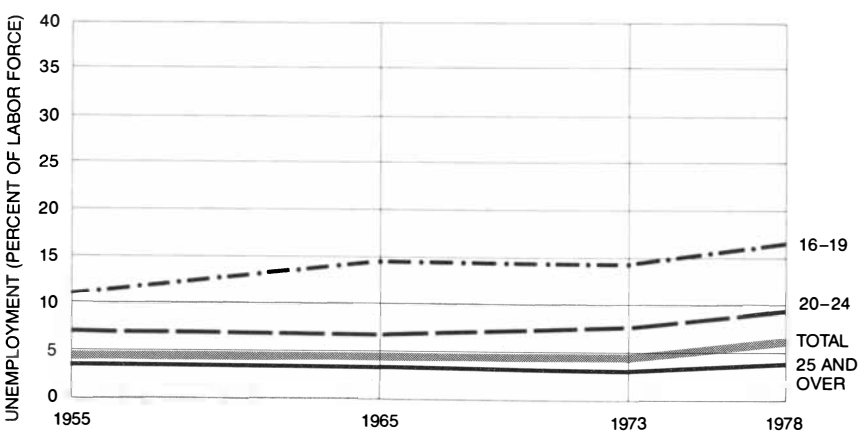
It is important to bear in mind that between the mid-1950's and the early 1970's the number of young people reaching working age each year approximately doubled, from about two million to about four million. The coming of age of the baby-boom generation coincided in part with another trend: the entry into the labor force of millions of women who had not sought work outside the home before. The conjunction of the two trends confronted the economy with a major challenge. The number of jobs did increase markedly with respect to earlier decades, but the labor force—the part of the population working or actively seeking work—increased even more. Whereas the unemployment rate reflects the failure of the labor market to provide jobs for those who want to work, another measure, the ratio of total employment to the population aged 16 and over (the *E/P* ratio), reflects the success of the labor market in providing jobs.

In spite of the big influx of young people into the labor market, reflecting the demographic bulge, the American economy was able in the case of white teenagers to create enough new jobs to enable the *E/P* ratio for that group to rise to an all-time high. White teenage females showed a one-third increase in their *E/P* ratio, reaching a level not much below that of teenage men. Young-adult white women from 20 through 24 showed an even more pronounced gain in their *E/P* ratio. Young-adult white males lost a few percentage points for reasons not immediately apparent; considering that their unemployment rate increased hardly at all, a reasonable guess is that the lower *E/P* ratio reflects a changing style of life, with a growing proportion of this group wanting to "knock around" before "settling down." Once again one must note that the experience of young blacks of both sexes was adverse. The *E/P* ratio for black teenagers declined and the trend for young adults was not favorable.

To probe below the surface of the labor-force participation of young people it is necessary to look at what proportion of them are enrolled in school. The unemployment of a 16-year-old high school junior may reflect no more than that he has lost the job he held as a delivery boy and has not yet found another. On the other hand, a 19-year-old high school dropout or graduate who is not currently enrolled in any educational or training program is likely to want (and need) a full-time job. The statistics on school enrollment warrant close scrutiny. In the first place they reveal a decline in the proportion of white men, both teenagers and young adults, who attended school in 1977 compared with the mid- or late 1960's. (The figures confirm my impression as a member of a university faculty that in the 1960's many young men stayed in school in order to avoid military service during the Vietnam war.) The experience of white women has been quite different. In every age category an increasing proportion of them enrolled in school.

The most striking gains are found, however, among black men and women. Contrary to a widespread impression, over the three decades there was a doubling or more in the proportion of older black teenagers enrolled in school. There were also gains of from three to seven times among young adults of college age. Without getting sidetracked from the main concern, it should be emphasized that in 1977 a larger proportion of blacks than of whites aged 18 through 24 were enrolled in school. No other social indicator linked to family income demonstrates a more favorable condition for blacks than for whites. The following figures shed some light on this anomaly.

In 1977 of the 30.5 million whites between the ages of 16 and 24, 18.6 million were employed, for an *E/P* ratio of 61 percent; the unemployment rate among this white group was 11.3 percent. The figures for blacks were quite different. Their *E/P* ratio was only 37 percent and their unemployment rate was 33 percent. There is some support in these data for the view that, confronted with poor



YOUTH UNEMPLOYMENT RATES are compared with the total U.S. rate (for the entire labor force 16 years old and over) and the rate for adults (25 years old and over). The data are for four nonrecession years. The rate is higher for both teenagers (16 through 19) and young adults (20 through 24) than for adults, and the rate for teenagers has risen particularly sharply.

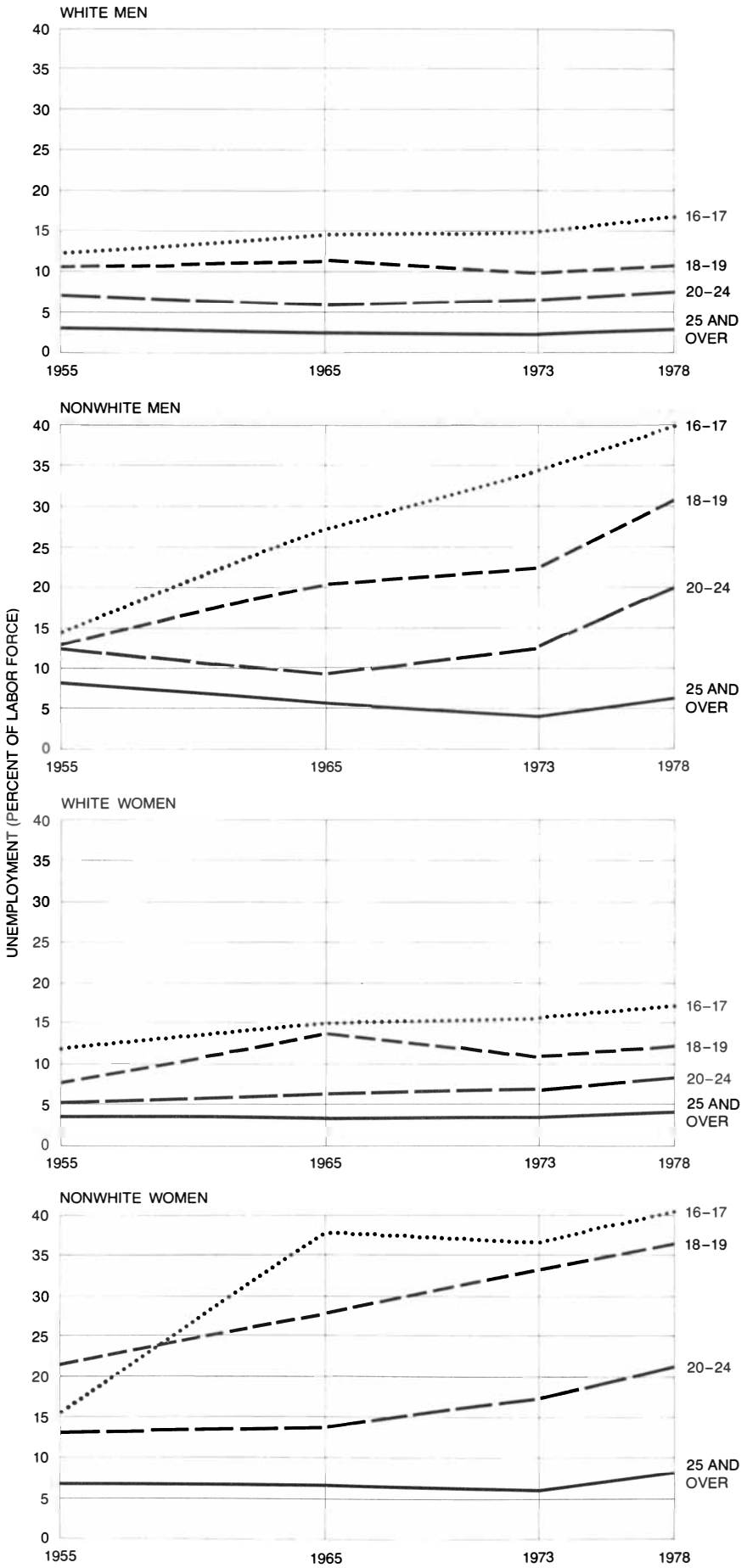
job prospects, more blacks prolong their education, but the fact is that school enrollment has never been determined primarily by employment opportunities.

Young people enrolled in school who are also in the labor force are overwhelmingly interested in getting part-time or part-year employment. Their major commitment is to school. Hence what the differentially lower *E/P* ratios and higher unemployment rates for blacks compared with whites reflect is a shortfall in the ability of blacks to find part-time work. The situation is different in the case of those who are no longer in school because they dropped out or were graduated and who are not pursuing any formal education or training program. The reasonable assumption is that most people in this group (although not all) are interested in finding a regular job. If one looks at the employment status of the nonenrolled group between the ages of 16 and 24, several points become clear: the strikingly lower *E/P* ratio among dropouts than among graduates, with only two in five of the black dropouts holding a job; the relatively low unemployment rate for white graduates, and the high rate (three times higher) for black graduates.

A review of the trend data and of additional information reflecting conditions in the labor market at the end of the 1970's reveals support for both the pessimists who warn about the deteriorating position of young people in search of work and the optimists who minimize the issue. As far as the teenage population is concerned the unemployment rates have worsened, but the *E/P* rates are at an all-time high. For young white adults the data show little deterioration; for young white women the *E/P* ratio rose by about a third in the past two decades. On almost every score, however, the situation of young blacks (teenagers and young adults, men and women) is worse in terms of the *E/P* ratio, the unemployment rate or both.

Many different (and often contradictory) explanations are offered to account for the trends reviewed above. One with the widest currency holds that a rise in the unemployment rate reflects a loss in the "work ethic." Young people are said to be less willing than their fathers and grandfathers were to take a job—any job—that is available. Clearly, however, this theory cannot be squared with the rise in the *E/P* level.

Critics of the performance of the



BREAKDOWN OF RATES by race, sex and age shows which groups have been hit hardest. Unemployment is somewhat worse for women than for men, has risen most sharply for youngsters 16 and 17 years old and is much higher for blacks and other nonwhites than it is for whites. Data are for the same nonrecession years as in the preceding illustration.

American economy emphasize that it has been running slack for many years, with an unemployment level far above the 3 or 4 percent said to define "full employment." In their view this slackness means there cannot be enough jobs to go around and young people with the least training and experience are likely to be left at the hiring gate. There is something to this view, but not a great deal: in the four years from early 1975 to 1979 the economy created 12 million new jobs, and still youth unemployment was high and black youth unemployment was very high.

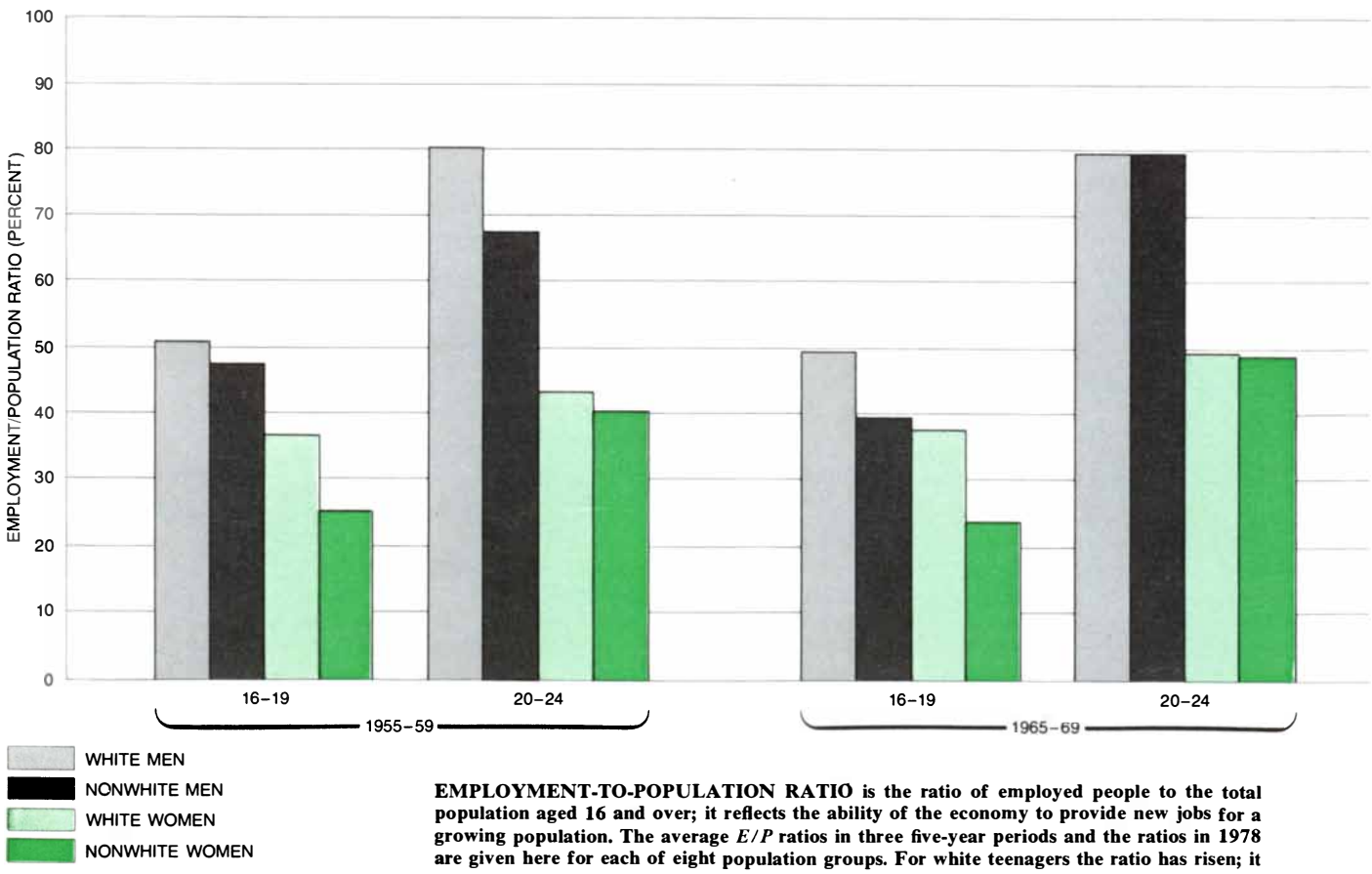
There are those who believe the youth unemployment problem is largely a self-inflicted wound reflecting a serious error in public policy: the raising of the minumum wage to a level where employers no longer find it profitable to hire young people. This hypothesis explains too much. With the *E/P* ratio at an all-time high employers are clearly hiring large numbers of youths. Moreover, the relation between what employers must pay a young person and what they must pay an adult has not changed in favor of the young over the past several decades, and it is the relative wage that determines employers' preferences. The only thing one can say for the minimum wage in this context is that it has not been helpful to some small number of young job seekers.

Two more proposed explanations should be noted briefly. The first stresses the lack of orientation to work and the limited competence that characterize many young people, particularly among minority populations in the inner city. Although some youngsters are indeed poorly prepared for work, the striking gains in the enrollment of blacks in school must be considered before placing too much weight on this explanation. Another hypothesis with wide currency is that many inner-city youngsters prefer to work at a somewhat questionable occupation rather than at a dirty, low-paying job; they can earn more in less time and do not have to submit to the discipline of the work place. This hypothesis cannot be squared with the minimum-wage explanation. If young people prefer to work at a questionable occupation rather than accepting a job at the present minimum wage, surely they would be even more likely to do so if the available jobs paid less.

Clearly there are more hypotheses than there are phenomena to be explained. Considering the large inflow—the doubling in the number of young people reaching working age—the rise in the *E/P* ratio for all teenagers in the past 25 years must be put alongside the rise in the unemployment rate. And the very small increase in the unemployment rate for young white adults (20–24) suggests that for most whites time does take care of most of the problems stemming from inability to find jobs as teenagers. This relatively optimistic interpretation surely does not hold for blacks, however. A great many young black men and women are having serious difficulties in the labor market. This is the phenomenon that requires close attention.

Let us look more closely at what the statistics indicate about the employment problems of young blacks. Teenage black males have unemployment rates of from 30 to 40 percent, more than double the rates for whites. Young black men and women (20–24) have unemployment rates of about 20 percent, from two and a half to three times the rates for their white counterparts. The *E/P* ratio for teenage black males dropped from 48 to 30 percent between the late 1950's and the late 1970's; meanwhile the rate for whites increased from 51 to 56 percent. The *E/P* ratio for teenage black females slipped from 25.2 to 23.5 percent over the past 25 years as the rate for whites advanced from 36.9 to 48.7 percent. Among young adults the *E/P* ratios for whites average about 15 percentage points higher than those of their black counterparts.

There is only one way to read statistics such as these. A disproportionately large number of young blacks are having serious and prolonged difficulties gaining a foothold in the world of work. What is worse is that many of those who encounter serious difficulties in their formative years (from 16 through 24) fail to acquire the experience, training,



EMPLOYMENT-TO-POPULATION RATIO is the ratio of employed people to the total population aged 16 and over; it reflects the ability of the economy to provide new jobs for a growing population. The average *E/P* ratios in three five-year periods and the ratios in 1978 are given here for each of eight population groups. For white teenagers the ratio has risen; it

competences and credentials that would earn them a regular job yielding a reasonable income in their adult years.

The long-term consequences of the widespread difficulties encountered by black teenagers and young adults in the labor market are reflected in the job experience of the age cohorts 25 through 29 and 25 through 34. In 1978 nine white veterans in 10 between the ages of 25 and 29 were employed but only eight in 10 black veterans. Of the nonveteran population 92.5 percent of the white men and only 80.4 percent of the black men were employed. If one looks at the work experience and earnings of 25- and 26-year-old noncollege men, one finds that in the course of the year whites worked 47 weeks and blacks worked 43; the hourly pay of whites was almost half again as much as it was for blacks ($6.98 v. $4.79), and the estimated annual earnings of white males of $13,100 were about 60 percent higher than the $8,200 earned by black males.

If one broadens the perspective to look at the income differentials for the entire cohort aged 25 through 34, one finds that the mean earnings of white men were only $12,400 compared with $10,200 for blacks, a spread of 18 percent. The comparable data for those who worked full time for the full year show earnings of $14,900 for white men compared with $12,400 for black men, a spread of 16 percent.

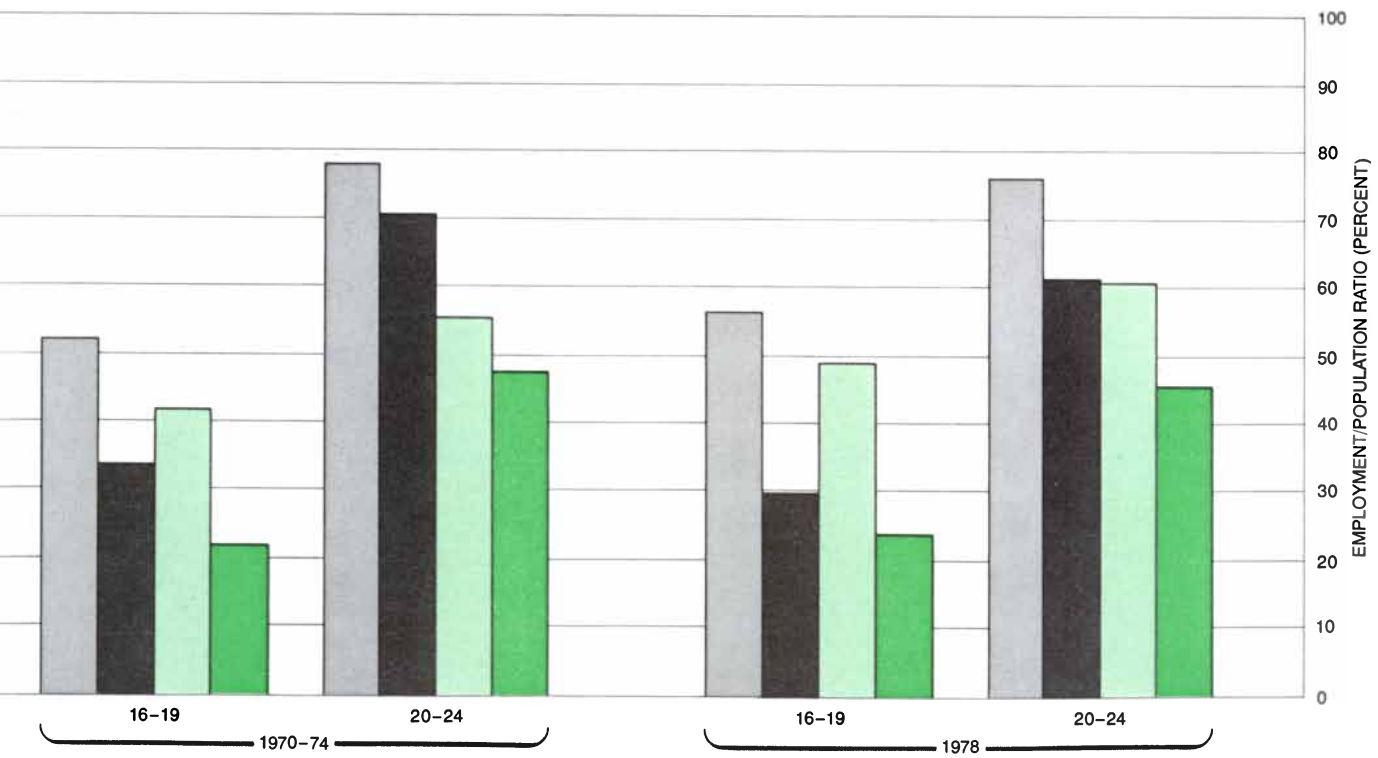
Although many blacks have succeeded in the past two decades in moving out of the less desirable occupations (those with the lowest pay, the highest unemployment rates, the least security and the fewest career opportunities), blacks are still heavily overrepresented at the lower end of the total distribution: one in three is employed as a service worker or laborer, and only one in six whites.

All these findings (and they could be added to) point to one simple conclusion: the poor experience of blacks in the labor market during their late adolescence and young adulthood leaves them permanently disadvantaged.

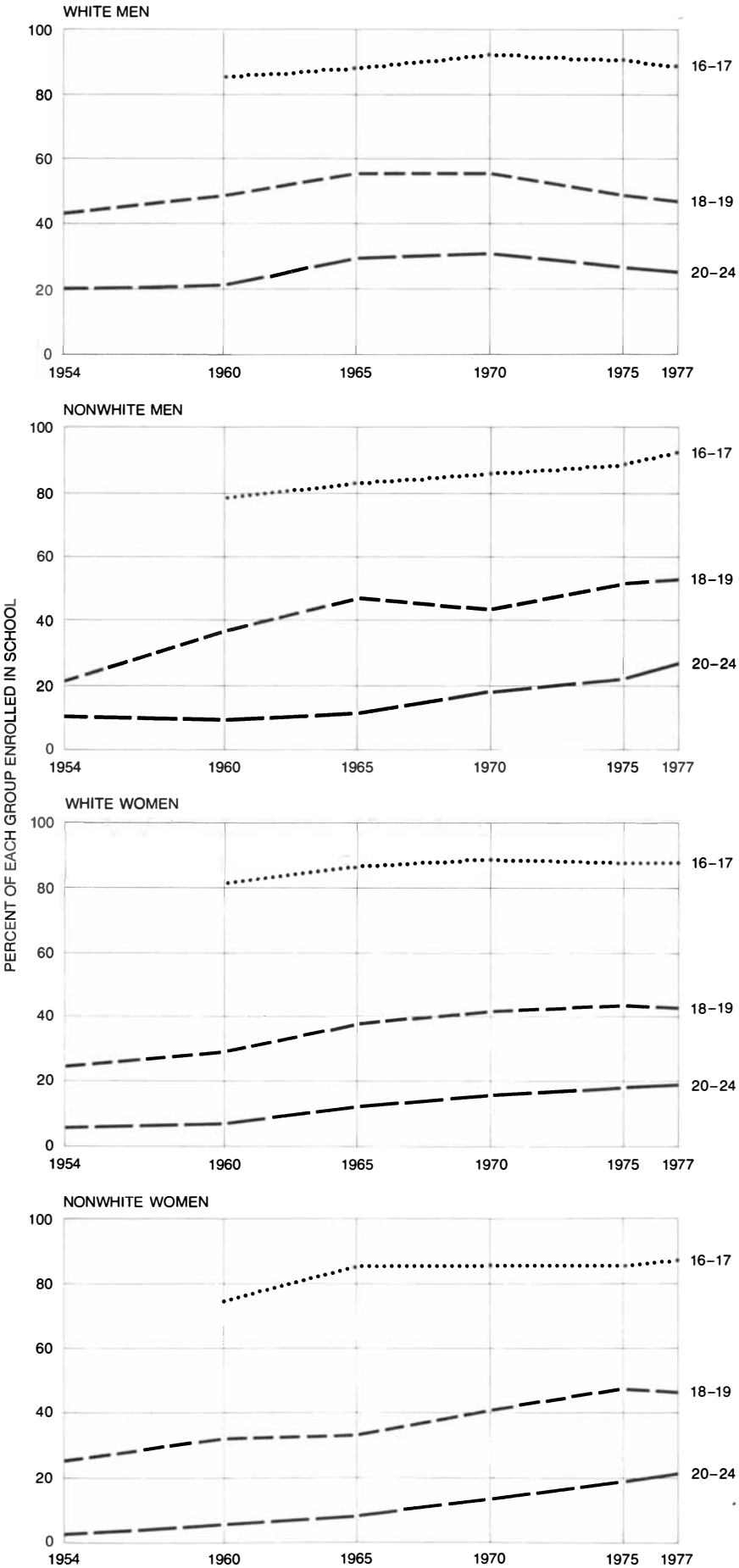
Although this emphasis on black youths is justified by the appalling facts about their high unemployment rates and their low labor-force participation, they are not the only vulnerable group. Young whites outnumber black and other minority young people by about nine to one, which means that most of the young people who are in trouble are white. Moreover, young Hispanics also have particular disabilities in the labor market. Their experience, in terms of unemployment and labor-force participation, falls about midway between that of whites and blacks, but the lack of long-term data specifically for Hispanics makes it impossible to analyze their situation in more detail.

The American economy is increasingly a service economy. Only about one job in three is in the production of goods, that is, in agriculture, manufacturing, mining or construction. Many, if not most, jobs in the service sector require some literacy, facility with numbers and communications skills: competences most young people acquire in school. Approximately one black youngster in four currently fails to graduate from high school. For many of them effective schooling really stops long before they leave or are pushed out, since a significant proportion become truants by the time they are 12 or 13 and many who remain in school pay little or no attention to their studies. To make things worse, many harassed teachers make no serious effort to teach.

Many minority children, brought up in homes without a father, often by a mother who cannot or for other reasons does not work, and living in neighborhoods where few people who do go to work regularly have much to show for it, see little point in taking school seriously or believing it can help them to get a job that will lead anywhere. If their early job history and work experience confirm their pessimistic expectations, many give up. Many white youngsters are introduced by a parent, a relative or a friend to an employer who is looking for workers. The path is smoothed for them; at least they will be interviewed. This is not the case for those black youngsters whose deviant dress, appearance and speech are likely to prevent their receiving an application form even



has risen sharply for white young-adult women and has declined a little for white young-adult men. Among nonwhites the ratio for male teenagers has declined sharply, as has the ratio for young-adult men in recent years; for women the trend is less pronounced. Data were developed by Robert L. Lerman of U.S. Department of Labor. Even when *E/P* ratio is favorable because proportion of the population 16 and over who have jobs is growing, unemployment will rise if labor force (those actively seeking work) grows faster than that population.



if they can get to an office where employers are interviewing.

Although many large employers have sought in recent years to increase the proportion of minority people on their payroll, that effort has surely not been made by many smaller employers. Discrimination in the job market, although it is less blatant, is still strong, and it adds markedly to the troubles young blacks face, particularly if they have inferior preparation for employment. And the steady out-migration of manufacturing jobs from the inner cities, where large minority populations are concentrated, to the suburbs and beyond has surely compounded the difficulties many young blacks (particularly men) face in getting a job they could do and that pays reasonably well.

The shift to services, poor preparation for work, lack of family support, employer discrimination and the relocation of manufacturing jobs all add up to suggest to black teenagers a self-fulfilling prophecy: Why bother? Society has no place for us.

What has the country tried to do to help these disadvantaged minority youngsters get a better start in life? Beginning in 1964 Congress has provided a sizable sum of money each summer (now in the $1-billion annual range) to provide work experience for disadvantaged young people of high school age. The youngsters are assigned eight-week jobs for which they are paid the minimum wage. Some of them learn something, many learn little. Some learn the wrong thing: that they can be paid without doing any productive work. Congress has looked on the Summer Youth Employment Program primarily as a way to "keep the cities cool."

Also started in 1964 was a small, expensive program (originally about $10,000 per person per year): the Job Corps. It is intended for the most disadvantaged youths, some tens of thousands of whom are offered an opportunity every year to enter a residential center where they receive remedial education, work orientation, skill instruction and help in pursuing further training or finding a job. In the case of those who are mature enough to complete most or all of the program, various evaluations suggest that the Job Corps is a worthwhile experience for both the individual and the nation. The Job Corps has been spared the distortion that afflicts most manpower programs as a result of the bargaining process that goes on in Congress: the tendency to "entitle"

SCHOOL-ENROLLMENT TRENDS have effects on youth unemployment. The percent of each age group that is enrolled in school has risen most sharply for nonwhites, perhaps in part because of difficulties in finding work.

so many potential recipients that the Federal funds come to be spread very thin, with the result that shallow services are provided for most enrollees.

The enactment in 1973 of the Comprehensive Employment Training Act (CETA) resulted in the consolidation of many Federally funded training and employment programs, including those intended for young people, usually under the authority of a state or local government acting as a "prime sponsor." The prime sponsors appear to have improved considerably the job experience offered by the Summer Youth Employment Program last year. Clearly, however, this is a limited program that can at best provide temporary jobs for a small proportion of the young people who need them.

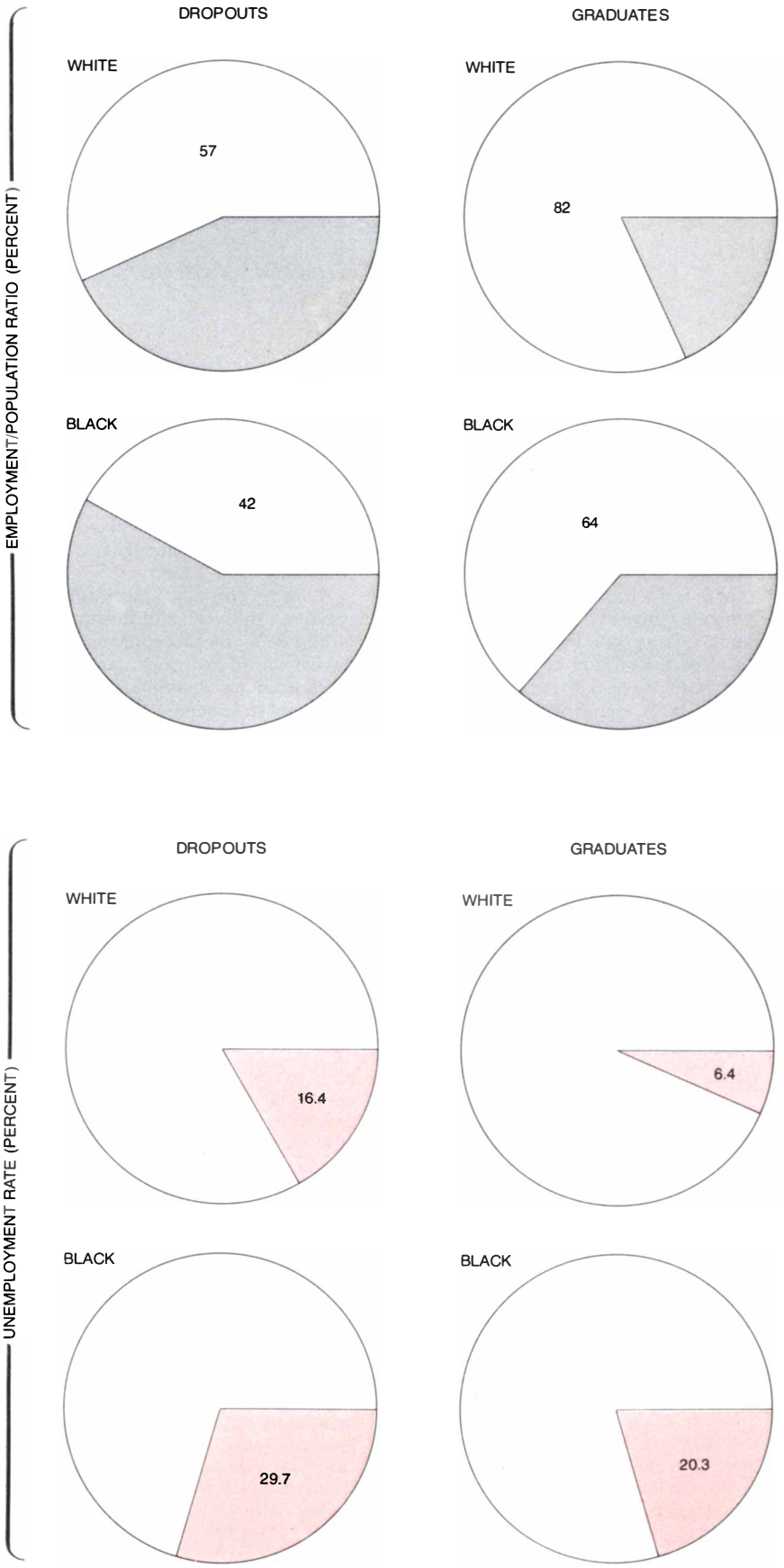
What more can be done? Last December, after a year and a half of study, the National Commission for Employment Policy made modest suggestions to the President and Congress:

1. A substantial number of young people, particularly those who come from minority-group families with low income and who have failed to acquire a high school diploma, face serious difficulties in making the transition from school to work. Unless their educational deficits can be reduced and eliminated, preferably while they are still in school, many will not be able to find and hold a regular job.

2. Only intensive programs, such as the Job Corps, that provide a broad range of services, including educational remediation, skill training and placement assistance, can be expected to reverse the cumulative disadvantages young people who are out of school and without the prospect of a job have faced since birth.

3. The Equal Employment Opportunity Commission should direct the attention of employers who want to expand their proportion of minority and female employees to the continuing supply of young people who complete remedial education and skill training. The Federal Government should explore the potentialities of including in its grant-in-aid programs and contracts an employment requirement that would involve a commitment on the part of recipients to hire a percentage of job-ready disadvantaged young people.

There is no one way, and surely no easy way, to bring minority youth unemployment down to an acceptable level, which is to say close to the level for whites. If the American people do not want to continue to pay the current high cost of such unemployment in terms of alienation, violence against people, theft of property, arson and suicide, and still higher costs to come, they surely have no option but to focus on its remediation until it is no longer a national scandal.



EMPLOYMENT STATUS in 1978 of whites and nonwhites aged 16 through 24 is given here for school dropouts and for high school graduates. The *E/P* ratio is lower and the unemployment rate higher for dropouts than for graduates. Among blacks only about two dropouts in five have a job; unemployment rate for graduates is three times worse than it is among whites.

The Superconducting Computer

A new microelectronic technology would replace transistors with superconducting switches. Computers made with them might carry out a billion elementary operations per second

by Juri Matisoo

The next milestone in the development of the high-speed digital computer is a cycle time of one nanosecond, or one billionth of a second. The cycle time is the interval between "ticks" of the computer's master clock; most high-performance computers today have cycle times of between 30 and 50 nanoseconds. How will a one-nanosecond computer be made? One obvious imperative is that the basic circuit elements of the computer, which can be likened to switches, be capable of changing their state in less than a nanosecond. What is equally important, signals will have to be communicated from one circuit element to another in much less than the cycle time. The latter requirement imposes the more fundamental limit on computational speed, and it carries with it a surprising implication: any ultrafast computer must be very small. An electrical signal can travel only about 15 centimeters in a nanosecond, and so no signal path can be much longer than that. It follows that the entire computer, comprising perhaps a few million circuit elements, will have to fit in a box no more than a few inches on a side. Attaining such high speed and high density may require an altogether new electronic technology.

There have been just two main computer technologies, the first one based on vacuum tubes and the second on transistors and other semiconductor devices. The introduction of the transistor brought significantly greater speed, in part because the transistor is an inherently faster switch than the vacuum tube but also because transistors can be packed closer together. At the present limit of semiconductor technology one computer of unusual design, the Cray-1, has reduced the maximum signal path to a few meters and has thereby achieved a cycle time of some 12 nanoseconds. Gaining an additional factor of 10 or more, however, may require heroic efforts. The problem is not simply one of making the circuits small enough to fit in the allotted volume; it is that high-speed semiconductor circuits give off a great deal of heat, amounting to several kilowatts in a large computer. If the millions of high-speed transistors that make up such a machine were packed into a few cubic inches, the heat evolved could not be removed fast enough and the computer might well melt.

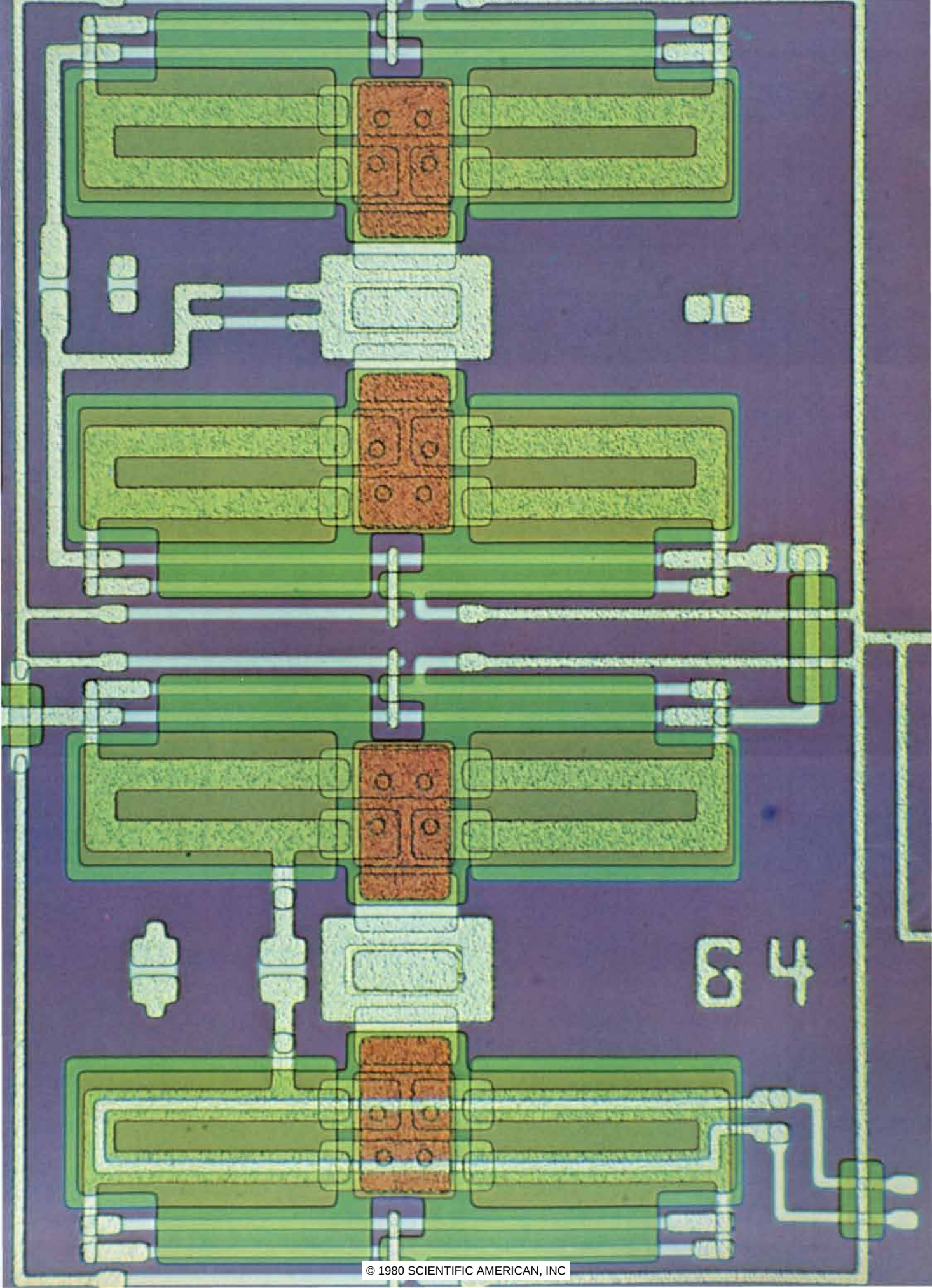
A new electronic technology that promises to overcome this impediment is based on the Josephson junction, a device whose operation depends on two extraordinary phenomena of quantum mechanics: superconductivity and the "tunneling" of electrons across an insulating barrier. Like the vacuum tube and the transistor, the Josephson junction can act as a switch, steering a signal into one circuit or another. Indeed, the Josephson junction is the fastest switch known, being capable of changing state in as little as six picoseconds, or six trillionths of a second. That is less than 1 percent of the contemplated one-nanosecond cycle time, and it is at least 10 times faster than an equivalent high-speed semiconductor device. Josephson-junction circuits can also store information, so that they could be adopted for both of the main functional units of a computer: the processor and the memory. What is most important, because the Josephson junction is a superconducting device its power consumption is exceedingly small, a matter of microwatts. A few million Josephson-junction circuits would therefore dissipate only a few watts. They could be packed together as tightly as the methods of fabrication would allow. Another consequence of employing a superconducting device is that the junctions must be cooled to within a few degrees of absolute zero; a Josephson-junction computer could operate only when it was immersed in a bath of liquid helium.

In the past few years all the basic circuit elements required for a Josephson-junction computer have been developed. They include both the logic devices needed to process information and the memory cells needed to store it. A computer based on these prototype components would not quite attain a one-nanosecond speed, but the exploitation of the technology has hardly begun. The first computer to be made would fill a cube two inches on a side and would have a cycle time of about two nanoseconds. In what follows I shall describe what such a computer would be like and how it would be made. First, however, it is necessary to discuss the two physical phenomena on which the technology is based: superconductivity and electron tunneling.

A superconductor is not merely a metal with zero resistance to the flow of an electric current. Such a metal can be imagined: as it was cooled its resistance would decline smoothly, without discontinuities, and the resistance would become zero only at a temperature of absolute zero. If a magnetic field was present when the last trace of resistance vanished, the field would be trapped in the metal.

The onset of superconductivity is quite different. As the material is cooled

SUPERCONDUCTING CIRCUITRY could serve as the basis of a digital computer that would operate some 50 times faster than most high-speed computers being made today. The basic circuit elements of the computer, a few of which are assembled here in an experimental array, are called Josephson-junction devices. A Josephson junction consists of two superconductors separated by a thin layer of insulator; here the junctions lie under the four small circles visible in each brown region. The junctions and the metallic loops that extend to each side of them make up Josephson interferometers, which function as extremely fast-acting switches. All the circuits needed to process and store binary information can be constructed of such devices. The circuit patterns were laid down by photolithography on the surface of a chip of silicon; the narrowest lines are about 2.5 micrometers wide. The colors result from the interference of light within the various layers of material. The chip was fabricated at the Thomas J. Watson Research Center of the International Business Machines Corporation. The photomicrograph was made by Fritz Goro with Hans Luhn of IBM, using a Zeiss Axiomat microscope.

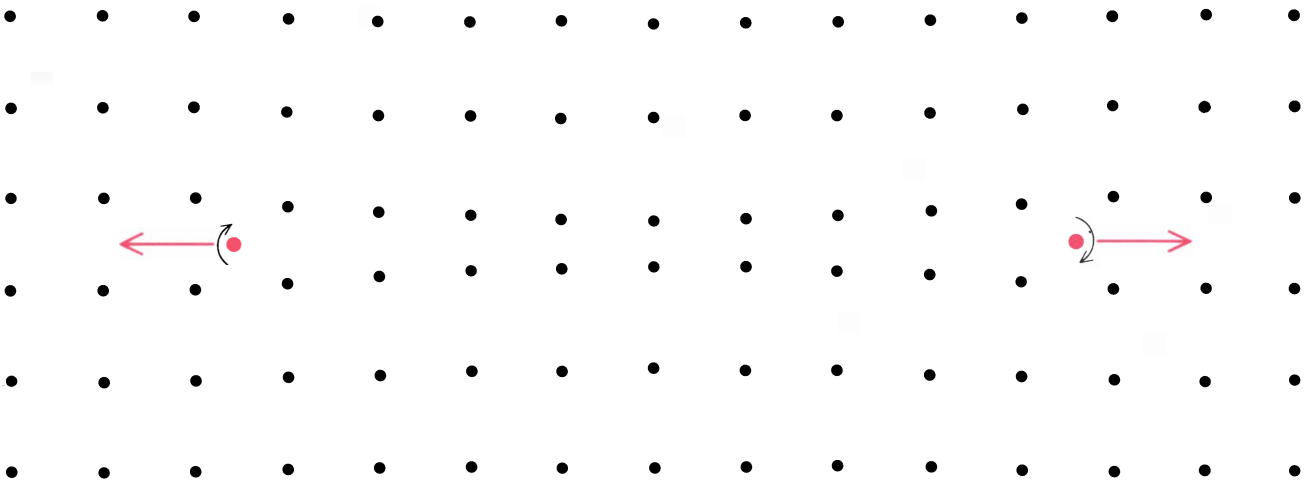


the resistance falls off gradually only until a threshold temperature is reached, which is typically several degrees Kelvin above absolute zero; then all remaining resistance disappears abruptly. Moreover, any magnetic field is expelled from the superconductor.

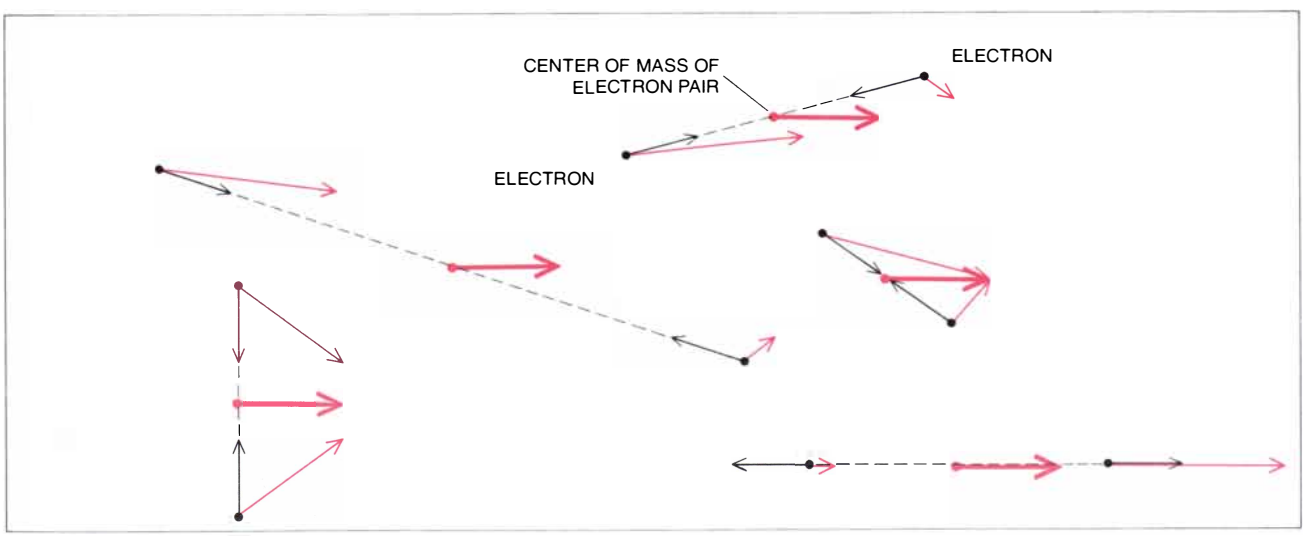
Superconductivity was first observed in 1911 (by Heike Kamerlingh Onnes), but a satisfactory explanation of it was not provided until 1957 (by John Bardeen, Leon N. Cooper and J. Robert Schrieffer of the University of Illinois). It is now understood that a superconductor differs from an ordinary metal—even an ordinary metal with zero resistance—in the very mechanism of electrical conduction. In the normal metal the current is made up of single electrons, and resistance arises from collisions of the electrons with metal atoms. In the superconductor current is carried by pairs of electrons, the electrons in a pair being bound together by a weak interaction with the surrounding metal lattice. Each pair consists of two electrons with opposite momentum, that is, of two electrons moving with equal speed in opposite directions.

In the Bardeen-Cooper-Schrieffer theory each electron pair can be dealt with as if it were a single particle situated at the center of mass of the two electrons. Although the individual electrons have considerable freedom of movement, it turns out that the motions of the centers of mass of the electron pairs are highly coherent. In fact, all the centers of mass have the same momentum. If there is no current flowing, and hence no net movement of charge, all the pairs have zero total momentum. If a current is flowing, all the pairs have the same net momentum directed parallel to the current. Because the pairs move in lockstep they do not collide with the atoms of the lattice, and the conductivity is infinite.

The force that binds together two electrons to form a pair is an indirect one. The negative electric charge of each electron attracts the positive charges of the surrounding metal ions and thereby slightly distorts the lattice, creating a region of enhanced positive charge; it is this charge that attracts the other electron. The binding force is extremely feeble, and so the pairs are easily dissociat-



MECHANISM OF CONDUCTION in a superconductor is different from that in an ordinary metal, even a hypothetical metal with zero resistance to the flow of an electric current. In the superconductor current is carried not by single electrons but by pairs of them, bound together indirectly through an interaction with the surrounding lattice of metal ions. The negative charge of an electron slightly distorts the lattice, creating a region of enhanced positive charge that attracts the second electron. The electrons in a pair have opposite momenta.



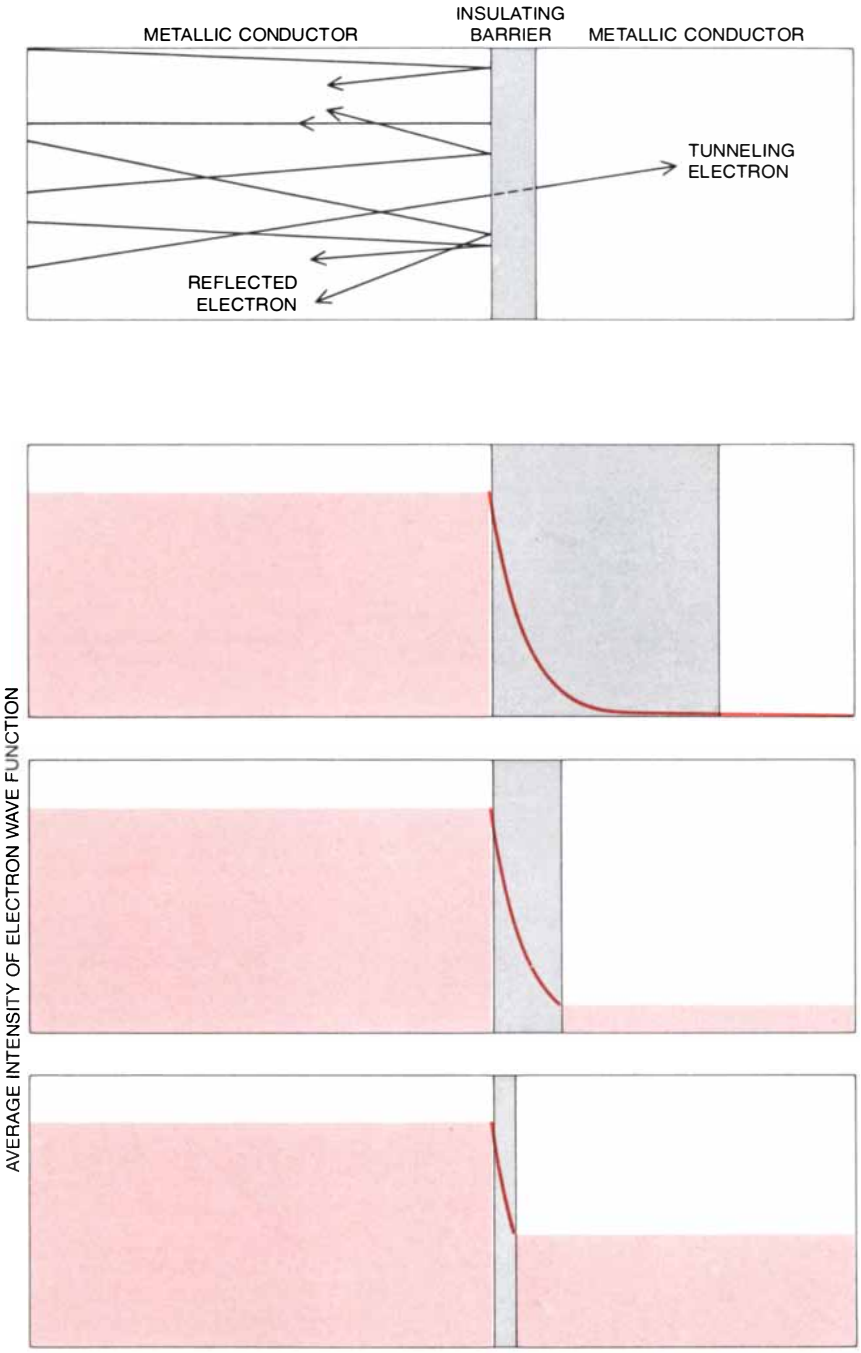
COHERENT MOTION of the electron pairs in a superconductor is responsible for the flow of a current without resistance. Each pair, when it is viewed in its own frame of reference (*gray dots and arrows*), consists of electrons moving in opposite directions. The total motion of the electrons, however (*light colored arrows*), is such that the centers of mass of all the pairs (*colored dots*) have the same momentum (*dark colored arrows*). Here the centers of mass are moving to the right, signifying that a current is flowing in that direction. All the pairs can have the same momentum only if none of the electrons is scattered by the lattice; such scattering is the source of resistance.

ed. The energy required to break up a pair is called the gap energy. It can readily be supplied by a thermal excitation of the electrons; that is why superconductivity is observed only at low temperature. It can also be supplied by a sufficiently strong magnetic field or electric current. As a result if a superconductor is exposed to too intense a magnetic field or is made to carry too large a current, superconductivity is extinguished and the material reverts to the metallic state, in which current is carried by single electrons.

In quantum mechanics an electron can be represented not only as a particle but also as a wave. In the same way each electron pair in a superconductor can be represented by a single wave. The correlation of the pair momenta implies that all the waves have the same velocity, the same wavelength and the same phase. In other words, at every instant and at every point throughout the volume of the superconductor all the electron-pair waves are at the same stage in their cycle. The wave representation of particle motion is essential to an understanding of the tunneling of electrons between normal metals and the tunneling of electrons or of electron pairs between superconductors, which is what takes place in a Josephson junction.

The process called tunneling is one that would have been considered impossible in the classical physics that preceded the development of quantum mechanics. Tunneling allows a moving electron or other particle to pass a barrier to its motion even when the particle has insufficient energy to surmount the barrier. The moving particle can be likened to a marble that rolls along a flat surface and then comes to a hill. According to classical physics, the marble will eventually appear on the other side of the hill only if it has enough kinetic energy to climb to the top. Quantum mechanics, on the other hand, predicts that there is some probability for the marble to appear on the other side of the hill even if the energy of the marble is too little to carry it to the top. The marble is said to have tunneled through the barrier represented by the hill (although of course no hole is left in the barrier). For macroscopic objects such as marbles and hills the probability of tunneling is nil, but for an electron confronted by a thin barrier the probability can be appreciable.

Tunneling is made less mysterious if the electron is thought of as a wave. The probability of finding the electron at any point in space is then given by the intensity of the wave at that point; the intensity in turn is simply the square of the amplitude of the wave. At a barrier the amplitude of the quantum-mechanical wave does not drop immediately to zero; instead it falls off smoothly, following an exponential curve, so that there is some small probability of finding the particle on the other side. How quickly the wave function declines depends on the height and the thickness of the barrier. It is notable that if either the height or the thickness were reduced to zero, quantum mechanics and classical mechanics would be in agreement: both would predict a probability of 1 for eventually finding the particle on either side of the (now missing) barrier, since the particle could move freely throughout the space available. As soon as the barrier acquires some nonzero thickness or height, however, classical mechanics requires that the probabilities change discontinuously, becoming 0 on one side of the barrier and 1 on the other side. Quantum mechanics provides for a smooth change in the probabilities. They reach 0 and 1, and again correspond to the classical prediction,



TUNNELING OF ELECTRONS can transport electric charge across an insulating barrier between two conductors. In classical physics all electrons would be reflected by such a barrier, but in quantum mechanics there is some probability that an electron will appear on the other side. The probability of finding an electron at any point is given by the intensity at that point of the wave associated with the electron. At the barrier the intensity of the wave does not fall immediately to zero (as it would in classical physics) but instead declines smoothly, following an exponential curve. A current of tunneling electrons can arise if the barrier is very thin.

only when the barrier becomes infinitely high or infinitely thick.

For an electron the equivalent of a hill is an insulating barrier separating two metallic conductors. Suppose a voltage is applied across such a junction. According to classical physics, the junction is an open circuit, and unless the voltage is high enough to cause arcing no current can flow. In quantum mechanics there is at least a small probability of an electron's crossing the barrier, the probability depending on the thickness of the insulating layer (among other things). For any appreciable current to flow the barrier must be very thin, typically less than 100 angstrom units. (One angstrom is equal to 10^{-8} centimeter.) The existence of such tunneling currents was first conclusively demonstrated in the early 1960's by Ivar Giaever of the General Electric Research Laboratories.

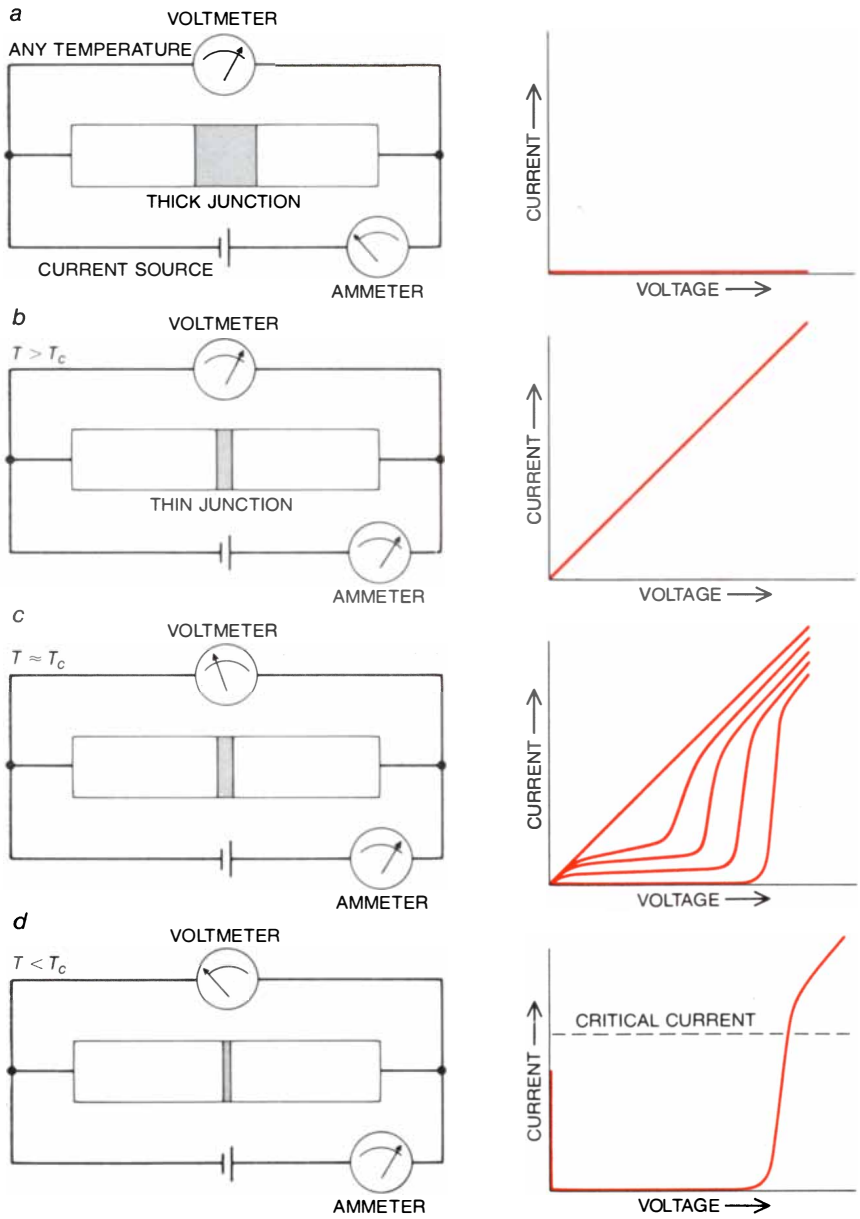
The tunneling currents described so far can be observed across an insulating barrier between conductors that are in the normal metallic state. In 1962 Brian D. Josephson, who was then a graduate student at the University of Cambridge, calculated the currents that could be expected to flow through a junction between two superconductors. He was led to predict several surprising phenomena, which are now called the Josephson effects.

Josephson found, as others had earlier, that a normal current of single electrons could cross the junction; such single electrons are present in the superconductor along with the bound pairs of electrons. In addition Josephson showed that the paired electrons could themselves cross the junction under some circumstances, forming a tunneling supercurrent. In other words, the barrier material, which would ordinarily be considered an insulator, could act as if it were not only a normal conductor but even a superconductor. A measurement across the junction would show not an open circuit but a completely short-circuited one, a circuit with zero resistance.

Josephson labeled such a junction a weak superconductor. It is weak because the interactions responsible for the formation of electron pairs extend across the junction only in attenuated form. As a result the maximum current the junction can support is much smaller than that of the bulk superconductor. In the same way the apparent superconductivity of the junction is also more easily extinguished by a magnetic field. Once the maximum current or magnetic field is exceeded the junction continues to conduct an ordinary tunneling current, but it no longer has zero resistance. Indeed, the resistance can be quite large.

The presence of either a magnetic field or an electric field in a junction between superconductors gives rise to still more bizarre effects. Josephson showed that a magnetic field causes a spatial variation in the current flowing through the junction. When the applied field is zero, the current density (the current per unit area) is uniform across the area of the junction. As the magnetic field increases, the current density takes on a sinusoidal variation in magnitude and direction. Thus the current can be flowing from left to right at one point in the junction while it is zero at another point and flowing from right to left at a third point. Because of this spatial variation the maximum net current that can be carried by the junction also depends sinusoidally on the strength of the magnetic field. The net current can have its greatest value when the field is zero. When the field reaches a value where there is one full cycle of the sinusoidal variation, equal currents flow to the right and to the left so that the net current is zero.

As the field increases further a net current is established once again, al-

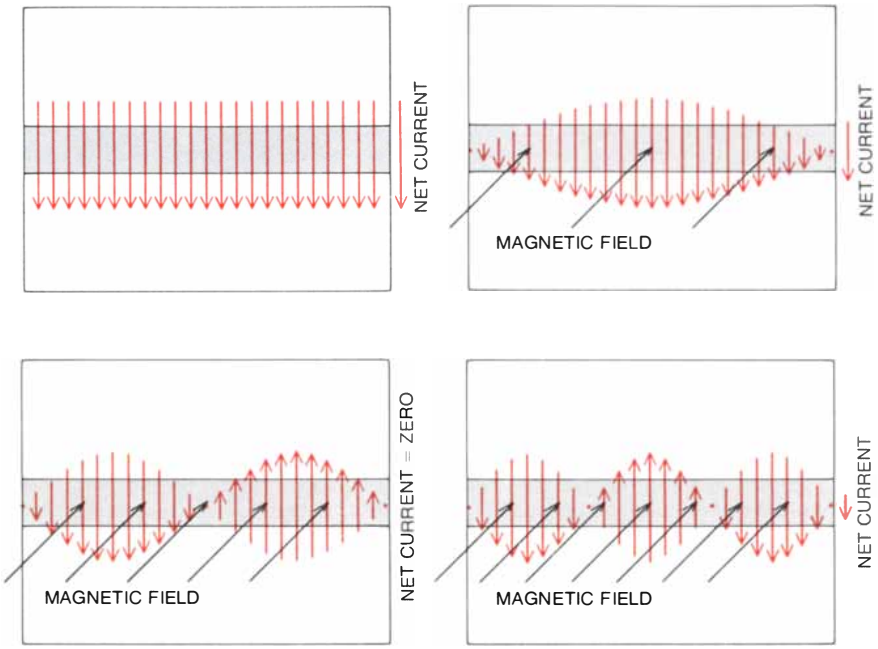


JOSEPHSON EFFECT describes the tunneling of electron pairs across an insulating barrier that separates two superconductors. The apparatus measures the current passing through a junction and the voltage developed across it. For a thick barrier at any temperature (*a*) voltage can be applied but no current flows. If the junction is made thinner but remains at room temperature (*b*), an ordinary tunneling current is observed; the voltage and the current vary in direct proportion. As the junction is cooled to the temperature at which the metal becomes a superconductor (*c*) the relation of the tunneling current to the junction voltage becomes nonlinear. Below the superconducting transition temperature (*d*) two modes of conduction are observed. As long as the current remains below a critical value the junction acts as a superconductor; it has no resistance and so no voltage is measured across it. If critical current is exceeded, the voltage jumps to a nonzero value and the junction becomes a resistive tunneling barrier.

though it never reaches the maximum, zero-field value. Mathematically the dependence of the net current on the magnetic field is said to be a nonmonotonic function: as the field increases, the maximum net current first decreases to zero, then rises again, then drops to zero again, and so on. The curve that describes the net current as a function of the applied magnetic field is the same one that describes the diffraction pattern generated when light passes through a pinhole or a narrow slit. By measuring the maximum sustainable supercurrent as a function of applied magnetic field and finding that it matched such a diffraction pattern, Philip W. Anderson and John M. Rowell of Bell Laboratories were able in 1963 to confirm the existence of the Josephson effect.

The response of the junction supercurrent to an electric field, or in other words to a voltage across the junction, is a sinusoidal variation with time. The current oscillates, moving across the junction first in one direction and then in the other, with a frequency proportional to the applied voltage. When the junction voltage is zero, the current is a direct current; even a small voltage, however, can give rise to a very-high-frequency alternating current. At a voltage of one millivolt, for example, the frequency is approximately 500 gigahertz, or 500 billion cycles per second.

The Josephson effects can be summarized as follows: In the absence of a magnetic field, and with a current below a critical value, a supercurrent flows through the Josephson junction just as if the superconductor were not interrupted by the insulating barrier. No voltage can be measured across the junction. When a magnetic field is applied, a spatial variation in the supercurrent develops; if the field is sufficiently strong, the supercurrent is abolished and a voltage appears across the junction. In the same way if the current through the junction exceeds a critical value, the superconducting property is lost and a voltage appears; in response to this voltage an alternating current of high frequency is generated at the junction.



MAGNETIC FIELD permeating the barrier layer of a Josephson junction introduces a spatial variation in the magnitude and direction of the junction current. At zero magnetic field the current density is uniform throughout the junction and at every point can take on its maximum value, which is the critical current at which the junction loses the superconducting property. When the magnetic field is applied, the maximum current density and the direction of current flow begin to vary from point to point, following a sinusoidal curve. The rapidity of the spatial variation, or in other words the number of sinusoidal half cycles, depends on the strength of the field. If there are an odd number of half cycles, a net current can flow, but its magnitude is reduced from the zero-field value. With an even number of half cycles the current is abolished.

Josephson junctions have been employed in measurements of fundamental constants, and a Josephson tunnel junction now defines the voltage standard of the U.S. The junctions have also been used to make exquisitely sensitive instruments for the measurement of magnetic fields. The investigation of the Josephson effect as a basis for computer logic and memory devices was first undertaken by me in the mid-1960's.

The simplest possible Josephson-junction logic element consists of a single switch. Two films of a metal such as lead or niobium are separated by a thinner layer of insulator. Atop the entire assembly is a third conductor, the control line, isolated from the other two conductors by a much thicker insulating coat. Lead and niobium are the metals most often chosen because they have comparatively high superconducting transition temperatures: 7.2 and 9.4 degrees K. respectively. Hence they are well below the transition at the temperature of liquid helium (4.2 degrees K.). The barrier is usually made of the oxide of the junction metal, oxides being in general excellent insulators.

In operation one side of the junction is connected through a resistor to a source of current and also to an output device. The other side of the junction is connected to the electrical ground of the system. If the supply current remains below the critical value, it passes through the junction in the superconducting state. Thus the junction provides a direct short circuit from the supply to ground, and no current flows into the output device. If a current is passed through the control line, however, it gives rise to a magnetic field that penetrates the junction layer. In the presence of this field the junction can no longer carry the full supply current in the superconducting mode, and it switches to the resistive state. As a result a voltage appears across the junction and most of the supply current is diverted into the output line. The resistance of the junction in the nonsuperconducting state can be as much as several hundred ohms, and so the junction forms an almost ideal switch. It has the effect of steering the current, either directly to ground through the junction or into the output device.

I was led to investigate such devices by three considerations: a hunch they could be switched quickly from one state to another, their evident low power consumption and the fact they have gain, in that the output current can be greater than the switching current applied to the control line. Initial experiments done in 1965 and 1966 in my laboratory at the Thomas J. Watson Research Center of the International Business Machines Corporation confirmed these conjectures.

The sensitivity of a Josephson junction to an applied magnetic field increases with the area of the junction, which argues for making the devices large so that the control currents can be reduced to a minimum. The switching speed of the junction, however, decreases as the area becomes larger. In recent devices the conflicting demands of speed and sensitivity are met by replacing a single junction with two or more junctions connected by a continuous superconducting loop. Such a multijunction device is called a Josephson interferometer or a superconducting quantum interference device (SQUID). The interference in question is closely analogous to the interference of light waves. Whereas the graph of maximum current v. magnetic field for a single junction reproduces the diffraction pattern of

light passing through a single slit, the corresponding graph for a two-junction Josephson interferometer yields the interference pattern of light passing through two parallel slits. The resemblance is not coincidental. In a closed superconducting loop that includes two Josephson junctions any disturbance of the electron-pair waves at one junction is immediately communicated to the other junction. For some values of the field the interfering waves are in phase, so that they interact constructively, and the maximum current can flow through the device; other values of the field lead to destructive interference and thereby abolish the supercurrent. In a device with three or four junctions the interference pattern is more complicated, but the underlying principle is the same.

The operating voltage of a Josephson junction is determined by the gap voltage and hence by the binding energy of a superconducting electron pair. The value of the gap voltage depends in turn on the material and on the operating temperature; the gap voltage has its maximum value at absolute zero, and it decreases to zero at the superconducting transition temperature. For materials that are candidates for computer technology the operating voltage is about three millivolts, 1,000 times smaller than typical voltages in semiconductor devices. The currents that circulate in the superconducting circuits are determined by the probability of tunneling across the Josephson junctions and hence by the nature of the oxide layer and its thickness. Typical currents are a few tenths of a milliampere.

An unusual property of Josephson-junction switches is that they are latching circuits. Once a pulse of current passing through the control line converts the junction from the superconducting state to the resistive state it remains resistive even after the control current is withdrawn. Indeed, no further inputs to the control line have any effect on the circuit. The reason is that once the device has switched there is a voltage across the junction, which in itself prevents the reestablishment of a supercurrent. The device can be reset to the zero-resistance state only by momentarily interrupting the supply current.

Although there are contexts in which the automatic latching of circuits is a convenience, the majority of the logic devices in the central processing unit of a computer must be reset at the end of each machine cycle. The unavoidable latching of Josephson-junction devices therefore places a constraint on the design of a power supply for the computer: it must be capable of interrupting the power to all logic circuits at the end of each cycle.

Another characteristic of Josephson-junction devices provides the key to an ingenious solution to that problem: a Josephson junction is indifferent to the direction in which current flows through it. In a semiconductor the polarity of voltages is of the greatest importance, and so the power supply for a semiconductor computer must provide direct current of fixed polarity. For a Josephson junction, on the other hand, interchanging all positive and negative voltages in the system, so that all currents are reversed, has no effect on the operation of the device. For this reason the logic array of the computer can be powered by alternating current. At the beginning of a cycle the power supply comes on and supplies current to the logic devices; at the end of the cycle the supply voltage drops to zero, resetting the logic array. When the next cycle begins, the process is repeated, but the supply voltage has the opposite polarity.

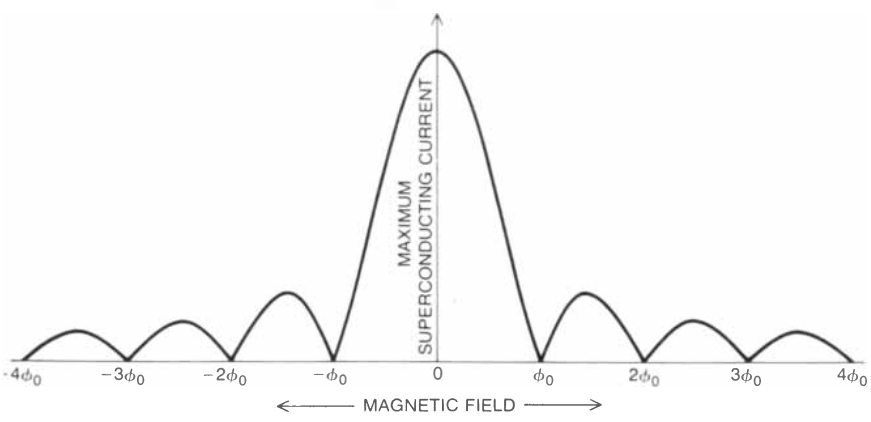
All the logical and arithmetical functions of the central processing unit of a digital computer can be defined in terms of two circuits: the *OR* gate and the *AND* gate. They are circuits that yield a single output signal depending on the values of two or more input signals. An *OR* gate gives an output of "true," or logical 1, if any of its inputs is a 1; the output is "false," or logical 0, only if none of the inputs is a 1. The *AND* gate has an output of 1 only if all its inputs are 1; otherwise the output is 0. In a Josephson-junction computer the presence of a current in the output line signifies a logical 1 and the absence of a current represents a 0.

A two-input *OR* gate can consist of a single Josephson interferometer equipped with two control lines. At the start of a machine cycle this dual-input device is in the superconducting state and all the supply current is shunted through it to the electrical ground of the system. A signal on either one of the control lines switches the junction to the resistive state and the supply current is thereby diverted into the output line. Thus an output signal appears if either one of the control lines receives a signal or if both of them receive signals. The output of the gate can serve as input for another interferometer, or indeed it can control an entire series of devices.

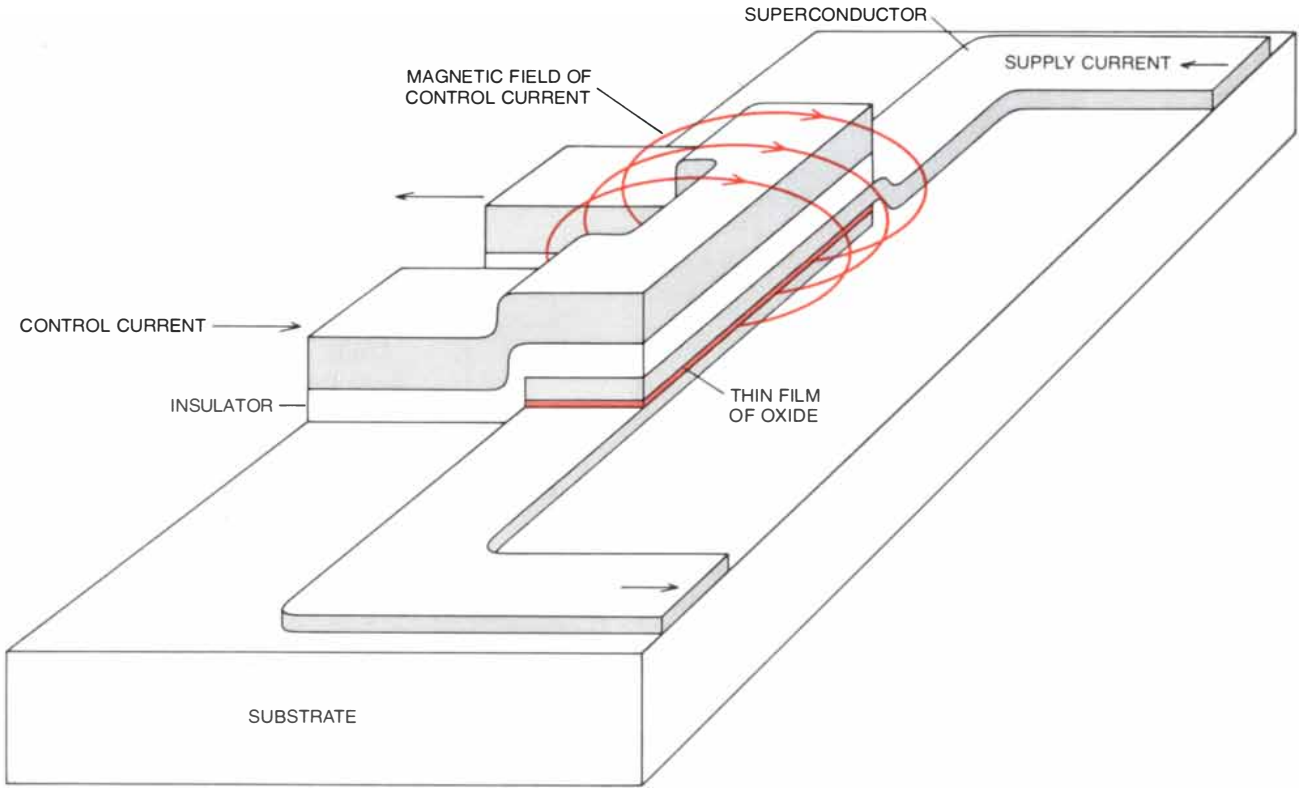
The most promising arrangement of circuit elements for executing the *AND* function is somewhat more complicated. It includes a special-purpose Josephson interferometer, called a current-injection device, that is switched not by a magnetic field but by the current flowing through the junctions. The current-injection device, which was devised by Tushar Gheewala of the Watson Research Center, acts as an adder: it responds to the sum of two input signals.

The inputs to the *AND* gate are initially applied to the control lines of two conventional interferometers; it is the output lines of these circuits that drive the current-injection device. At the beginning of a cycle the injection device is in the superconducting state and carries a current from the power supply to ground. It can absorb the additional current from either one of the input circuits without switching to the resistive state, but if both inputs are present, the maximum superconducting junction current is exceeded. The device then switches, and the supply current is diverted to the output. The current-injection device consists of a two-junction interferometer in which the superconducting loop that connects the junctions is asymmetrical: one arm has a higher inductance than the other. The asymmetrical configuration enhances switching when two inputs are presented simultaneously but inhibits switching when only one input signal is received.

In the central processor *OR* gates, *AND* gates and a few other kinds of cir-



MAXIMUM SUPERCURRENT that can be sustained by a Josephson junction is an oscillating function of the applied magnetic field. The graph has the same form as a graph of the amplitude of light waves diffracted by passage through a slit. The fact that a greater current can be carried at zero magnetic field than at any other value offers a simple means for switching a Josephson junction from the superconducting state to the resistive state. In the absence of a magnetic field a supercurrent near the allowable maximum is established. When a magnetic field is introduced, the current exceeds the critical current and the junction develops resistance.



JOSEPHSON-JUNCTION SWITCH is converted from the superconducting state to the resistive state by the application of a magnetic field. The junction consists of two strips of a superconducting metal, such as a lead alloy, separated by a thin film of the oxide of the metal. A separate control line is isolated from the junction electrodes by a much thicker layer of oxide. The junction is initially superconducting, so that the supply current is shunted directly to ground without resistance. A pulse of current in the control line gives rise to a magnetic field that penetrates the junction layer and abolishes the superconductivity. In response a voltage then develops across the junction.

cuits are combined to form functional units that operate according to instructions provided by a computer program. One array of gates, for example, might carry out the operation of addition: given two numbers (in binary form) as input, it would calculate their sum as its output. Another set of gates might compare two binary numbers, issuing as output a logical 1 if they are equal and a logical 0 if they are different. The functions selected during any machine cycle are determined by the instructions that make up the program. The instructions themselves are decoded by another array of gates. The organization of these many units, or what is called the architecture of the computer, need not be any different in a Josephson-junction computer from what it is in a computer based on semiconductor technology.

At the beginning of a machine cycle both the data to be operated on and the instructions that specify the operation are stored in circuits called latches or in arrays of latches called registers. Unlike the systems of gates that carry out the logical and arithmetical processing of information, the latches and registers must be powered continuously so that information is not lost between cycles. On a signal from the master clock the instruction to be executed next is decoded, yielding a set of signals that control the configuration of the various logic elements. The binary signals representing the data are then inserted into the logic array, where they are transformed according to the decoded instruction. Before the cycle ends and the logic gates are reset the transformed data must be stored in another set of registers. For some instructions complete execution may require more than one cycle. In those cases the instruction must be divided into a sequence of elementary operations each of which can be carried out within a single cycle.

The maximum speed of the central processor is determined by the time that is needed for an individual gate to change state, by the number of gates a signal must pass through and by the speed with which signals move from one gate to the next. Since all operations must be concluded before a cycle ends, the cycle must last long enough to allow for the worst case.

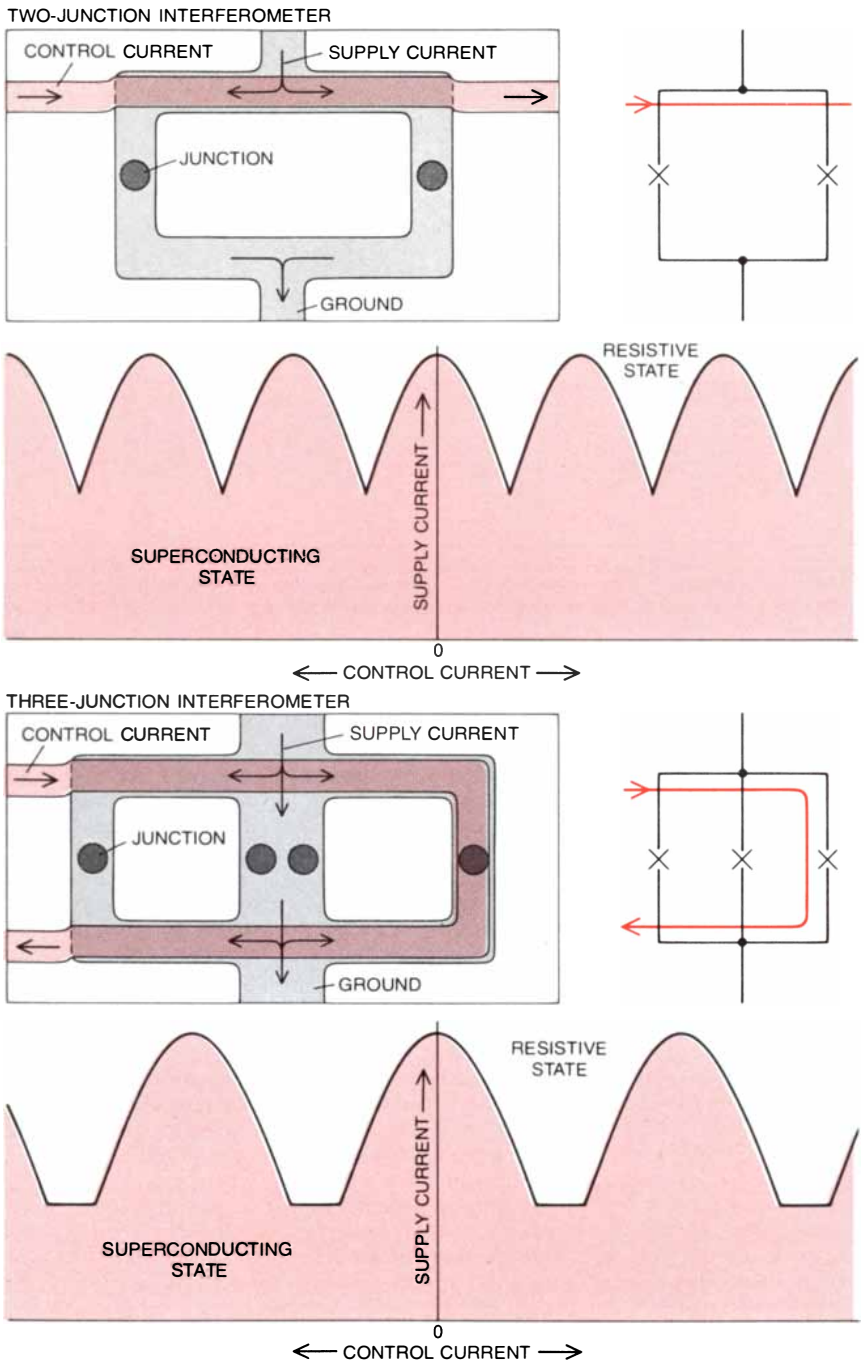
The time required for a signal to pass from the input of one gate to the input of the next can be divided into two components: a switching delay, in which the Josephson junction changes from the superconducting state to the resistive state, and a propagation delay, in which the output of the junction is transmitted to the next device. The switching of a Josephson-junction device begins when a current in the control line establishes a magnetic field that penetrates the tunneling layer. In the presence of this field the junction is no longer able to carry the supply current in the superconducting mode and a voltage appears across the junction. Part of the switching delay is the period required for this voltage to reach its ultimate value. Even after the junction voltage has developed, however, the current is not instantaneously transferred to the output line. The junction, being made up of two conductors separated by a thin insulator, constitutes a small capacitor, and the remainder of the switching delay is the time needed to charge this capacitance. The capacitance increases in proportion to the area of the junction; in part that is why larger junctions switch slower.

The total switching delay of the Josephson-junction interferometers being considered for computer applications is exceedingly small. The rise time, or the time for the output signal to change from the logical-0 state to the threshold of the logical-1 state, is typically 15 picoseconds. With one sample of Josephson-junction devices David B. Tuckerman, a graduate student working at the Watson Research Center, has measured a rise time of 10 picoseconds. Even the measurement of an interval that brief

was made possible only by employing Josephson-junction technology.

The propagation delay between gates obviously depends on the length of the output line and on the speed with which signals pass through the line. In a room-temperature computer the signal-transmission properties of metallic conductors can severely constrain the maximum operating speed. A rapidly changing signal is distorted and attenuated after only a few centimeters in such a conductor. As a result the signal diffuses instead of propagating as a wave.

In a superconducting computer those problems can be avoided by designing the output circuit as a superconducting transmission line with characteristics that are nearly optimum for the conveyance of a rapidly changing signal. In particular the line has negligible effective resistance for signals at all frequencies up to more than 1,000 gigahertz. (It might be thought that the resistance of a superconductor would always be zero, but in fact it is only the resistance to a steady current that is exactly zero.)



MULTIJUNCTION INTERFEROMETERS are more sensitive and switch faster than a simple one-junction switch. The devices are called interferometers because the maximum supercurrent they can conduct is determined by the interference of electron-pair waves at two or more junctions. For some values of magnetic field the interference is constructive and the junctions maintain their superconductivity; for other values of the field destructive interference converts the device to the resistive state. For the two-junction interferometer (*upper diagram*) the curve relating the maximum superconducting supply current to the control current has the same form as the interference pattern generated by light passing through two parallel slits. The three-junction interferometer (*lower diagram*) yields a threshold curve equivalent to a three-slit interference pattern. (For convenience in fabrication the three-junction device is actually made with four junctions, but two of them are so close together they can be considered a unit.)

The transmission line consists of a thin film of superconductor laid down over an insulated, superconducting ground plane. A pulse of current travels through the line as a wave with a phase velocity of between a fourth and a third the speed of light in a vacuum. A signal with a rise time as short as a picosecond can be transmitted a few centimeters with little distortion or attenuation. To prevent the signal from being reflected by the end of the transmission line, the line is terminated with an impedance that matches the impedance of the line itself. Such terminations are seldom possible in a semiconductor computer because they bring an unacceptable increase in power consumption.

An indefinite number of gates can be driven by the output of a single circuit; all that is necessary is to arrange the gates serially along the transmission line. (The output of a semiconductor circuit, in contrast, can power only a few gates without intermediate amplification.) Each gate adds a load to the transmission line and introduces a delay of about five picoseconds.

The total delay of Josephson-junction circuits has been measured by building cascades of gates, with the output of one gate connected to the input of the next. For a signal to ripple through a sequence of 10 *OR* gates requires as little as some 130 picoseconds, which is appreciably less than the delay associated with one equivalent semiconductor gate. The average delay of 13 picoseconds per gate is the smallest ever achieved in a logic circuit. It consists of a six-picosecond switching delay and a seven-picosecond propagation delay. Of course, a linear chain of 10 *OR* gates does not reproduce very realistically the organization of a computer's central processor. Under more plausible operating conditions, in which each gate has four inputs and three outputs, the average delay is about 35 picoseconds per gate.

These measurements were made with circuits in which the narrowest conductors were about 2.5 micrometers wide. At that size about 1,000 gates could be fitted on a square chip a quarter of an inch on a side. The total power dissipation of such a chip would be about 10 milliwatts. There is no question the devices could be made much smaller, with line widths of less than a micrometer. Reducing the size of the devices will

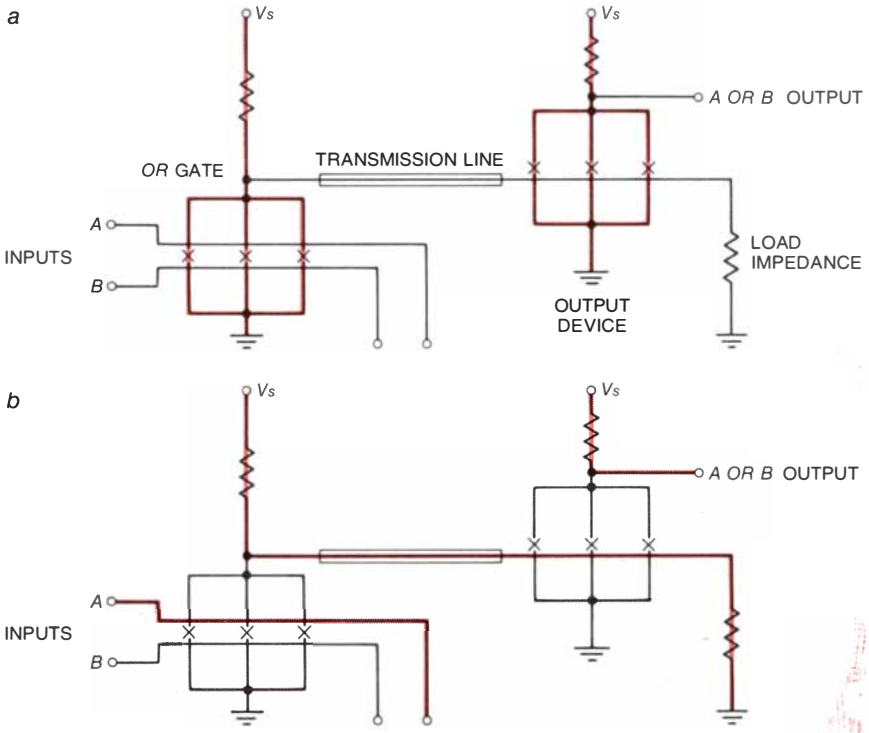
bring several gains in speed. It will lower the inductance of the control line and the capacitance of the junction, thereby improving the switching speed. It will also reduce the average distance between gates, resulting in a shorter propagation delay.

Supplying power to a high-performance computer can be a major challenge. For a large room-temperature computer the supply voltages are measured in tens of volts and the currents in thousands of amperes. In a Josephson-junction computer the operating voltages are smaller by a factor of 1,000 and the currents are smaller by a factor of 10, so that only one ten-thousandth as much power is needed. It is still essential, however, to control or confine disturbances in the power-distribution system, which would otherwise disrupt the operation of the machine.

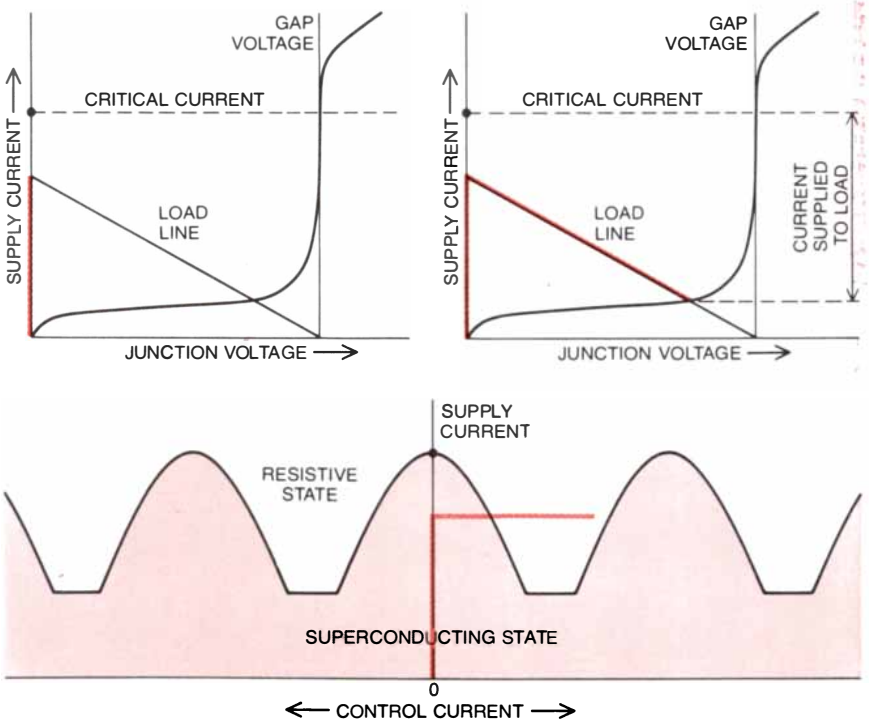
The disturbances result from a sudden change in the demand for current when a device changes state; they are analogous to the dimming of the house lights when the electric motor in an appliance turns on. One solution to this problem is to design the switching devices so that the power demands of the two logic states are identical. Actually it is never possible to make them exactly equal, but the ratio of the two demands can be made close to 1 by increasing the power dissipation in the resistance associated with the supply itself. For example, suppose a device demands one microwatt in the logical-1 state and two microwatts in the logical-0 state; the demand then changes by 100 percent when the device switches. If the supply resistor dissipates five microwatts, however, the total change in demand is from six microwatts to seven microwatts, or 17 percent. This technique is difficult to apply in semiconductor circuits, where power consumption is already high, but in the Josephson-junction technology one can easily afford to dissipate five times as much power in the supply resistance as in the logic device itself.

Even with such heavy ballasting of the power supply, regulation is still needed, and it is advantageous to put the regulator as close as possible to the switched load. The regulator can be a Josephson junction, but one operated with a current greater than the maximum supercurrent. Whenever the voltage across this regulator exceeds the gap voltage, the current is shunted to ground. By placing many such regulators throughout the computer any disturbance in the supply voltage is absorbed before it can propagate through the system. In practice each regulator consists of four junctions connected in series, so that the voltage level is stabilized at four times the gap voltage, or about 12 millivolts.

A concept for a complete power-supply system for a Josephson-junction



LOGICAL "OR" GATE, a basic circuit of the central processor of a computer, consists of a three-junction interferometer with two control lines. When the device is first turned on (*a*), the gate is superconducting, so that the supply current is shunted to ground and no voltage appears at the output transmission line. An input applied to either of the control lines switches the gate (*b*) and its resistance increases from zero to several hundred ohms. As a result the supply current is diverted into the output line, which serves as the control line for a second gate. The device is called an *OR* gate because it can be triggered by a single input either on control line *A* or on control line *B;* two inputs also switch the device. The gate latches automatically: once a voltage has developed, superconductivity is recovered only when the supply current is interrupted.



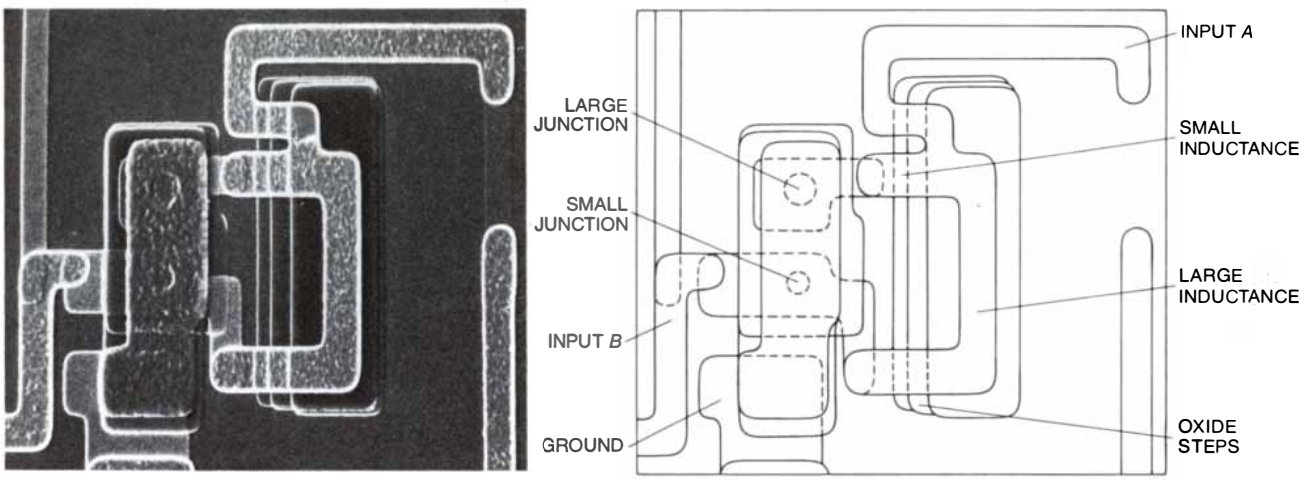
STEERING OF CURRENT into the output line takes place rapidly when the *OR* gate switches to the resistive state. Initially the supply current flows through the interferometer loop at zero voltage (*upper left*). An input has the effect of lowering the critical current (*upper right*), with the result that a voltage appears across the junction. The state of the system follows a trajectory called the load line, whose slope is fixed by the impedance of the output circuit. Loss of superconductivity is caused by the magnetic field generated by the control current (*lower graph*).

computer has been described by Frank F. Fang and Dennis J. Herrell of the Watson Research Center. As I indicated above, it is convenient to operate most of the components of the computer on alternating current. The ultimate source of supply is an oscillator at room temperature that produces alternating current with a sinusoidal waveform, like that of ordinary house current but at a much higher frequency. The unregulated alternating current is distributed throughout the computer by superconducting transmission lines. On each chip the voltage is reduced to the appropriate level by a small transformer, whose "windings" are thin films of superconductor. The supply regulators on the chip then clip the peaks off the sinusoidal waveform, giving each half cycle a trapezoidal form.

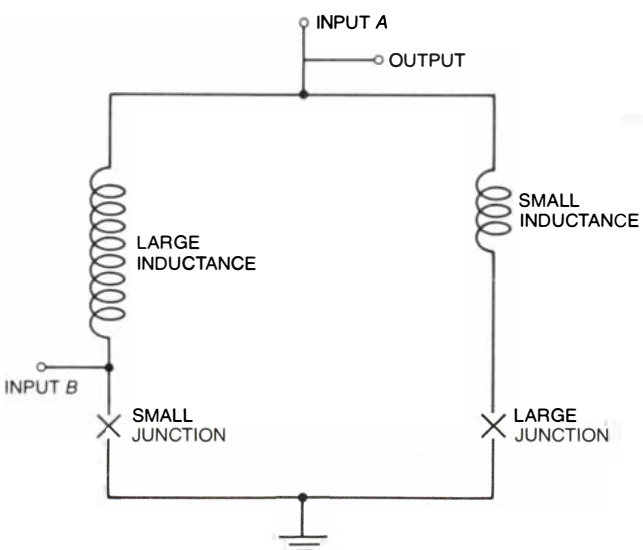
In Fang and Herrell's concept this system not only powers the computer but also provides its master clock. The purpose of a clock in a computer is to synchronize all events so that, for example, all the inputs to a gate arrive simultaneously. A serious problem, called clock slew, can arise if the clock signal itself does not reach all parts of the machine at the same time. In order to avoid clock slew the power and clock signal in the Josephson-junction computer will be distributed through a treelike network in which all branches are about the same length.

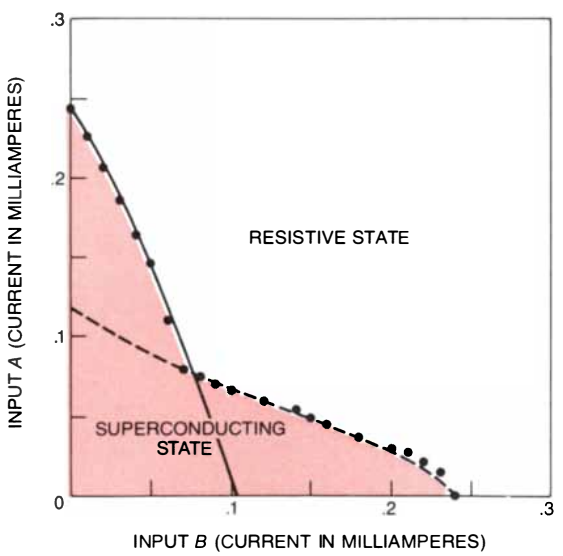
If the cycle time of the computer is to be one nanosecond, each full cycle of the alternating-current supply voltage must last two nanoseconds. Hence the supply frequency is 500 megahertz.

If a computer is to operate at maximum speed, it must be able to retrieve data and instructions from the memory unit within a single cycle of the processor, or within at most a few cycles. Moreover, a very fast computer will be expected to handle large tasks, and so the memory must also be large, capable of storing some tens of millions of bits of information. It is not economically feasible to make a very fast memory very large; it may not even be technologically feasible to do so. The compromise that has been reached for semiconductor computers is to employ a hierarchy of memory elements. The central processor is closely tied to a memory called the cache, which has a limited capacity but is very fast; the cache is filled by a more capacious but slower main memory, which in turn can draw on a still larger and slower mass-stor-



LOGICAL "AND" FUNCTION is carried out by a special-purpose interferometer called a current-injection device. An *AND* gate yields an output signal only when it receives input signals on all its input lines. At the left is a scanning electron micrograph of the device itself, which was designed by Tushar Gheewala of the Watson Research Center. The component parts of the device are labeled in the map at the right. No control lines are employed; instead the injection device switches in response to the currents in the interferometer loop itself.





CURRENT-INJECTION DEVICE acts as an adder of electric currents, which switches from the superconducting state to the resistive state only when the sum of two currents exceeds a threshold. The currents divide asymmetrically in the interferometer loop because of differences in inductance. As is shown in the graph at the right, either one of the inputs by itself can trigger the gate only if the current is greater than about .25 milliampere. If both inputs are present, the gate changes state when each input supplies as little as .1 milliampere.

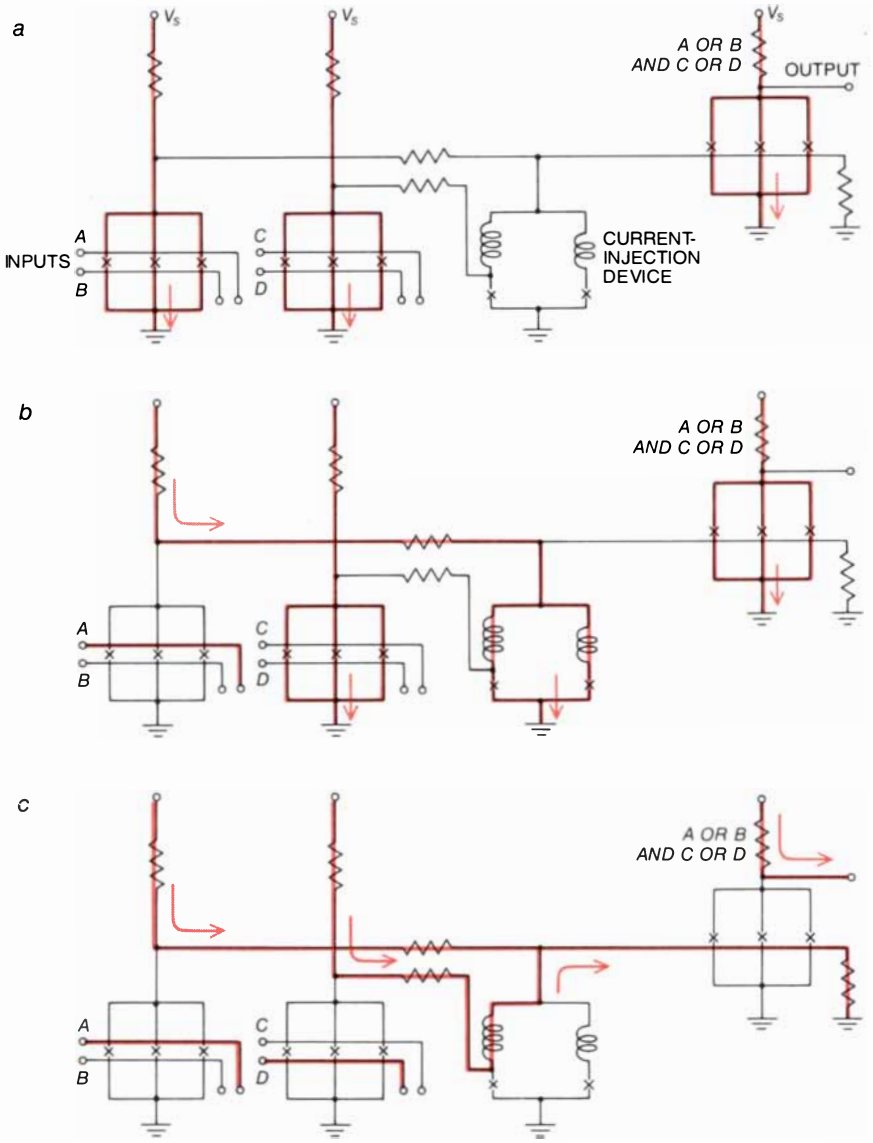
age memory; the mass storage is often a magnetic disk or tape. The efficient operation of the memory hierarchy depends on programs that shuttle information back and forth between the subsystems in such a way that the data and instructions needed immediately are almost always to be found in the cache.

A corresponding hierarchy of memories would be employed in a Josephson-junction computer. The storage cells of the cache memory would be comparatively large and complex (and therefore costly), but information could be stored in them or retrieved from them faster than from any other computer memory yet built. In the main memory speed would be sacrificed to reduce the size and power consumption of the memory elements, so that more cells could be fitted on a chip. Mass-storage devices would operate at room temperature and might not differ in basic design principles from those employed today.

The quantum-mechanical nature of superconductivity provides a natural mechanism for the storage of digital information. If a current is established in a loop of superconductor, it generates a magnetic field that passes through the center of the loop. The direction of the field is determined by the direction of the current. The magnitude of the field and that of the current are quantized, that is, they can assume only certain discrete values, and if they change, they do so only by jumping from one allowed value to another. What is more, both the current and the magnetic field are persistent: they remain unchanged even after the driving voltage is removed. Information can be stored in such loops by letting one quantized state correspond to a binary 1 and letting a different state represent a 0.

A cell of the cache memory consists of a superconducting loop broken by a Josephson junction. A control line (the "write" line) is laid down over this junction so that it is coupled to it magnetically. In addition a junction is buried under one arm of the loop and is controlled by the current in the loop. The superconductor connected to the second junction makes up the "read" line.

When a current is passed through a superconducting loop, it divides into two equal streams, like a river parting to flow around an island. If the current is then removed, no magnetic flux is trapped in the loop; the zero-flux state represents a binary 0. To store a 1 in the memory cell, currents must be supplied simultaneously to the loop itself and to the write line. The current in the write line forces the junction in one arm of the loop to switch to the resistive state, thereby diverting all the loop current into the other branch. When both currents are removed, the switched junction automatically resets, closing the loop, and a persistent current is established.

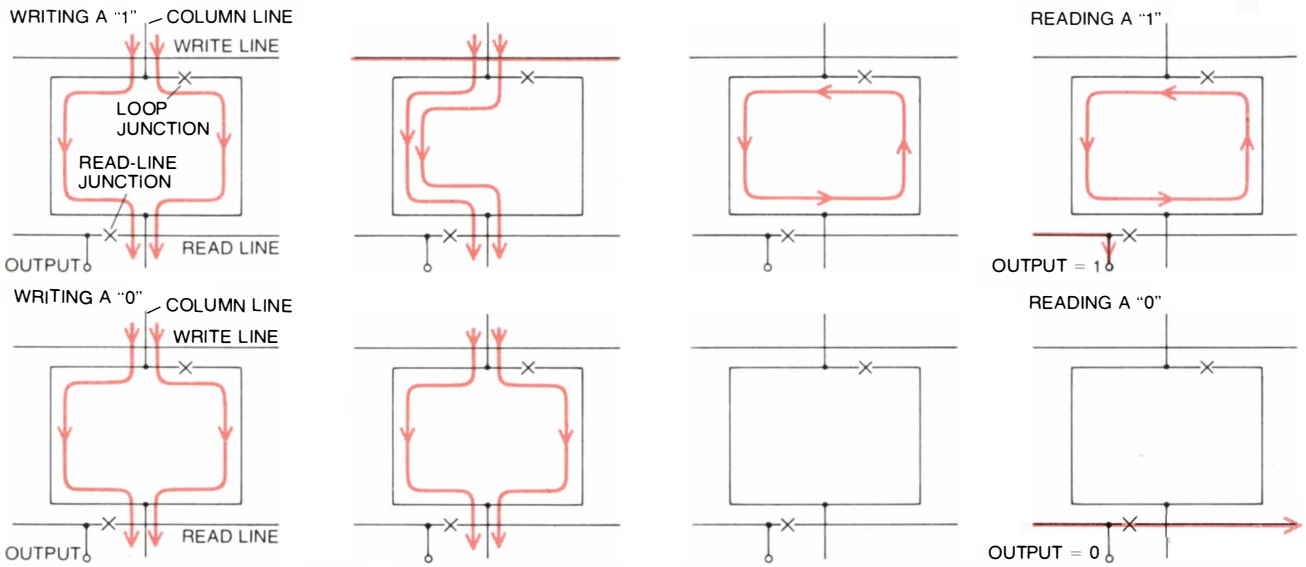


OPERATION OF THE "AND" GATE relies on the current-injection device to sum two inputs. Here the inputs are themselves *OR* gates, so that the circuit as a whole executes the more complicated logical function symbolized by the expression *A OR B AND C OR D*. In the initial state (*a*) both *OR* gates are superconducting and no current reaches the current-injection device. Actuation of one of the *OR* gates gives rise to a signal on the output line (*b*), but the signal is diverted by the current-injection device, which becomes superconducting. When both *OR* gates have been triggered, the current through the current-injection device exceeds the critical level and it switches to the resistive state (*c*). The current is then steered to the output device.

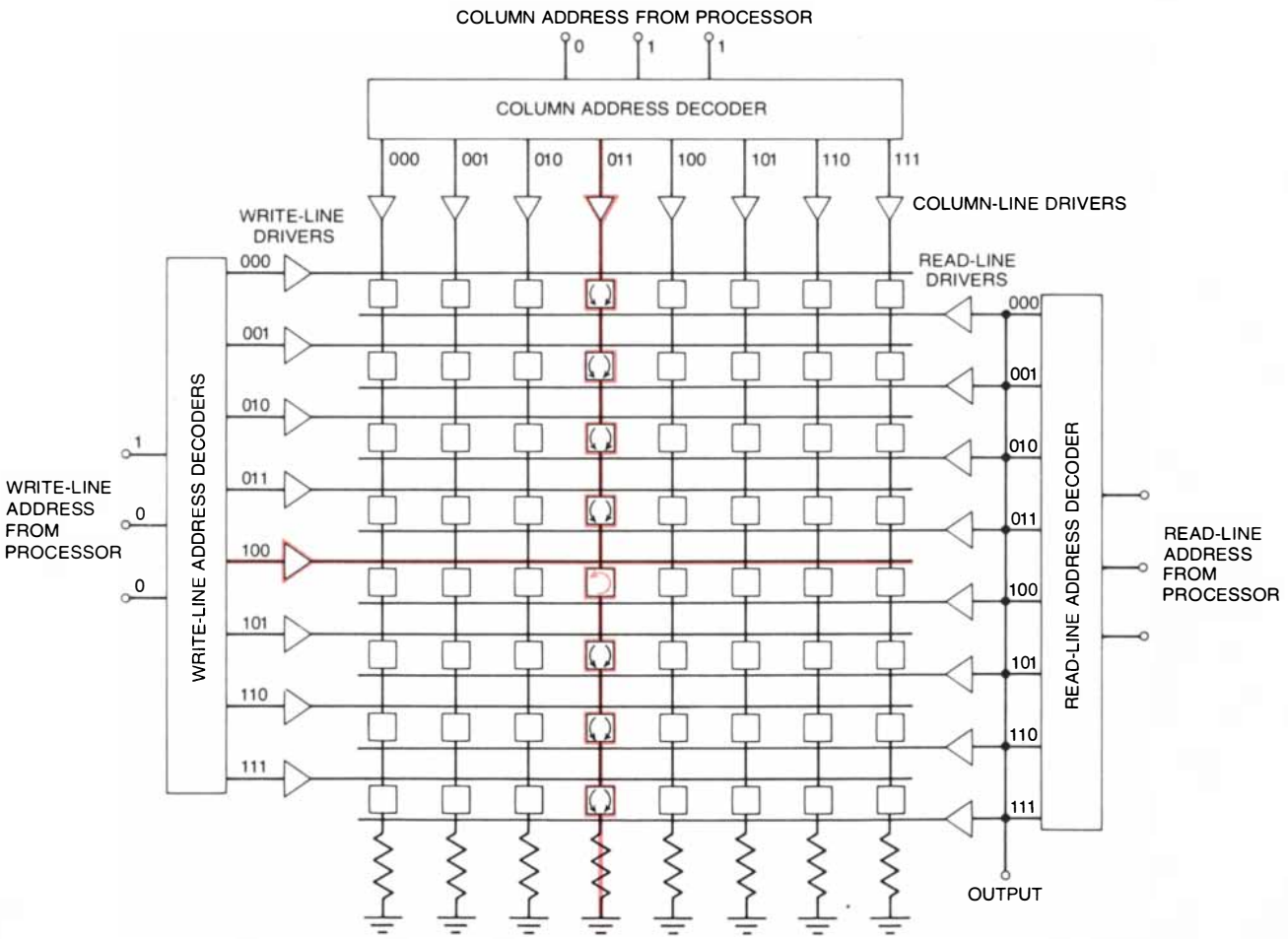
In present designs two quanta of stored magnetic flux correspond to a binary 1.

To read the contents of a memory cell, currents are applied simultaneously to the cell loop and to the read line. If there is no stored flux, the loop current again divides symmetrically, and the junction in the read line remains superconducting. If the loop holds the two quanta of magnetic flux signifying a 1, all the loop current is channeled into one branch of the loop, which also serves as the control line for the read-line junction. As a result the read-line junction switches and a signal appears at the output. It should be noted that the storage of information does not depend on the supply of current to the memory cells; the persistent currents will circulate through the loops as long as the temperature is maintained below the superconducting transition point. Moreover, reading the contents of a cell does not erase the information in it.

A cache-memory chip would bear a square array of cells, so that each cell could be addressed as the intersection of a row and a column. The loops would be connected in series to form the columns; each row would be defined by a write line and by a read line. Certain ancillary circuits would also have to be included on the chip, such as decoders that would actuate the appropriate column and row when presented with the address of a cell, and drivers to supply



STORAGE CELL for a cache, or high-speed memory, consists of a superconducting loop with a Josephson junction in one branch and with provisions for creating and detecting a persistent current in the loop. To store a bit of information in the cell, currents are supplied simultaneously to the loop itself (the column line) and to the "write" line, which is coupled magnetically to the junction in the loop. If a signal is applied to the write line, the junction switches to the resistive state, diverting all the current into the other branch of the loop. When both applied currents are turned off, the junction regains its superconductivity and a quantized, persistent current circulates in the loop, representing one bit of information: a binary 1. Writing a binary 0 into the cell requires the same sequence of events, except that no current is applied to the write line, with the result that no persistent current is established in the loop. The presence or absence of a persistent current can be detected by applying currents simultaneously to the column line and the "read" line. The read line includes a junction buried under one arm of the loop and controlled by the current in that arm. If a persistent current exists in the loop, the column-line current is channeled into one branch of the loop, and it switches the read-line junction. Hence the read-line current is steered to the output.

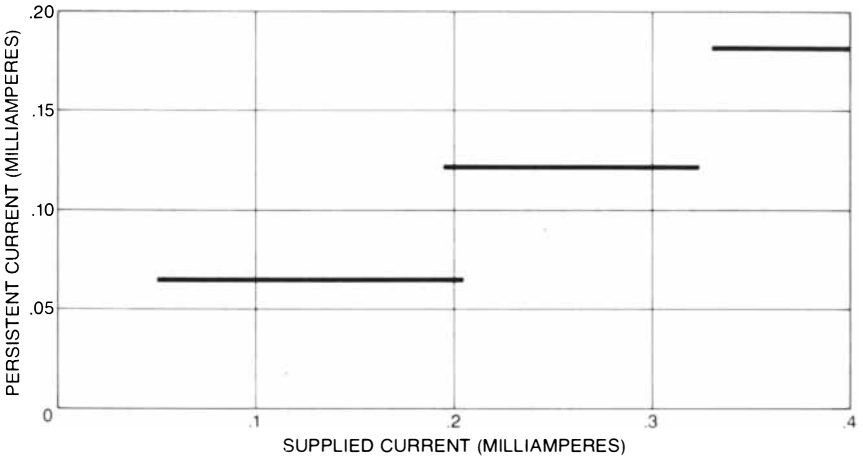


CACHE-MEMORY CHIP is organized as a square array of storage cells. The complete chip is to have 64 rows and 64 columns, for a total capacity of 4,096 bits, but only an eight-by-eight segment is diagrammed here. Any cell can be selected by powering one column and either a write line or a read line. The cache is the fastest unit in a hierarchy of memories, but it also has the smallest capacity per chip.

the currents for the columns and rows. Although no complete chips have yet been made, the individual components—the cells, the drivers and the decoders—have all been designed and tested. A single cache-memory chip will hold an array of 64 rows by 64 columns, giving a total information capacity of 4,096 bits. Reading a bit will take about 500 picoseconds and writing a bit will take twice as long, or one nanosecond. Power dissipation will be about six milliwatts.

The storage cells for the main memory are simpler, and they can therefore be packed together at higher density: 16,384 (2^{14}) will fit on a chip. The saving in size is accomplished by altering the geometry of the superconducting loop and by eliminating the read line and its associated junctions. The memory cell is simply a two-junction interferometer in which the presence or absence of a single quantum of magnetic flux constitutes a bit of binary information. As in the cache memory, coincident currents along a row and a column are employed to select a cell for reading or writing. In reading, however, the entire device switches to the resistive state when a 1 is read, erasing the information; another memory cycle is then required to rewrite the original information back into the cell. A 2,048-bit section of a main-memory chip has been constructed. The full-scale chip is expected to have an access time for retrieving information of about 15 nanoseconds and a power consumption of about 40 microwatts.

In an operating computer information would be stored and recalled not as single bits but as "words" of perhaps 64 bits each. In the memory organization proposed here blocks of 64 chips would be accessed in parallel. A word would be formed by drawing a single bit from each chip.



PERSISTENT CURRENT in a memory cell is quantized; it can assume only discrete values. In the cell measured the smallest possible stored current is about .06 milliampere and the next allowed current is about .12 milliampere. Currents intermediate between these values are never observed. The quantization of the current reduces ambiguity in storage of digital information.

A computer made up of Josephson junctions constitutes a radical departure from a well-established semiconductor technology. The fabrication of Josephson-junction components relies, however, almost entirely on methods learned in the development of semiconductor devices. The substrate material chosen for the Josephson-junction chips is silicon, not because of its semiconducting properties but because techniques for forming precise microscopic structures on silicon are well established. Circuit patterns are defined photolithographically, as they are in making semiconductor devices. First the entire surface of the silicon is coated with a photosensitive substance called a resist. The pattern of the circuitry is defined by a mask, which leaves some areas of the resist exposed to light and blacks out others; alternatively the pattern can be traced out by a steered electron beam. The exposed parts of the resist are then washed away and metal is laid down in the exposed tracks. Several dozen chips can be made at the same time on the surface of a "wafer" sawn from a large single crystal of silicon.

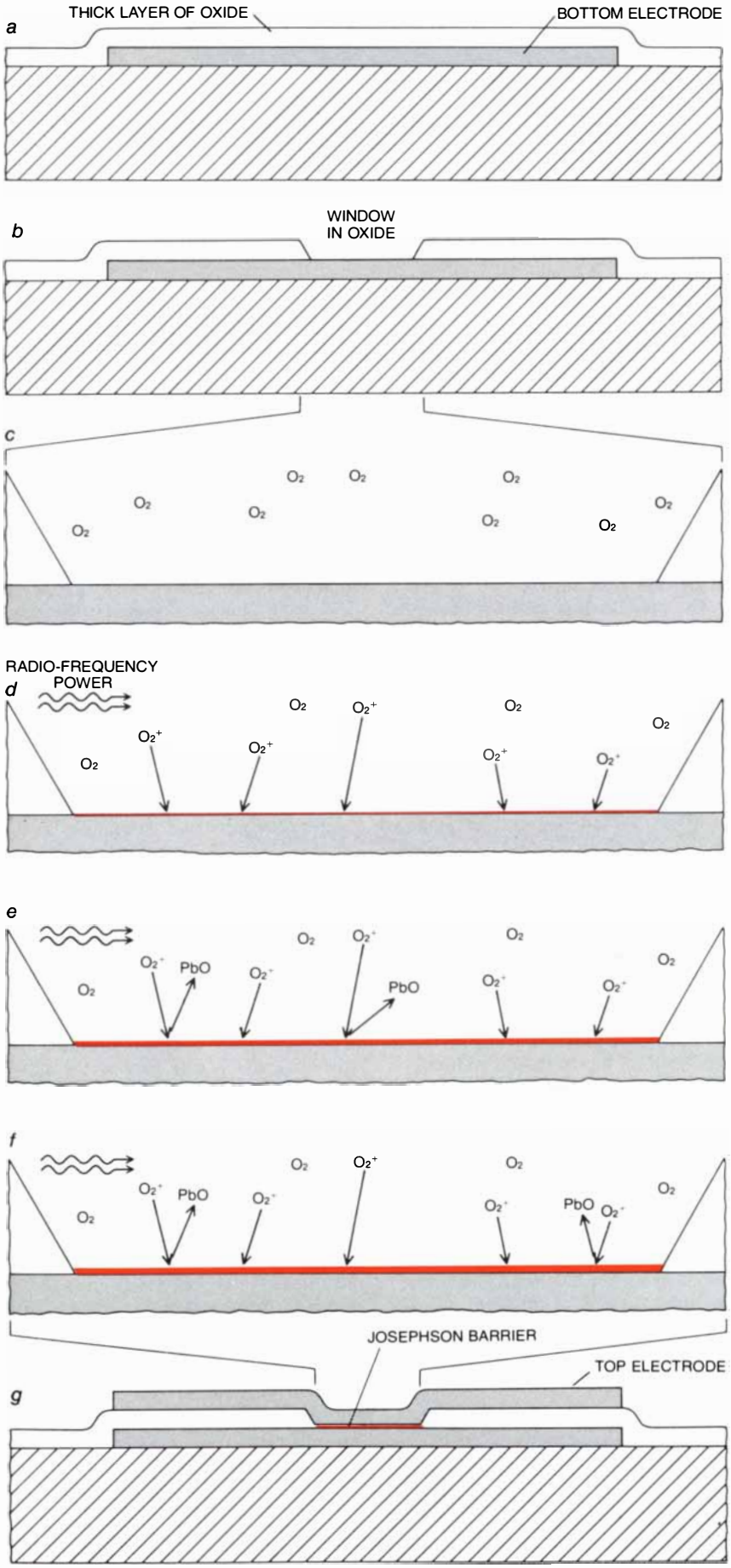
The manufacture of Josephson-junction chips may be easier in some ways than the manufacture of semiconductor components. The reason is that the elements of the Josephson-junction device all lie above the surface of the chip, whereas semiconductors require impurities to be diffused into the silicon itself. In the fabrication of a Josephson-junction chip the first step is the deposition of a superconducting ground plane of niobium, which is covered by an insulating layer of oxide. Then the bottommost superconducting traces are laid down. At the Watson Research Center my colleagues and I have been making the superconductors of an alloy of lead, indium and gold. They are generally between 2.5 and five micrometers wide and about .2 micrometer thick. Additional layers of insulator and metal are deposited on top of these conductors.

By far the most critical step is the formation of the thin oxide layer that serves as the junction barrier. Because the tunneling probability is an exponential function of the thickness of the barrier even a slight variation in dimensions can cause a large change in the properties of the device. The optimum thickness is usually about 50 angstroms, or .005 micrometer. In addition to controlling the thickness of the layer it is also important that no metal "whiskers" extend through the oxide layer, since they would create a superconducting short circuit.

In principle it should be possible to control the thickness of the tunnel barrier by controlling the time the metal is exposed to oxygen, but unavoidable contamination of the metal surface leads to unpredictable variations in the rate of oxidation. James H. Greiner of the Watson Research Center has devised another method for forming the barrier that has proved to be highly reliable. The base, or bottom, electrode of the junction is first given a thick coat of oxide, and a window is opened in this layer where the junction is to be formed, exposing the bare metal again. The wafer is then mounted in a vacuum chamber, where oxygen is introduced at low pressure and is ionized by a radio-frequency discharge. Because the wafer forms one electrode of the radio-frequency circuit the oxygen ions strike the metal surface at high velocity, and at first they have a high probability of combining with the metal to form an oxide. As the thickness of the oxide film increases, however, the rate of oxide formation declines. Moreover, a competing process begins to gain importance: when a molecule strikes a thick layer, it may not add to the oxide coat but may instead knock loose an existing oxide molecule. Ultimately the rate of oxidation and the rate at which oxide is removed reach equilibrium, and the thickness of the barrier thereafter remains fixed. This "terminal" thickness is determined not by the duration of the process but by the oxygen pressure, the radio-frequency power and the temperature. It is readily controlled.

In order to minimize the length of signal paths in a Josephson-junction computer the set of chips, which carry all the active components, must be assembled with extraordinary care. In a semiconductor computer each chip is usually encapsulated in its own plastic or ceramic package and soldered to a large printed-circuit board with many other separately packaged chips. That kind of assembly is much too wasteful of space for a high-speed superconducting machine.

The optimum packaging plan would pack all the chips into the smallest possible volume and provide direct, point-to-point connections between them. That is not practical because of the complexity



of the interconnections, but a packaging system that yields a fairly high density of circuits has been devised. It was introduced by Wilhelm Anacker of the Watson Research Center.

The plan calls for bonding the unencapsulated chips upside down to a carrier "card" about an inch on a side. Several hundred small balls of solder connect contact pads on the chip with corresponding pads on the card. The chips are packed together as closely as possible on both sides of the card. Power dissipation does not limit the density of chips, as it does in a semiconductor computer. The heat generated can be removed directly to the liquid helium; there is no need for heat sinks. Interconnections between chips on a card are provided by two layers of wiring deposited on the card. The wires take the form of superconducting transmission lines.

The card itself and most other parts of the assembly will be made of silicon, like the chips. The adoption of a single material reduces thermal strain when the computer is cooled from room temperature to liquid-helium temperature. Several cards, spaced a tenth of an inch apart, are plugged into a board or frame; interconnections between cards are provided by a removable wiring module that plugs into the back of the board. The ability to remove single cards or wiring modules will facilitate repair or modifications.

Perhaps the cleverest feature of this packaging system is the means for establishing secure electrical connections where the cards and the wiring modules plug into the board. Contact is made through platinum micropins some 75 micrometers in diameter. These plug into small voids in the board, which are filled with mercury. At room temperature the mercury is liquid, and so the

FABRICATION of the tunneling barrier is the most difficult step in the manufacture of a Josephson-junction device. A method devised by James H. Greiner of the Watson Research Center reliably forms a layer of insulating oxide some 50 angstrom units thick. The bottom electrode of the junction is first coated with thick oxide (*a*), then a window is opened in the oxide to expose a patch of bare metal (*b*). In a chamber containing oxygen at low pressure (*c*) the device is mounted on one electrode of a radio-frequency discharge system. The discharge ionizes some of the oxygen, which cleans and oxidizes the metal (*d*). At first the oxide layer builds rapidly, but the rate decreases as the oxide coat grows thicker. What is more, another process begins to compete with oxidation: some oxygen ions do not bind to the metal but instead knock loose an existing oxide molecule (*e*). Eventually the rate of oxidation and the rate of oxide removal are equal (*f*); thereafter the thickness of the barrier remains constant. The thickness at which equilibrium is reached is determined by oxygen pressure, radio-frequency energy and the temperature. When the barrier is completed, a second electrode is deposited over it (*g*).

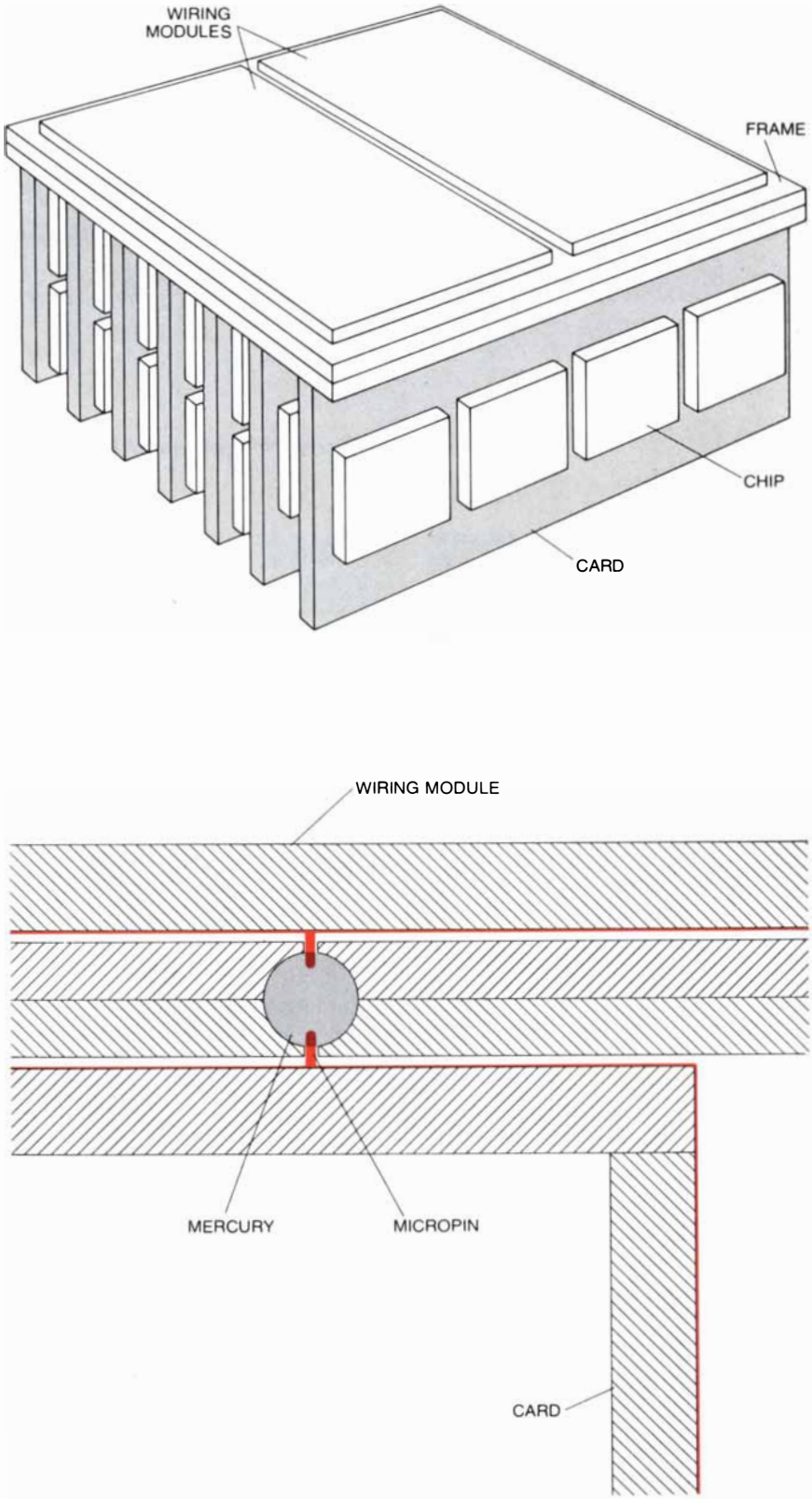
cards and modules can readily be inserted or removed; at 4.2 degrees K., however, the mercury is a solid. Thus it is a kind of solder, but one with a melting point below room temperature.

The need for a continuous supply of liquid helium to cool a Josephson-junction computer is not as troublesome as it might seem at first. Indeed, the cost of the helium refrigerator is comparable to the cost of the much larger power supply and the cooling system that are required by a semiconductor computer. It is true that the helium liquefier dwarfs the computer itself, but the liquefier is no larger than a home refrigerator. A cooling capacity of about 10 watts will suffice.

The components described here—logic circuits with a single-gate delay of 35 picoseconds, a cache memory with an access time of 500 picoseconds and a main memory with an access time of perhaps 10 nanoseconds—cannot be assembled to make a high-performance computer with a one-nanosecond cycle time. Instead the minimum cycle time is estimated to be about three nanoseconds. That is nonetheless very fast: such a computer might be expected to execute on the order of 100 million instructions per second. Moreover, Josephson-junction technology is young; there is every reason to believe cycle times of less than a nanosecond will eventually be achieved.

It is not unreasonable to ask why anyone would want a computer 50 times faster than most of the fastest computers being made today. There are some computational tasks in which speed itself is important. A perennial example is long-range weather prediction, which is now limited by the time required to follow the changes in a computer model of the atmosphere. (A prediction of the weather five days hence is of little value if it takes 10 days to formulate it.) A few other fields, such as cryptology, also make prodigious demands on computer resources and could benefit directly from higher speed.

Those are rather special applications, and if they were the only ones contemplated, the large capital investment needed to develop a new electronic technology would scarcely be worthwhile. The major uses of the Josephson-junction computer are likely to be more mundane. It will be employed for the routine processing of insurance premiums, tax returns and payroll records. It will serve multiple users and multiple functions in the central computing departments of universities. In most such applications it makes no difference whether a task that takes a million machine cycles is completed in one millisecond or 50 milliseconds. The point is that a computer running 50 times faster can do 50 times more, perhaps for the same cost.



HIGH-DENSITY PACKAGING of a Josephson-junction computer is essential to minimize the length of signal paths between circuits. Chips bearing all the active components are bonded upside down to carrier "cards" made of silicon. Connections are made directly from the surface of the chip to superconducting transmission lines incorporated into the card. Several cards plug into a board or frame, and connections between the cards are provided by wiring modules that plug into the other side of the board. Electrical contact between the cards and the wiring modules is provided by "solder" joints, in which a drop of mercury bridges the gap between two micropins; when the computer is immersed in liquid helium, the mercury becomes solid. For a computer with a cycle time of one nanosecond the assembly would be about an inch on a side.

The Role of Gravity in Quantum Theory

An experiment with a neutron interferometer, an instrument in which neutron waves interfere, has shown that the laws of quantum theory apply in the presence of gravitational fields

by Daniel M. Greenberger and Albert W. Overhauser

Quantum mechanics and the general theory of relativity (the modern theory of gravity) are the end products of revolutions in the way physicists interpret the world. Until recently there has been no experimental connection between these two fundamental theories. The wave properties that quantum mechanics attributes to subatomic particles are normally evident on the atomic scale of about 10^{-8} centimeter, and gravitational effects become appreciable only on the stellar or the cosmic scale.

This situation has now been changed by the development of the neutron interferometer, an instrument that enables neutron waves to interfere with one another over a distance of several centimeters. The neutron interferometer is in effect an enormously powerful amplifier that compounds microscopic events so that they can be monitored on the macroscopic scale. The instrument has made it possible to measure the effect of the earth's gravity on the phase of a neutron wave, an effect that was long considered to be too weak to measure. Although experiments with the neutron interferometer cannot probe the details of the theory of gravity, they do offer an important insight into the quantum-mechanical interpretation of the equivalence principle, a cornerstone of general relativity. This principle states that the effect of being at rest in a gravitational field is equivalent to the effect of being at rest in an accelerated coordinate system.

Neutron waves interfere in the same way that water waves and light waves do. When two trains of waves of equal amplitude meet, they simply superimpose. When the waves are exactly in phase (crests coinciding with crests and troughs coinciding with troughs), they interfere constructively and so the resulting amplitude is twice as great; when they are exactly out of phase (crests coinciding with troughs), they interfere destructively and so they cancel out.

If surface waves (say water waves) spread out from two slits that are closely spaced along the same line, they superimpose to form an interference pattern. The points of constructive interference in this pattern fall along lines at characteristic angles from the line of the slits. The same is true of the points of destructive interference. These characteristic angles depend on the ratio of the wavelength to the separation of the slits. When the wavelength and the slit separation are about the same order of magnitude, the angles of constructive interference are substantial. When the wavelength is much less than the slit separation, the angles of constructive interference are so small that the pattern cannot be detected.

If there are more than two equally spaced slits in the surface, the angles of constructive interference are the same as those for two slits. The more slits there are in the surface, however, the more sharply defined the constructive angles are. Think of it this way. Assume that the waves from two adjacent slits are slightly out of phase when they reach some distant point, that is, the crests do not quite overlap. Then at that point the wave from the next slit is out of phase by twice as much, the wave from the succeeding slit is out of phase by three times as much, and so on. As a result the waves from many slits will create complete chaos, leading to total cancellation. For a surface with many slits the only distant points at which a wave can be detected are those at which the waves from the separate slits add up exactly, mainly at the points that lie along the precise angles of constructive interference.

For X rays, which are electromagnetic waves of high energy with a wavelength typically on the order of 10^{-8} centimeter, the ideal scattering medium is a crystal, in which the spacing of the atoms is also on the order of 10^{-8} centimeter. The X rays are scattered not by slits but by atoms in the planes of atoms that make up the crystal. Since there are 10^8 atoms per centimeter, the angle of reflection (the Bragg angle) is defined with great precision: about 10^{-7} degree. The reflected beam can be made monochromatic (that is, made to have a sharply defined wavelength) because only that wavelength will scatter at the appropriate angle. X rays have therefore been able to contribute much to the understanding of the atomic structure of crystals: the sharp scattering patterns can be deciphered to reveal the geometrical arrangement of the atoms.

Neutrons, like other subatomic particles, exhibit characteristics of both particles and waves. The wave interpretation, which was forced on physicists by the experimental facts, was initially resisted by them. Yet quantum theory works exceedingly well, and in many cases it is easier to develop an intuitive feeling for the behavior of quantum-mechanical systems than it is for their classical analogues. Quantum-mechanical experiments that are the equivalent of simple two-slit experiments with water waves can be done, and they demand a wave interpretation for subatomic particles.

Like X rays, neutrons of the appropriate wavelengths are scattered by crystals. Such scattering is the basis of the neutron interferometer. An X-ray interferometer was developed at Cornell University in 1964 by Ulrich Bonse and Michael Hart. It was mistakenly thought that the instrument would not work for neutrons, and so the first neutron interferometer was not operated until 1974 by Bonse and by Helmut Rauch and W. Triemer of the Austrian Nuclear Institute in Vienna. Here the crystal is one of silicon that must be es-

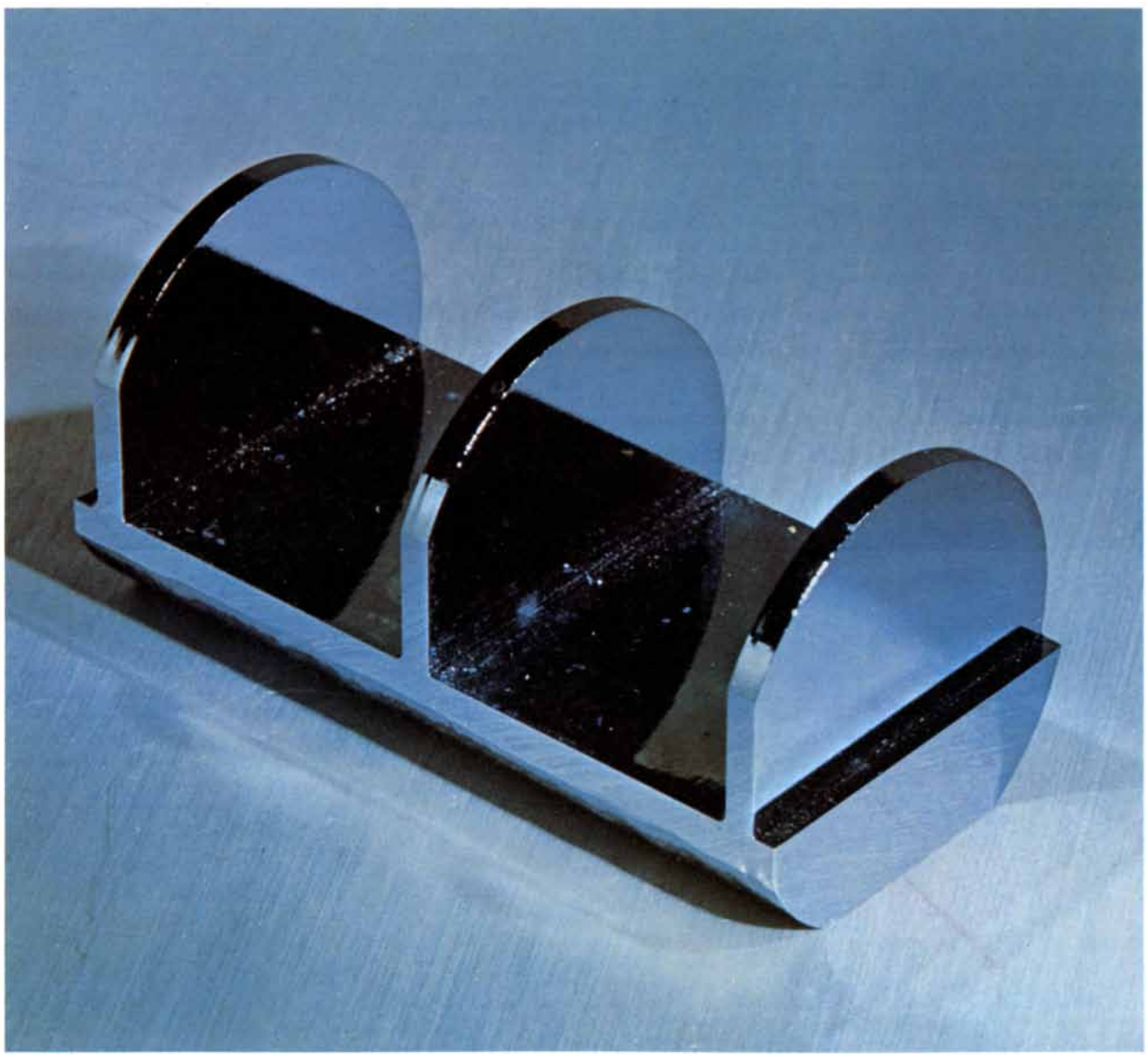
sentially perfect: a single crystal up to 10 centimeters long that is completely free of dislocations and other defects in its regular atomic structure. In a typical interferometer design a cylindrical crystal about eight centimeters long and five centimeters in diameter is cut away to leave three semicircular "ears," or slabs, connected by the remainder of the cylinder. The ears are about .5 centimeter thick and about three centimeters apart.

A typical beam of neutrons that enters the interferometer is about a centimeter wide. Since the wavelength of the neutrons is only 10^{-8} centimeter, the beam propagates between the ears in what is essentially a straight line, as a flashlight beam would. The neutrons of this wavelength are thermal neutrons: they have roughly the same kinetic energy they would have if they were in random motion at room temperature.

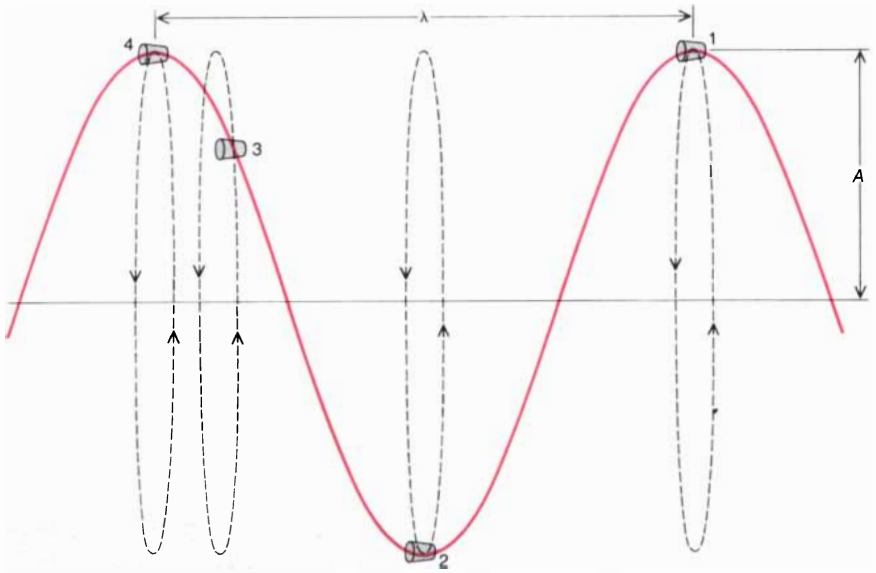
A neutron wave, like any other wave, has an amplitude and a phase, which can be described by a wave function ψ. The physical interpretation of the wave function is based on the fact that the square of the amplitude at any point in space determines the probability of finding the neutron at that point. If an experiment were repeated many times, a neutron detector at that point would register the number of neutrons, which is proportional to the square of the amplitude of the wave function there.

The propagation of the wave is described by the Schrödinger equation, which in the realm of quantum mechanics replaces Newton's classical laws of motion. The wavelength of a particle such as a neutron equals h/p, where h is Planck's constant (6.625×10^{-27} erg-second) and p is the particle's momentum (its mass times its velocity). For example, in a neutron interferometer a neutron with a wavelength of 10^{-8} centimeter has a speed of about 10^5 centimeters per second, which is about 10^{-5} times the speed of light.

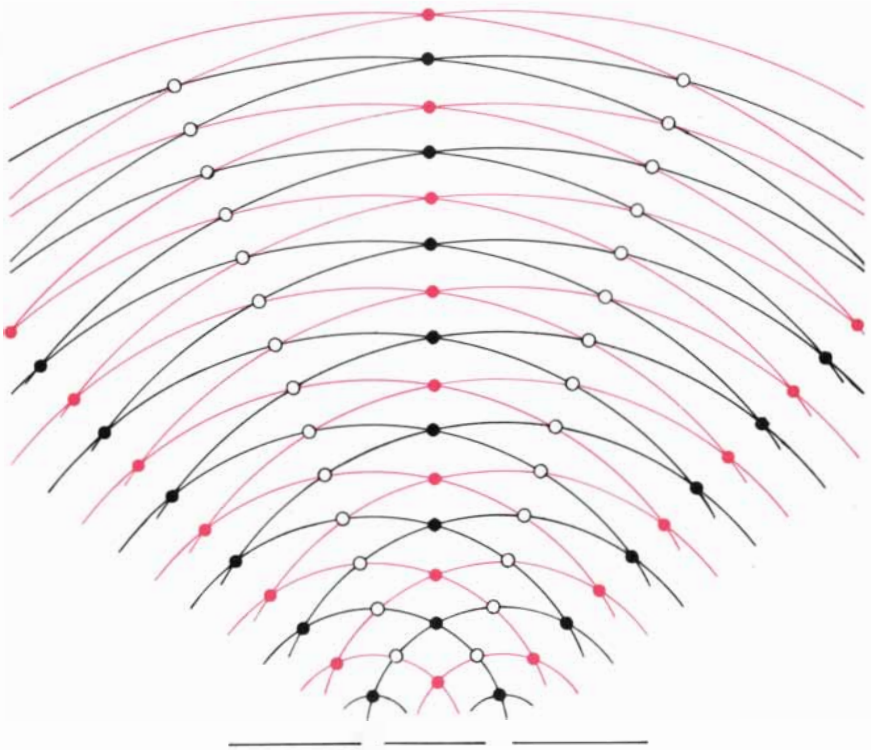
When a beam of neutrons strikes



TYPICAL NEUTRON INTERFEROMETER consists of a single perfect crystal of silicon about eight centimeters long and five centimeters in diameter. The crystal has been carefully cut away by optically controlled diamond tools to leave three "ears," or projections, connected by the bottom part of the crystal. The ears are each half a centimeter thick. Since the ears are all carved out of one crystal, the atoms in them are precisely lined up. The instrument is in the laboratory of Clifford G. Shull at the Massachusetts Institute of Technology.



SERIES OF CORKS FLOATING ON A WATER WAVE demonstrates the properties of wave motion. As a wave traveling to the right passes a cork in the water the cork bobs up and down periodically with limited horizontal motion. The amplitude of the wave (*A*) is the maximum displacement of the cork from its equilibrium value. Corks *1* and *4*, which are separated by a distance λ equal to the wavelength, are considered to be in phase because their motions are identical. Corks *1* and *2*, which are separated by the distance λ/2, are considered to be out of phase because their motions are exactly the opposite. The motion of cork *3* lags slightly behind the motion of cork *4*, and so these two corks are considered to be slightly out of phase.



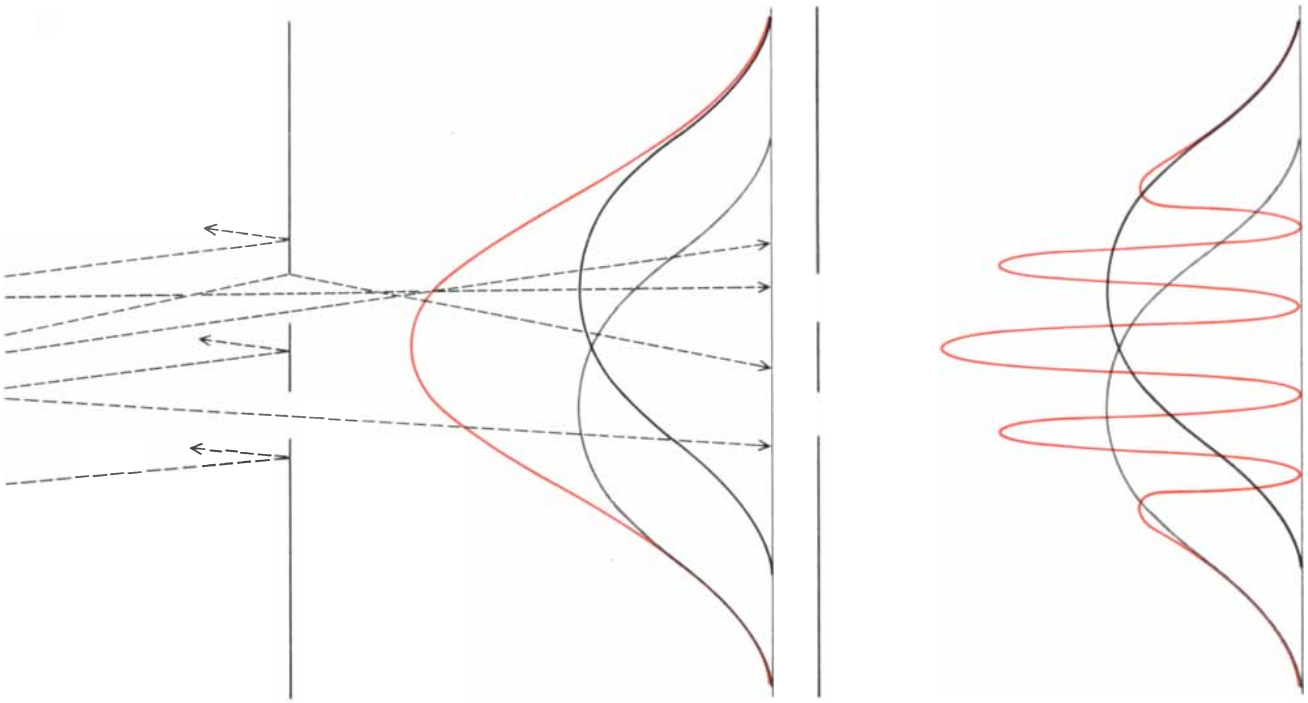
INTERFERENCE PATTERN OF TWO WAVES of equal amplitude spreading out circularly has points of maximum intensity called antinodes at the solid dots and points of zero intensity called nodes at the circles. The colored lines represent wave troughs and the black lines represent wave crests. Whenever two waves meet, they interfere, or superimpose. At the antinodes the waves are in phase, which means crests coincide with crests and troughs coincide with troughs (constructive interference), and at the nodes the waves are out of phase, which means the crests coincide with the troughs (destructive interference). The points of constructive interference fall along lines at certain characteristic angles from the line connecting the slits. The angles are determined by the ratio of the wavelength to the separation between the slits. Waves in three-dimensional space tend to spread out spherically. On a flat surface such as the one shown here the waves spread out circularly. The waves were generated by directing a single wave at two narrow slits. Each slit acts in effect as the point source of a new circular wave.

the first ear in the interferometer at a Bragg angle of, say, between 20 and 30 degrees, it is scattered by planes of atoms perpendicular to the face of the crystal. This kind of scattering, called Laue scattering, gives rise to two beams: a transmitted one at the Bragg angle θ from the scattering planes and a diffracted one at the same angle but on the opposite side of the scattering planes. In other words, the emerging beams form a *V* whose vertex lies at the back of the first ear. At the second ear each of these beams is again Laue-scattered, the four emerging beams forming a *W* whose vertexes lie at the back of this ear. And at the third ear the two diffracted beams are Laue-scattered into two detectors that monitor the beams' difference in phase.

Since the interferometer was made from a single crystal, the atoms of the third ear are lined up exactly with the atoms of the first and the second. This means that the interferometer is a macroscopic system with a built-in microscopic ordering to within 10^{-8} centimeter. If there were many dislocations or other imperfections in the crystal, the atoms in the three ears would not be lined up, which would destroy the coherence of the neutron beams. Moreover, if the ears were not carved out of a single crystal but were physically separated from one another, it would be impossible to line them up precisely.

It is important to realize that the neutron beams of the interferometer are scattered not by the surface of the ears but from the planes of atoms in them. When a neutron travels from the air into the crystal, its speed remains the same to one part in 10^6, and so minor variations in the thickness of an ear would only slightly disrupt the coherence of the neutron beam. As a result the ears need not be machined to an accuracy of a few wavelengths. In any event such accuracy would be technologically impossible. In contrast, visible light travels approximately twice as fast in air as it does in a lens. This means that a small irregularity in the lens only several wavelengths deep would significantly alter the speed of the light wave and hence alter its phase in unpredictable ways. Fortunately the wavelength of visible light is much longer than the wavelength of a thermal neutron, and so it is possible to make high-quality lenses with imperfections several wavelengths deep.

The limit on the coherence of a neutron beam is set not by the uniformity of the thickness of the ears but by the Heisenberg uncertainty principle. That principle, which puts an intrinsic limit on the precision of any wave phenomenon, determines the length over which the neutron waves are coherent. According to the uncertainty principle, the more sharply the wavelength of the beam is defined, the more the beam is spatial-



TRADITIONAL TWO-SLIT EXPERIMENT shows the difference between the classical behavior of a macroscopic particle and the quantum-mechanical behavior of a subatomic particle such as a neutron. In the experiment at the left a beam of macroscopic particles that is fairly well collimated is directed through two slits at a target screen. The black curve represents the distribution of particles at the target when only the first slit is open. The gray curve represents the distribution when only the second slit is open. The colored curve represents the distribution when both slits are open. The colored curve is the sum of the black and the gray curve, because when both slits are open, each particle passes through one of the slits. If the experiment is done not with macroscopic particles but with neutrons (*right*), the distribution when both slits are open (*color*) resembles a typical two-slit interference pattern. In this case it cannot be said that the neutron passed through either one slit or the other as a "classical" particle would. There are certain positions on the target screen where many particles land and other positions where no particles land. This means that the effects of the two slits can superimpose either constructively or destructively. Both the phase and the amplitude of the wave emerging from each slit are important. Nevertheless, each neutron also exhibits particlelike properties: it lands at one point on the target screen. The neutron wave determines the probability that the neutron will land at a particular point on the target screen. The probability is proportional to the square of the amplitude of the neutron's wave function. The interference pattern reduces to the classical interference pattern in the limit where the wavelength is much smaller than the slit size.

ly spread out. Since only wavelengths very close to the wavelength for perfect Bragg-angle scattering are allowed in the crystal, this defines the extent to which the beam is spread. It turns out that the waves are coherent over a length of about 10^{-3} centimeter. The interferometer must be machined to within that tolerance.

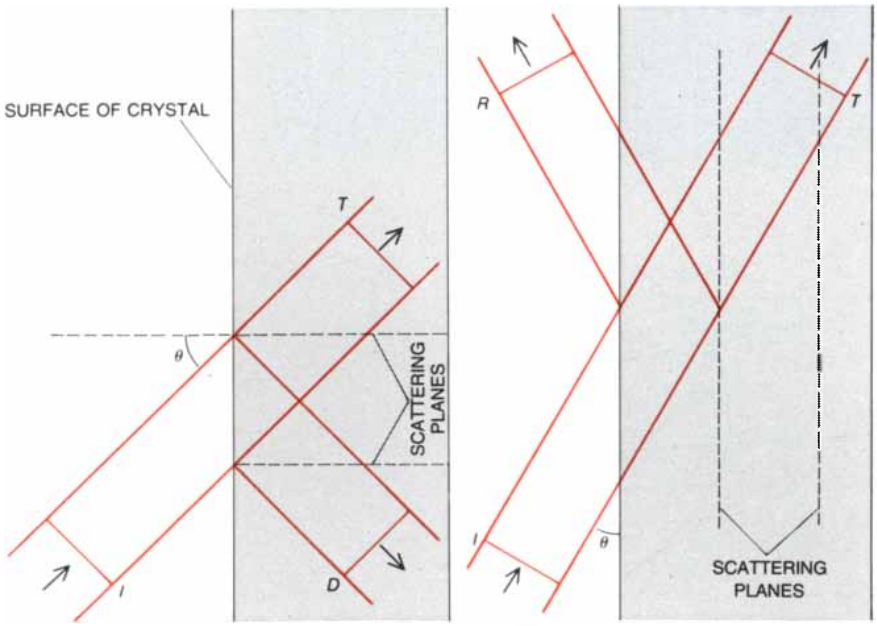
Although it is not strictly necessary to understand what happens inside each of the ears in order to understand how the interferometer operates, we shall mention the effect because it is interesting in its own right. When the incident wave strikes an ear at the correct angle, the beam unexpectedly travels through the crystal perpendicularly to the crystal face, splitting into a transmitted and a diffracted part only as it emerges from the ear. This behavior is called the Borrman effect.

The function of the interferometer depends on the relative counting rates of the two detectors receiving the beams from the third ear. When the two components of the split beam recombine at the third ear, each component impinging on the ear gives rise to a transmitted beam and a diffracted beam. Therefore the beam each detector receives is actually the sum of two beams, the transmitted beam from one of the split beams and the diffracted beam from the other. If a force is applied to create an asymmetry between the split beams, there will be a shift in the phase of one beam in relation to the other. That in turn will give rise to a phase shift between the two beams going to the first detector and a different phase shift between the two beams going to the second detector. Since each neutron must go somewhere, the total beam intensity is conserved. This means that if the beams going into one detector add constructively, increasing the counting rate there, then the beams going into the other detector must add destructively, decreasing the counting rate there.

Imagine that all the neutrons were going into one detector. Now suppose a weak force is applied to the neutron beams, a force so weak that it can barely slow up one of the split beams by just half a wavelength in relation to the other beam in the course of its traveling through the entire apparatus. That phase shift would be sufficient to send all the neutrons into the other detector. This makes the neutron interferometer an incredibly sensitive instrument able to take a coherently split neutron beam that has traveled about eight centimeters and sense that one of the component beams has lagged behind the other by less than one atomic spacing. Moreover, the neutron interferometer transforms this minute phase shift into a macroscopic change in the relative counting rates of the detectors.

The necessary asymmetry between the beams can be introduced in many ways. One way is to put a metal plate in the path of one beam so that the plate interacts with the beam, generating a phase shift. Another way is to apply a weak magnetic field to one beam. Still another way is to create a gravitational field across the interferometer by tilting it so that the beams are at different heights.

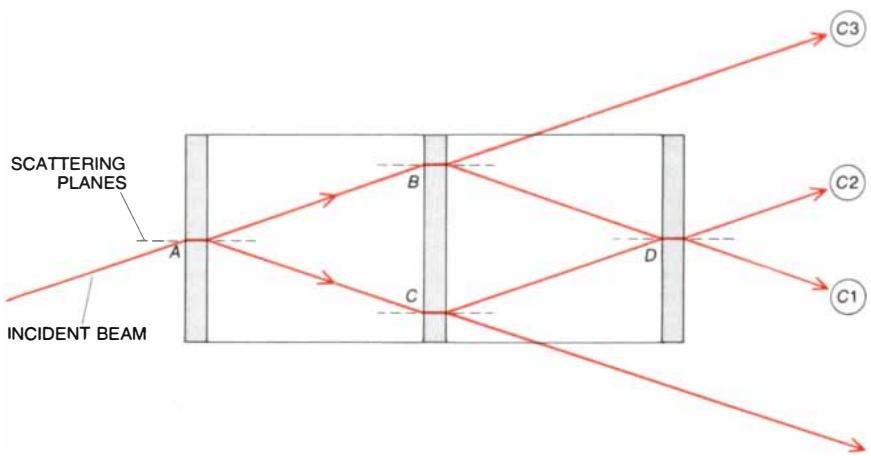
Although the interference of neutron waves is similar to the interference of light waves, there are some significant differences between the two kinds of waves. When the neutron is regarded as a "classical" pointlike particle, that is, a particle whose behavior can be approx-



LAUE AND BRAGG SCATTERING are the two ways a beam could be scattered by the planes of atoms that make up a crystal. In Laue scattering (*left*) if the angle of incidence is the correct one, the incident beam (*I*) will be scattered off planes perpendicular to the crystal face. The correct angle is named the Bragg angle (θ), which is defined by the ratio of the wavelength to the spacing of the atomic planes. The result is a transmitted beam (*T*) and a diffracted one (*D*). This kind of scattering takes place in the neutron interferometer discussed here. In Bragg scattering (*right*) an incident beam of the appropriate Bragg angle is scattered off planes parallel to the crystal face. The result of the scattering is a transmitted beam and a reflected one (*R*).

imately explained by laws of physics known before the emergence of quantum mechanics, it has no wave properties. Those properties can be explained only by quantum-mechanical laws. Since the wavelength of the neutron is determined by Planck's constant, which never enters into classical physics, all interference effects necessarily involve quantum-mechanical processes. Light, on the other hand, is classically a wave, so that its wave properties do not call for a quantum-mechanical interpretation.

The neutron has a mass and a magnetic moment, whereas the photon (the quantum of electromagnetic energy) has neither. This means that a magnetic field will cause a neutron to rotate but will not affect a photon. It also means that the neutron interacts much more strongly with gravity. Although light waves can be bent by gravity, in a light-wave interferometer the effect is negligible. The effect of gravity on the phase of the neutron waves, however, is measurable. The length of light waves is 10^{-5} centimeter, and since the length of the neutron waves in the neutron interferometer is 10^{-8} centimeter, they can resolve effects on a smaller scale.



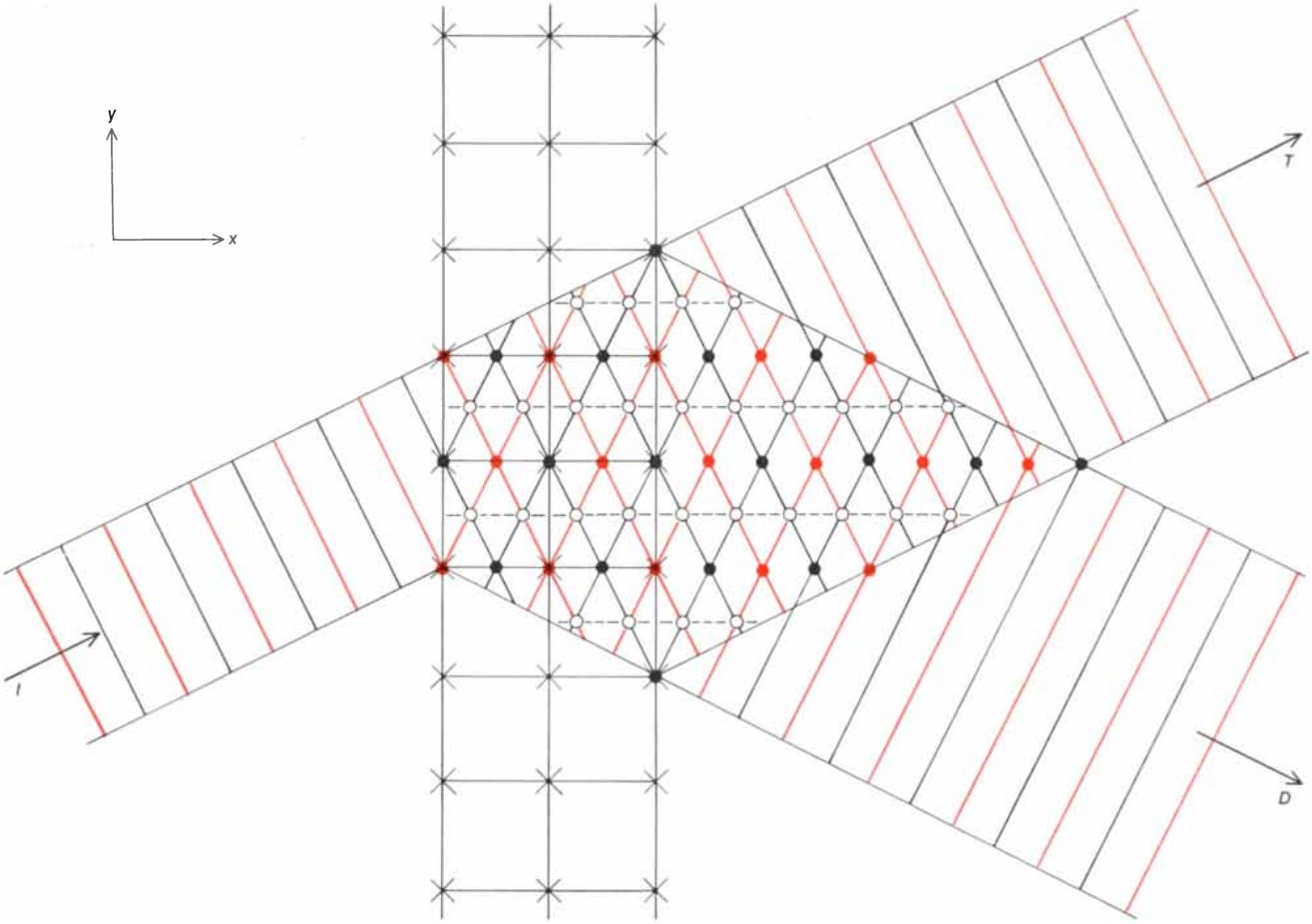
TOP VIEW OF THE NEUTRON INTERFEROMETER shows how an incident beam of neutrons is Laue-scattered by the first ear and then again by the second ear. At the third ear the beams are recombined and scattered into two neutron counters (*C1 and C2*). The third counter (*C3*) monitors the original beam. The relative phase of the two diffracted beams (*ABD v. ACD*) determines the counting rates. If the entire exit beam were striking counter *C1*, a relative phase shift of half a wavelength between the diffracted beams would redirect the exit beam completely to counter *C2*. Inside each ear the neutron beam propagates perpendicularly to the face of the crystal (the Borrman effect) and splits into two beams only on leaving the crystal.

The most important experiment that has been done so far with the neutron interferometer measured the effect of the earth's gravity on the phase of the neutron wave. The experiment was carried out by Roberto Colella of Purdue University, one of us (Overhauser) and Samuel A. Werner of the Ford Motor Company; it is therefore referred to as the COW experiment. The gravitational field was introduced by tilting the interferometer so that the two neutron beams were at different heights. Before the COW experiment was done in 1975 it was already known experimentally that the neutron falls in the earth's gravitational field as any other massive particle does. That fall, however, is strictly Galilean, or classical. The question is whether one can observe an effect of gravity on the wave nature of the neutron. The way to do this is through an interference effect, for which the neutron interferometer is ideally suited (provided the effect is large enough to detect).

The gravitational force is extremely weak at the atomic level. In the macroscopic domain the gravitational force is predominant because of the accumulated gravitational effects of a vast number of particles. Gravity at the surface of the earth is generated by the 10^{52} protons and neutrons that make up the earth. The electric repulsion between two protons is 10^{36} times greater than their gravitational attraction. Two protons the typical atomic distance of 10^{-8} centimeter apart exert an electric force on each other that is 10^{16} times greater than the gravitational force exerted on either of them by the entire earth.

If gravity is so weak on the atomic scale, how can it cause interference effects in the neutron interferometer? The answer is that such effects can be made to show up because of the ability of the neutron interferometer to compound interference effects over macroscopic distances.

The wavelength of a neutron wave entering the crystal at the appropriate angle is matched to the lattice spacing of 10^{-8} centimeter, so that each time the wave passes a plane of atoms it has



BORRMAN EFFECT in the neutron interferometer is that a beam unexpectedly travels through an entire ear in a direction perpendicular to the crystal face before it splits into a transmitted component and a diffracted component. The Borrman effect is seen only in perfect crystals. The crystal acts as a waveguide: multiple Laue scattering generates a standing-wave pattern in the *y* direction whereas the *x* component of the incident wave flows in the *x* direction. (A standing wave is a wave in which the antinodes and the nodes are stationary.) The flow of energy in the crystal is chiefly in the *x* direction parallel to the scattering planes. The standing-wave pattern has antinodes (*solid dots*) along the lines of atomic nuclei (*crosses*) in the scattering planes, and so it interacts strongly with the silicon crystal. There is another coherent wave with nodes (*circles*) at the scattering nuclei, so that this wave interacts extremely weakly with the silicon crystal.

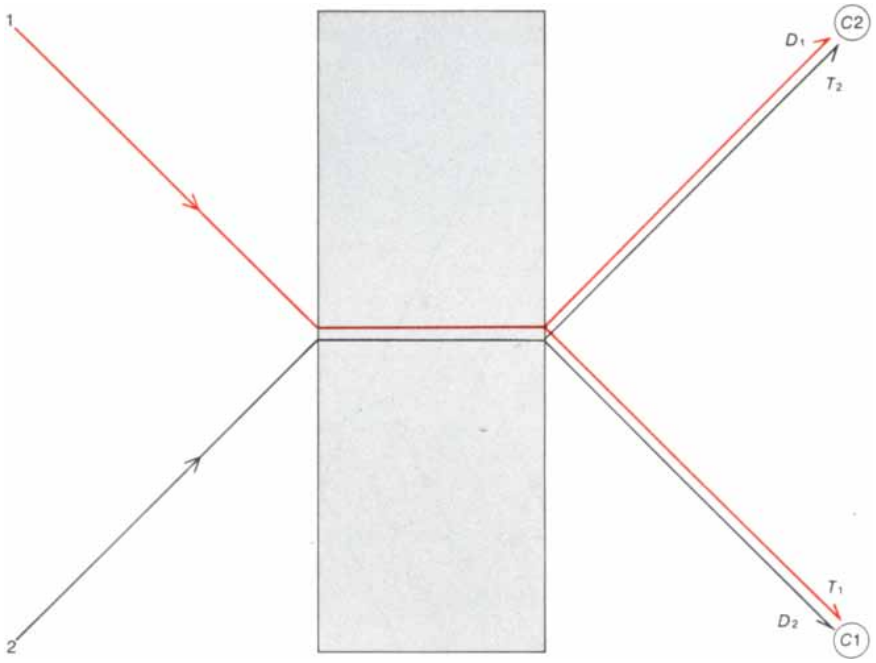
gone through one oscillation. The gravitational potential-energy difference between two components of a neutron beam spaced 10^{-8} centimeter apart is 10^{15} times smaller than the kinetic energy. Even if the neutron wave function is kept coherent over a height difference of a centimeter (as can be done in the interferometer), the gravitational potential-energy difference between the two beams is 10^{7} times smaller than the kinetic energy, so that normally this energy difference would have a negligible effect on the wave function of a neutron wave.

The wave, however, is coherent over the entire 10-centimeter length of the crystal, and over that distance it oscillates 10^{9} times. The rate of oscillation that is accountable to gravity is 10^{7} times smaller, but in the course of the neutron wave's trip across the crystal it manages to oscillate as many as 100 times extra because of gravity. As weak as gravity is, it has a measurable effect on the wave function because the neutron wave is coherent on a macroscopic scale.

The way to measure the effect is to first pass the neutron beam through the crystal when the crystal is horizontal. In that situation the two split beams in the interferometer are at the same height and there is no gravitational effect. Next the interferometer is rotated about the incident beam to put the split beams at different heights and hence at different gravitational potentials. As the height difference increases so does the difference in phase, which shows up as a difference in the relative number of neutrons counted by the two detectors. In the COW experiment gravity gave rise to as many as 20 extra oscillations, and in an improved version of the experiment the phase difference accountable to gravity was verified to well within 1 percent.

This phase difference had to be separated from a classical side effect of gravity. Gravity also pulls on the crystal, and so as the crystal is rotated to put one neutron beam above the other, gravity slightly distorts it, which in turn affects the relative phase of the beams. Fortunately this classical effect can be effectively monitored with a beam of X rays. Moreover, by inserting into one of the neutron beams an aluminum strip .002 inch thick the investigators induced an extra phase shift of a quarter of an oscillation. This known effect served as an experimental control to verify that neutrons were not repelled by the earth but attracted by it.

The experiment demonstrated that a weak gravitational field shifts the phase of a neutron wave by the precise amount predicted by the Schrödinger equation. In other words, gravity appears in the equation as any other force would. This result was fully expected. It nonetheless had distinct implications for the interpretation of the equivalence



COUNTING RATE of a counter (*C1 or C2*) depends on the phase relation between the two partial beams that enter it. As the two beams (*1 and 2*) that entered the third ear of the crystal emerge from it, they each split into a transmitted component (*T*) and a diffracted component (*D*). Each counter receives the transmitted component of one beam and the diffracted component of the other beam. If a small applied force causes the phase of one of the beams, say *2*, to be shifted in relation to the other one by an angle ξ, then the transmitted component (T_2) will also be shifted by ξ, and the diffracted component (D_2) will be shifted by ξ plus 180 degrees, making the components out of phase. As a result the counting rate of one of the detectors will increase and the counting rate of the other detector will decrease, although the sum of the two counting rates will remain the same because each neutron must go into one of the detectors.

principle in quantum mechanics, which we shall discuss below. For now we shall note that Colella and one of us (Overhauser) have shown that the experiment verifies that the equivalence principle applies on the microscopic scale governed by the laws of quantum mechanics.

Imagine an observer falling toward the interferometer with the acceleration of gravity. To him a neutron in the interferometer would not be falling at all, since he is falling with it. He would see the neutron moving in a straight line between collisions with the ears of the interferometer. He would also see the ears accelerating upward. What this means is that he sees a neutron in one split beam approaching the second ear at a certain velocity and a neutron in the other split beam approaching the ear at a different velocity. The velocity difference causes the neutron beam to shift in frequency. This is the familiar Doppler shift: an observer approaching a wave sees the crests arrive sooner, so that he observes a higher frequency, whereas an observer receding from a wave sees a lower frequency.

We have done a detailed analysis in the coordinate system of the accelerated observer and have proved that the overall phase shift he sees is the same as the phase shift produced by gravity in the interferometer system. In other words, if one accepts that the Schrödinger equation works for a free particle, one has only to apply it to the case of a beam meeting an accelerating crystal and one will have proved that this case is equivalent to the case of a falling beam meeting a stationary crystal. The argument applies to what is called the strong form of the equivalence principle, a point we shall also take up below.

There is another interpretation of the COW experiment that is extremely interesting. According to the general theory of relativity, a gravitational field affects the rate of a clock. In a weak gravitational potential the time difference (Δt) that accumulates between two clocks in a time t is $\Phi t/c^2$, where Φ is the gravitational potential difference between the clocks and c is the speed of light. The entire interference effect in the COW experiment can be attributed to the difference between the time on a clock moving along with one beam and the time on a clock moving along with the other beam.

The time difference, which is due entirely to the gravitational potential difference of the clocks as they move through the interferometer at different heights, is the famous gravitational red shift Albert Einstein predicted in 1916 in his original paper on the general theory of relativity. Unfortunately although this interpretation is very suggestive, it is not necessary, because the effect can be explained by nonrelativistic quantum theory in which gravity is treated as an ordinary force without appealing to relativity at all.

We now turn to two other elegant experiments that have been done with the neutron interferometer. The first is based on the fact that the interferometer is rotating with the earth as the neutron beam passes through it. (The beam itself is free of the earth between collisions with the ears.) This rotation, like gravity, affects the phase of the beam, although the slow angular velocity of one rotation every 24 hours results in an effect on the interferometer beam of only about 2 percent of the gravitational effect. This small effect was nonetheless detected by Colella, Werner and J.-L. Staudenmann of the University of Missouri with a sensitive interferometer made accurate to 10^{-4} centimeter by an optically controlled milling device with a diamond saw.

The experimenters were able to separate the weak effect of gravity from the even weaker effect of rotation by passing the two beams vertically through the interferometer so that gravity would affect them equally and hence leave their relative phase unchanged. This experiment, which is the quantum-mechanical version of one done by G. Sagnac in the early part of the century, verified the applicability of the Schrödinger equation to an experiment actually carried out in an accelerating coordinate system. Incidentally, it provided an esoteric quantum-mechanical demonstration of the Copernican theory that the earth rotates, for those who still have a lingering doubt.

The other experiment with the neutron interferometer, done independently in 1975 by a group in the U.S. and a group in Europe, confirms an amazing but straightforward prediction of quantum mechanics. According to quantum theory, if a neutron (or any other particle with a half unit of "spin," or intrinsic angular momentum, such as the electron or the proton) is rotated 360 degrees, the sign of the wave function of the particle is reversed. In classical physics, of course, an object that has been rotated 360 degrees is in exactly the same geometrical state it was in before it was rotated. The sign reversal is possible in quantum mechanics because experimental results depend only on the square of the wave function.

Here the neutrons were made to rotate 360 degrees by passing one beam in the interferometer through a magnetic field. If the beams interfere constructively before the field is turned on, they interfere destructively after it is turned

on, and vice versa. The neutron must be rotated 720 degrees for it to be unaffected by the rotation. This result, which runs completely counter to classical intuition, is a perfect example of what Eugene P. Wigner has called the "unreasonable effectiveness" of abstract mathematics in its ability to predict physical phenomena. Nevertheless, the consequences of rotation had been indirectly verified many times because the effect of a rotation on a wave function enters into many experiments. Although it was important to demonstrate this effect directly, the outcome was never in doubt. The COW experiment broke new ground because never before had a gravitational field affected the specific wave properties of a particle in a quantum-mechanical experiment.

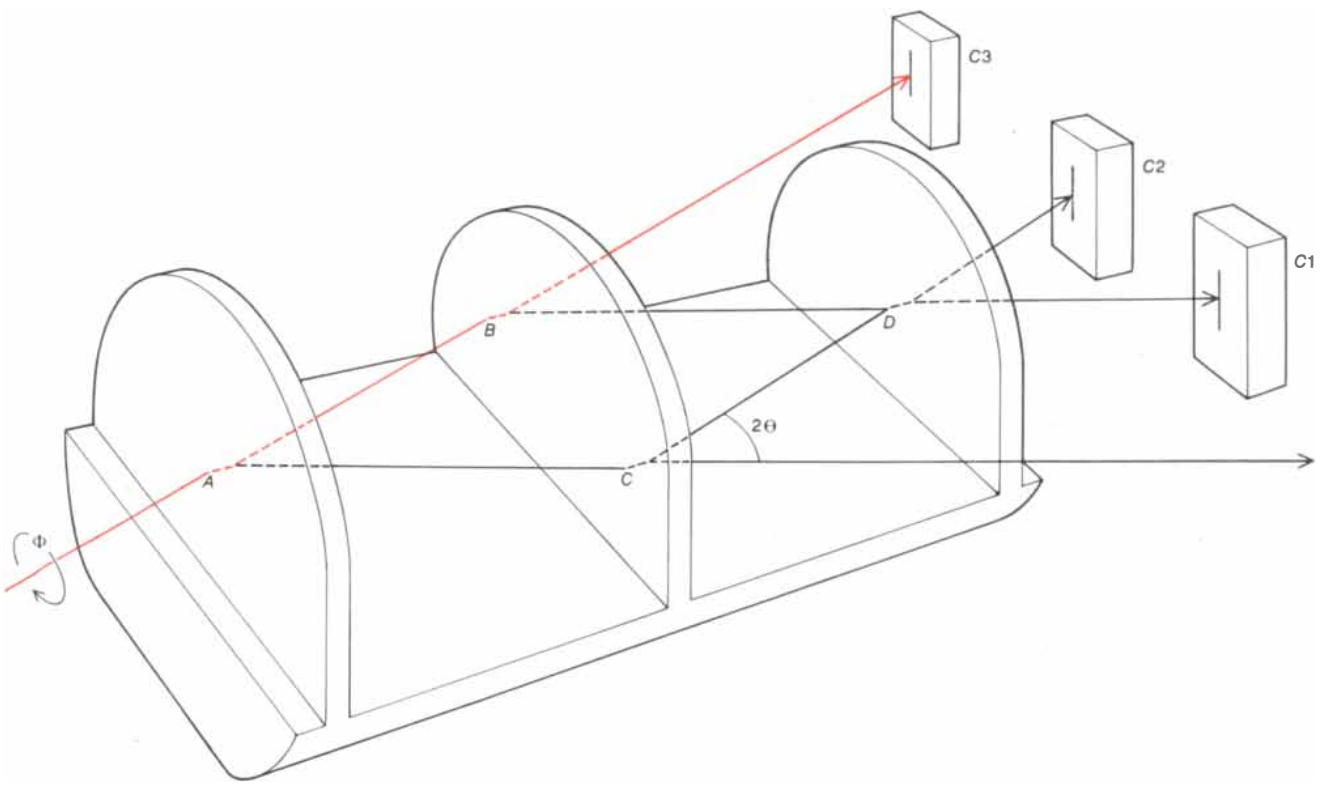
In order to assess the significance of the COW experiment one must consider gravity's relation to the other three natural forces: the strong nuclear force, which holds the nucleus together, the electromagnetic force, which binds atoms and determines chemical structure, and the weak nuclear force, which is responsible for most nuclear decays. It is known that gravity controls the large-scale structure of the universe, even though it is extremely weak on the microscopic level. It was Einstein's dream to unify large- and small-scale phenomena in one grand theory. Until a few years ago, however, there was no discernible experimental connection between them.

Each of the four forces of nature known today has a different strength and operates on a different scale. And yet it has recently proved possible to construct a unified theory of the weak nuclear force and the electromagnetic force. Michael Faraday, James Clerk Maxwell and Einstein developed a superstructure in which electricity and magnetism were two aspects of the same phenomenon. It is now recognized that the weak interaction is a third aspect of the same phenomenon, which would become apparent at extremely high energies. Last year's Nobel prize in physics honored Sheldon Lee Glashow and Steven Weinberg of Harvard University and Abdus Salam of the International Center for Theoretical Physics in Trieste for recognizing this relation. Their work is the first step toward the discovery of a "philosopher's stone," which would uncover a harmony in nature beyond anything ever dreamed of by the ancient alchemists. There is some indication that the strong force could be incorporated into such a theory and a few clues that even gravity might be incorporated.

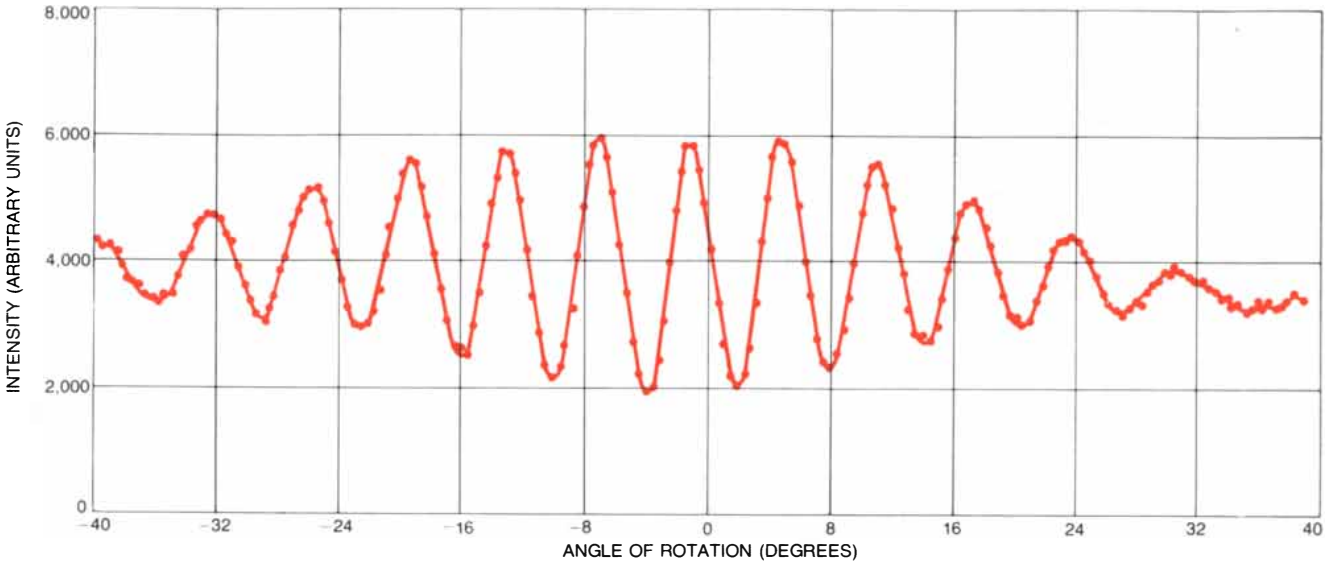
We want to point out, however, that there are good reasons for maintaining an attitude of open-minded skepticism about the role of gravity in any unification scheme put forward so far. For example, if the basic laws of quantum mechanics apply to situations dominated by gravitational fields, the phenomena they predict would be difficult to interpret. Consider a neutron with mass m bound gravitationally to a particle with mass M by the Newtonian force GmM/r^2, where G is the gravitational force constant and r is the distance between the particles. This situation is formally identical with the one in which an electron and a proton are bound electrically by the Coulomb force e^2/r^2, where e is the charge of the electron.

The energy and the separation of the two particles in their smallest orbits around each other can easily be calculated by quantum theory. The electrical case is the familiar Bohr atom, and the gravitational case is found by replacing e^2 by GmM. For neutrons attracting each other this procedure yields an almost inconceivably low energy and an almost inconceivably large separation of 10^{25} centimeters, which is close to the size of the universe. Such ludicrous numbers raise the question of whether the concept of wave coherence, or for that matter of a wave function, makes sense in this connection.

Moreover, according to quantum theory, gravitational fluctuations would be-



DIFFERENCE IN HEIGHT between beams in the interferometer is introduced by rotating the apparatus about the incident beam (*AB*). This gives rise to a gravitational potential difference between the beams, which alters their phase. This alteration shows up as a change in the count of the detectors, which is a measure of the effect of gravity on the quantum-mechanical wave properties of a neutron.



READING OF THE FIRST DETECTOR as a function of the angle of rotation of the neutron interferometer is shown for a typical data run. The reading never falls to zero because the two beams are not perfectly coherent. This data run is from an improved version of the original neutron-interferometer experiment, which verified the phase shift due to gravity to well within 1 percent of the predicted value.

come significant only at dimensions of about 10^{-32} centimeter, a fantastically small scale with respect to anything that is currently known. An extrapolation down to 10^{-32} centimeter would be an even greater transition than the one from the macroscopic scale to the nuclear scale that led to the development of quantum mechanics and altered completely the accepted picture of how nature operates.

These considerations are not meant to dismiss current thinking on how quantum theory applies to gravity but merely to indicate that caution is clearly called for. Since the numbers are so outlandish, there is no reason to take for granted the theory that predicts them. At every stage in its development the theory will have to be tested experimentally, but whenever it correctly predicts a phenomenon, a significant intellectual victory will be won. Before the COW experiment there was no reason to be complacent about the correctness of the current picture of quantum gravity, even on the level of very weak gravitational fields acting as small perturbations.

One still should not be complacent, because there is a deep conceptual problem caused by the difference between the usual theoretical treatment of classical gravitational phenomena and that of quantum-mechanical phenomena. The difference is based on the role played by mass in the two kinds of phenomena. Galileo observed that all bodies fall with the same acceleration in an external gravitational field. Here "external" means that the bodies themselves are too small to contribute measurably to the field. Robert H. Dicke of Princeton University has called this observation the weak equivalence principle to distinguish it from a stronger formulation we shall discuss below.

From the viewpoint of classical physics in discussions of equivalence one thinks of releasing a particle with some initial position and velocity. Gravity then gives the particle a definite acceleration. If a particle with a different mass was released with the same initial position and velocity, it would follow the same trajectory because the acceleration due to gravity is independent of the particle's mass. To put it another way, the position and the velocity are the natural variables for discussing the problem because the mass has no intrinsic role. In fact, the problem can be reformulated so that the mass drops out.

Einstein recognized the significance of Galileo's observation. He realized that since all particles that start with the same position and velocity follow the same path, there is no input from the nature of the particle itself. The motion of a particle in a gravitational field depends only on its environment, that is, only on the properties of space and time. To explain why all particles follow the same curved trajectory Einstein replaced the concept of an external gravitational field with the concept of a curved space-time. The theory of gravity is in effect reduced to a branch of geometry.

From the viewpoint of Einstein's theory a particle is said to obey the geodesic equation: the particle takes the "shortest" path in the curved space-time. The geodesic equation replaces the classical law of inertia: free particles in flat space tend to travel in a straight line, which is of course the shortest path in flat space. Like Galileo's observation, Einstein's formulation speaks not of mass but of position and velocity. We can summarize this point by introducing the geometrical weak equivalence principle, which holds classically. The principle states that there are no physical effects at all in an external gravitational field that depend on the mass of a point particle.

A more general formulation can be achieved by replacing the geometrical weak equivalence principle with the strong equivalence principle. This principle states that as far as the locally observed laws of physics are concerned, being at rest in a gravitational field is equivalent to being at rest in an accelerated coordinate system. The strong equivalence principle not only indicates why all objects must fall with the same acceleration in a gravitational field but also provides a powerful tool for incorporating the gravitational field into a physical system. If it is known how a system behaves in the absence of a gravitational field, the strong equivalence principle provides a way of determining how the system will behave in the presence of a field. All one has to do is to transfer the system to an accelerated coordinate frame, which is equivalent to introducing a gravitational field.

The general theory of relativity specifies the mathematical procedure for making this transformation and for distinguishing in a higher order the difference between real gravitational fields and the effects of acceleration. For example, once the Schrödinger equation is known for the case with no gravitational field it can be written for the case with a gravitational field. It was the strong equivalence principle that the COW experiment confirmed.

Everything we have said so far about gravity seems to be purely geometrical. Yet surprisingly it turns out that the result of the COW experiment is incompatible with the geometrical weak equivalence principle because interfer-

ence effects in quantum mechanics depend on the mass. It is only in taking the average values of the trajectory parameters that the mass drops out. How, then, does the mass enter the quantum-mechanical picture? The answer lies in the quantization procedure itself. This is the conceptual problem that we alluded to above.

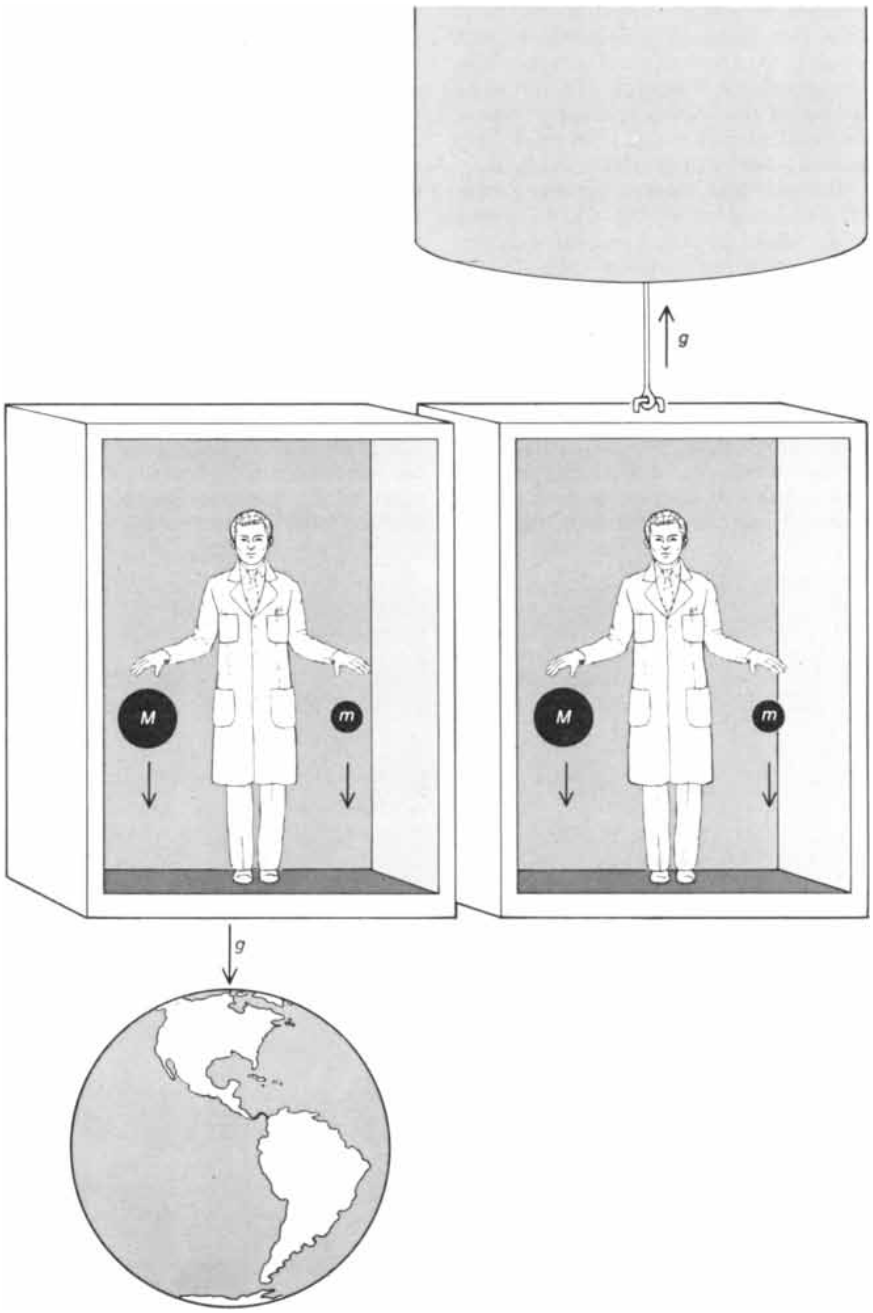
The energy of a photon is equal to Planck's constant (h) times the frequency (f). This equation goes back to Einstein's work of 1905. Although the equation is quite simple mathematically, it is quite deep physically because it connects two disparate concepts. The frequency is a specific wave property, whereas the energy is a dynamical feature that can be measured when matter absorbs or emits a photon. The equation for the energy is equivalent to the statement that the photon's momentum (p) equals Planck's constant divided by the wavelength (λ).

It was Louis de Broglie who applied the formula $p = h/\lambda$ to define the wavelength of the waves that quantum mechanics attributes to ordinary matter. Like the energy formula $E = hf$, the momentum formula connects a wave property, the wavelength, to a dynamical one, the particle momentum. The interference between matter waves, which is an essential part of quantum mechanics, is the phenomenon that underlies the neutron interferometer. Since the wavelength of a neutron depends on the momentum, which is equal to the mass times the velocity, it depends on the mass as well. This means that from the outset the mass is incorporated into the wave nature of the neutron. In other words, the importance in quantum mechanics not of velocity but of mass times velocity has deep theoretical roots as well as having been securely established by experiment.

In a sense the question of the relative importance of velocity and momentum goes back to the different approaches of Galileo and Newton to mechanics. Galileo observed that all objects are equally accelerated by gravity. His intellectual heir is Einstein, who put the observation in geometrical terms. On the other hand, Newton recognized that accelerations are caused by forces that change momenta, which depend on mass. Only in the case of gravity does the mass drop out.

In the 1820's William Rowan Hamilton reformulated Newton's laws of mechanics so that they expressed the laws of mechanics in a way that did not depend on the particular coordinate system chosen to describe the problem. The formulation highlights any underlying symmetries that may be present. Hamilton himself was aware that his formalism expressed a powerful analogy between particle phenomena and wave phenomena, an analogy that Schrödinger exploited 100 years later in developing quantum mechanics when the experimental facts demanded it. The formalism has as its basic variables the momentum and the position, and it meshes perfectly with de Broglie's work. As a result quantum mechanics predicts that all phase-dependent phenomena, whether or not they are in a gravitational field, depend on the mass through the wavelength. This feature is intrinsic to quantum mechanics.

Quantum mechanics makes clear-cut predictions about the effects that will be seen in a weak gravitational field such



CLASSIC ELEVATOR "THOUGHT" EXPERIMENT, developed by Albert Einstein, demonstrates the strong equivalence principle: The effect of being at rest in a gravitational field (*left*) is the same as the effect of being at rest in an accelerated coordinate system (*right*). At the left a man in an elevator in outer space experiences a real gravitational field due to a large mass that is near him, and so he feels himself pulled down toward the floor of the car. If he drops simultaneously a small mass (m) and a large mass (M), they will fall with the same acceleration g and therefore reach the floor at the same time. Now imagine instead that the gravitational field has been replaced by a rocket that pulls the elevator upward with a uniform acceleration g (*right*). The man will still feel himself pulled down toward the floor of the elevator with the same force. When he releases the two masses, they will maintain a constant upward velocity, although the elevator floor is rising with acceleration g to meet them. As a result they appear to be falling with acceleration g, as they did in the gravitational field. Therefore the man in the elevator cannot tell the difference between the situation at the left and the one at the right.

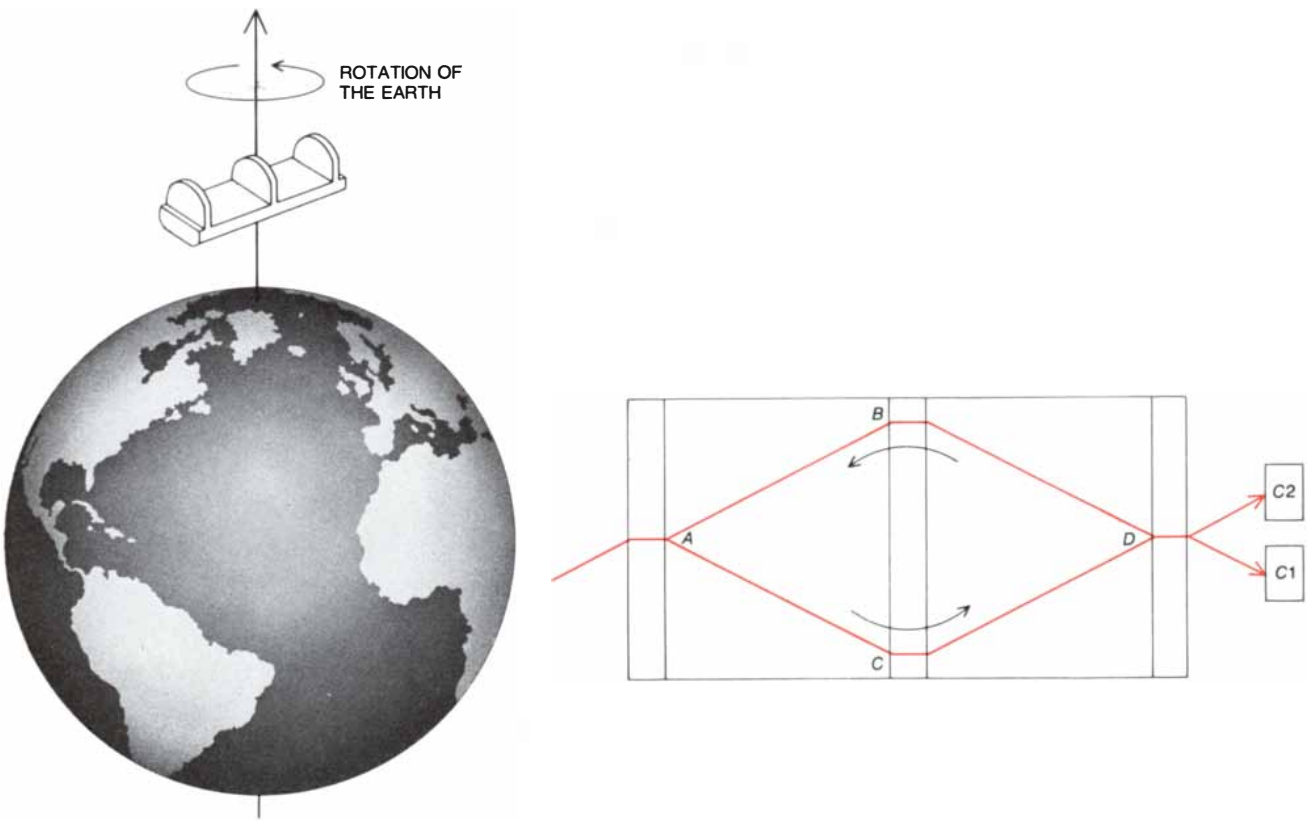
as the one in the COW experiment. The classical gravitational approach, however, is geometrically formulated not in terms of position and mass but in terms of position and momentum, and so the two theories do not speak the same language. The two great traditions, the geometrical one of Galileo and the dynamical one of Newton, seem to have been heading in different directions for three centuries. Suddenly they confront each other in the application of quantum theory to gravity. Therefore it is not at all trivial for the COW experiment to have demonstrated that quantum mechanics actually works in gravitational fields.

For example, without the experimental confirmation of the COW experiment would it really be so obvious that the correct gravitational potential to add to the Schrödinger equation is simply the classical one? In classical physics the potential has a form that guarantees the mass will drop out of the problem. In quantum mechanics, however, such is not the case. For example, in a gravitational Bohr atom, where a particle of mass m is bound to a much heavier particle of mass M, the radius of the lowest quantum state is a function of the mass m. This means that m can be determined from a measurement of the particle's radius in this state. The mass disappears only for average values over states that have extremely high quantum numbers, which behave in an essentially classical manner.

Since quantum mechanics contradicts the geometrical weak equivalence principle, with its requirement that the mass drop out of the problem, it was important to test the Schrödinger equation in an experiment where gravitational forces were present. The test was necessary even though the Schrödinger equation has proved to be enormously successful for nongravitational problems. The COW experiment was this test, and it demonstrated convincingly that the Schrödinger equation works in the presence of gravitational fields.

Since the phase shift depends on mass even in the case of a gravitational field, it seems in retrospect almost accidental that the mass drops out of the classical gravitational equations. Weinberg has emphasized that most of the features of the gravitational field can be derived from its mathematical symmetry properties, as is true for any other field in quantum theory. This interpretation tends to bother theorists who prefer to think of gravity as being intrinsically related to geometry. Nevertheless, since the COW experiment confirms the applicability of quantum mechanics even in the presence of gravity, including the nongeometrical mass dependence, the experiment seems to be a step in the undermining of the purely geometrical point of view.

Yet one strange feature of all of this is that in most cases where a symmetry manifests itself in a classical theory, the quantum version of the theory tends not to eliminate the symmetry but to greatly strengthen it. The failure of the classical geometrical conception of gravity in the realm of quantum mechanics would run counter to this trend. Perhaps, then, nature still has some major surprises in store for physicists before they finish the task of smoothly joining the theory of gravity and the theory of quantum mechanics. Einstein once said, "Nature is subtle, but she is not malicious." Unfortunately it sometimes takes a great deal of hindsight to appreciate the distinction.



EFFECT OF THE EARTH'S ROTATION on the interference pattern of neutron beams (the Sagnac effect) is best understood by imagining the neutron interferometer to be at the North Pole (*left*). As the earth rotates, the interferometer rotates with it. The neutron beam, however, travels in a straight line between collisions with the interferometer ears because it is not attached to the rotating earth. An overhead view of the interferometer (*right*) shows that the rotation causes one side (C) to move away from the beam and the other side (B) to move toward the beam. These different relative velocities will give rise to a shift in frequency between the two components of the split neutron beam. This is the familiar Doppler shift. The net result is that the interference pattern of the neutron beams is shifted by the rotation of the earth. The magnitude of the shift is different at other latitudes on the earth, although the underlying mechanism is the same.

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*At least we suppose so. Insufficient real time has rolled by to speak from experience.

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SCIENCE AND THE CITIZEN

Political Problem

After more than two years of study the 66 nations that took part in the International Nuclear Fuel Cycle Evaluation (INFCE) have finished their examination of current and proposed reactor systems, nuclear-fuel cycles and waste-management problems stimulated by the fears expressed by President Carter three years ago: that the spread of nuclear material usable for weapons resulting from the growth of civilian nuclear-power programs threatens to place nuclear weapons within the reach not only of more nations but also of determined terrorists. In order to emphasize his concerns about nuclear proliferation President Carter announced in April, 1977, that the U.S. would forgo the reprocessing of spent nuclear fuel and restrain the development of reactors designed to breed plutonium. Moreover, he declared, the U.S. would not approve the export of enrichment or reprocessing technology to other countries. The INFCE was subsequently organized to consider the issues the President had raised.

Inasmuch as several European nations were heavily committed to reprocessing and breeder development it is remarkable that the reports of the working groups, eight in all, were issued without separate or dissenting views. There was, first of all, agreement with the U.S. statement (which had originally been questioned by some) that it is possible to use the plutonium produced by power reactors to build nuclear weapons even though it contains undesirable isotopes of the synthetic element. The isotope preferred for weapons is Pu-239. Power-reactor plutonium incorporates substantial amounts of certain isotopes (particularly Pu-240 and Pu-242) with such a high rate of spontaneous fission that they would tend to initiate a chain reaction prematurely and make the yield of a weapon unpredictable.

The report implicitly concedes that unpredictability alone is not an adequate deterrent to the diversion of power-reactor ("commercial grade") plutonium for weapons. The report states, however, that "the use of commercial-grade plutonium is an unattractive route to the manufacture of nuclear weapons as compared with weapons-grade plutonium produced by a dedicated program." It further observes that "a decision by a government to construct nuclear weapons is obviously a political decision motivated by political considerations that are beyond the scope of this study."

The 519 experts who held 61 meetings focused much of their examination on conclusions previously reached by a U.S. study group that stimulated President Carter's original pronouncement. U.S. representatives to the INFCE advanced three main theses: that certain fuel cycles promise to be inherently more resistant to proliferation than current fuel cycles are, that uranium reserves are large enough so that it is unnecessary to recycle the plutonium and uranium in the spent fuel from conventional reactors, and that the commercialization of breeder reactors can be postponed for the same reason. In support of these propositions the U.S. also argued that the reprocessing of spent fuel would not be economic (at least in the absence of breeders) and that spent fuel containing plutonium would be no more difficult or hazardous to store than reprocessed wastes from which most of the plutonium had been removed.

The U.S. won least support on the first proposition and ultimately agreed (after "swallowing hard," according to one American observer) that "no single judgment about the risk of diversion from different fuel cycles can be made that is valid both now and for the future." This conclusion was reached after a study of 22 reactor types and their fuel cycles.

On the question of uranium resources and the lack of a need for recycling plutonium the U.S. won limited support. In the absence of information from the U.S.S.R., from other countries of eastern Europe and from China, the INFCE was obliged to limit its projections of future demand for nuclear power to what it calls the "world outside the centrally planned economies area" (WOCA). The installed nuclear capacity within WOCA today is about 125 gigawatts electric, or GW(e). This corresponds to somewhat more than 125 nuclear power plants, since many early plants are smaller than the current typical size of 1 GW(e) (1,000 megawatts). For the year 2000 the INFCE projections of nuclear generating capacity within WOCA range from 850 to 1,200 GW(e) and for the year 2025 from 1,800 to 3,900 GW(e). The American representatives proposed much lower figures, but went along with the higher projections. The corresponding demand for uranium was judged to range from 90,000 to 160,000 tons per year in 2000 and from 75,000 tons (following the introduction of breeders) to 430,000 tons per year in 2025.

The study estimates that the uranium industry should be able to meet annual requirements up to the year 2025 for the low-growth projections even without recovery of plutonium from spent fuel, the "once through" strategy. If, however, nuclear capacity conforms to the high-growth projections, the uranium industry cannot hope to achieve annual supply levels beyond the year 2000 if a once-through strategy is generally adopted. The working group on fast breeder reactors calculates that if breeders, which create more fissionable material than they consume, are developed vigorously, the amount of uranium required by 2025 could be reduced "by at least a factor of four, on either the high or low projections of nuclear power demand." The INFCE report concludes that "countries with nuclear power programs will wish to have available robust policy options [meaning breeders] affording some protection against the possibility that uranium, at some time in the future, will become effectively unavailable."

The economics of the breeder reactor was hotly debated. The U.S. argued that breeders, even after development, will cost from 25 to 75 percent more than light-water reactors of the same capacity. The report concedes that "a new level of technology is required for breeder development and [that] costs will be high for a national program." It observes, however, that if breeders are introduced on a substantial scale, they will not only extend the supply of uranium but also help to hold down its price. As for the economic choice among once-through light-water reactors, light-water reactors with the recycling of plutonium and breeder reactors with the recycling of plutonium, the report concludes that "no one fuel cycle can be said to have an economic advantage in all cases."

The groups studying spent fuel and waste management saw no insurmountable barriers to safely storing high-level wastes with or without the presence of plutonium and in effect supported the U.S. position. The report emphasizes that the major environmental and health hazard in nuclear power is not in the reactor wastes but in "the natural radioactivity in mill tailings from uranium mining operations and from the uranium 238 that for certain fuel cycles is emplaced in an underground repository. As a consequence the radiological impact of waste management is mainly correlated with uranium demand and is largest for the once-through fuel cycles and smallest for the [fast breeder reactor] cycles."

In summary the American representatives to the INFCE meetings can be pleased that the final report does not conclude that reprocessing is essential for the economical operation of light-water reactors, that it does not conclude that reprocessing is essential for waste management or for eking out uranium supplies and that it does not offer much of an economic case for breeder reactors. What the report does conclude is

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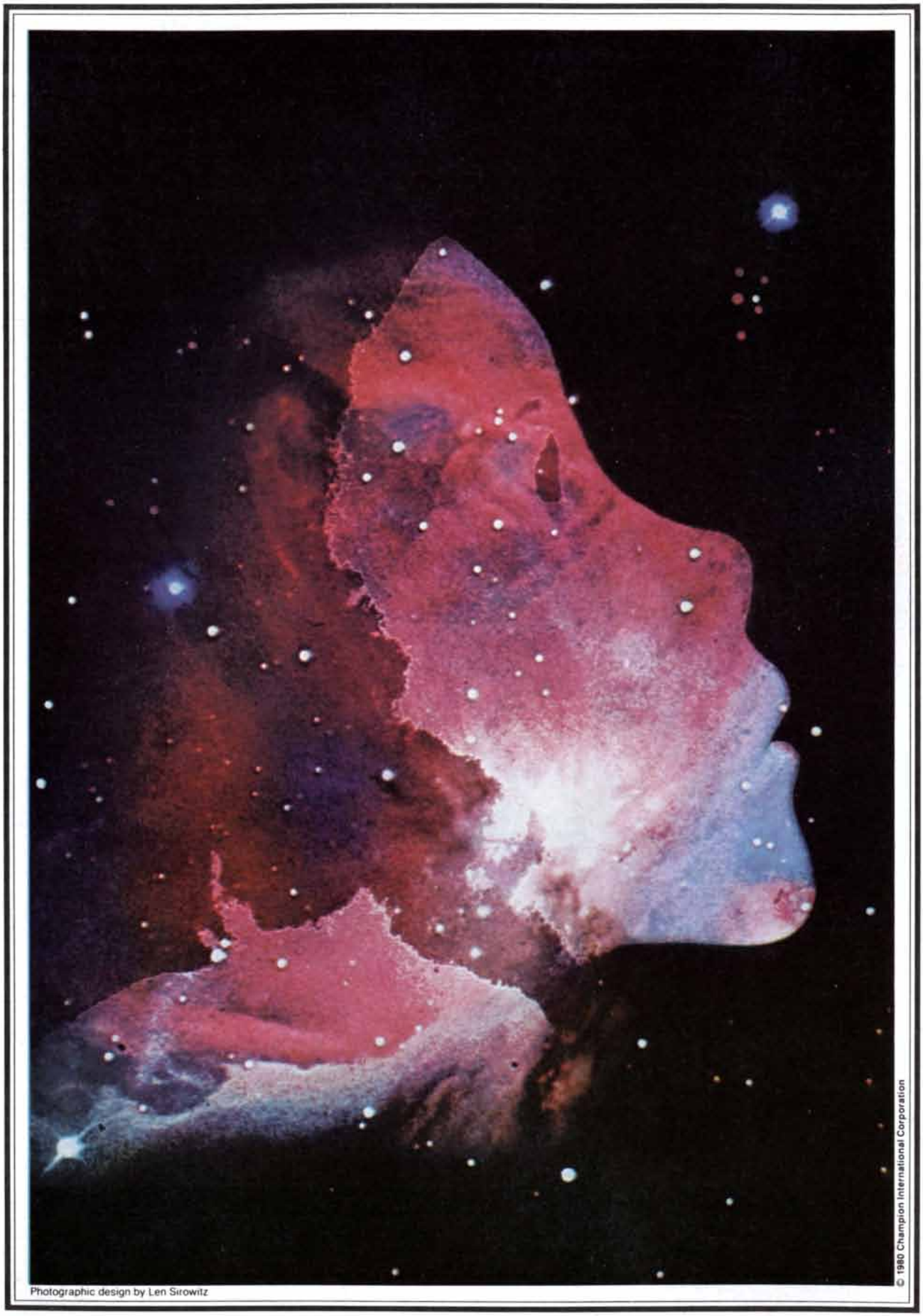

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While there is as yet no direct evidence of extraterrestrial life, complex organic molecules have been found throughout the universe. Man has landed space probes on only two planets—Mars and Venus—and the vital ingredient water was found on both of them.

Indeed, scientists have already derived a formula which strongly indicates that there must be many, many technological civilizations out there, and there are huge radio-telescopes trained on the skies, listening. So it should not come as a complete surprise if one day an astronomer looks up from a printout and reports that someone just said hello.

The benefits of an exchange of information could be enormous. They might give us short cuts that would save us a few hundred years of Research & Development. They might present us with practical fusion power which, so far, has eluded earth's scientists. (It could solve the energy shortage in a flash.) Is cancer universal? Progress report, please. And the cold? Is it really common?

There will also be a few problems. How will earthly religions handle the new facts? How will we manage to get along with an alien race that has a different culture, ethics, habits, expectations, rituals, and maybe even four arms, when sometimes we even have trouble getting along with the couple next door, not to mention other nations.

On the other hand, maybe these differences will teach us something fundamentally enlightening about differences, and we'll end up getting along better with each other here on earth. Just that would literally be a gift from the heavens.

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that the linkage President Carter perceived between the growth of civilian nuclear power and the proliferation of nuclear weapons cannot be broken by some clever choice of a new kind of fuel cycle. Weapons, it declares, are still a political problem.

Group Therapy

Few concepts in mathematics have proved more powerful than the concept of a group: a collection of objects or operations of unspecified character that can be combined in accord with a set of well-specified rules. Groups essentially describe different types of symmetry, and so the study of these abstract structures—the branch of mathematics called group theory—provides fundamental insights into such diverse fields as arithmetic, particle physics and crystallography. Because groups are such useful objects mathematicians have long sought to break them down, to identify the basic components of which all groups are composed. Early this year news of the long-awaited construction of two special groups, one by a mathematician at the University of Michigan and the other by a group of mathematicians at the University of Cambridge, brought group theorists closer to this goal. The groups, known as F_1 (or "the monster") and J_4, may be the last pieces in a jigsaw puzzle that has taken more than a century to put together.

The building blocks of group theory, analogous to the elementary particles of matter or the prime factors of integers, are called simple groups. Just as any integer can be uniquely expressed as a product of prime numbers, so any group can be uniquely represented as a "composition" of simple groups. To analyze groups, then, mathematicians would like to make a complete catalogue of all the different types of simple groups. In particular they would like to classify all the simple groups with a finite number of elements: the building blocks of finite groups.

There are some 18 infinite families into which most of the known finite simple groups fit. A few groups have been encountered, however, that not only do not belong to any of these families but also do not seem to form any family of their own. They are called the sporadic finite simple groups, and if there are infinitely many of them, then the efforts to classify the finite simple groups have all been in vain. Fortunately there is good reason to believe the number of sporadic groups is finite, and indeed many mathematicians believe the sporadics that have already been identified, a total of 26, complete the list of finite simple groups. In mathematics as in particle physics, however, the existence of an object can often be predicted long before it can be proved, and until quite recently only 24 of the sporadics had been con-

structed. At the beginning of this year two sporadic finite simple groups had yet to be constructed: F_1 and J_4.

The way mathematicians construct a group depends to a large extent on whether the group has a natural representation as the transformations of some geometrical object, for example the rotations of a polyhedron in space. If a group does not have such a natural underlying geometry, then its existence must usually be proved by a brute-force method that relies on extended computer calculations. This was the case with J_4, a group with 86,775,571,046,077,562,880 (or $2^{21} \times 3^3 \times 5 \times 7 \times 11^3 \times 23 \times 29 \times 31 \times 37 \times 43$) elements, whose existence was first predicted in 1975 by Zvonimir Janko of the University of Heidelberg. The Cambridge mathematicians who finally constructed the group (David Benson, John Horton Conway, Simon P. Norton, Richard Parker and Jonathan Thackray) first applied new theoretical techniques developed by Norton to establish that if J_4 did exist, it had to be generated, or built up, from a pair of 112-by-112 matrixes of binary digits (0's and 1's). Elaborate matrix calculations were then required in order to show that the group generated by the two matrixes was in fact J_4. These calculations were done by a computer program, which reached the desired result at 4:00 A.M. on February 20.

F_1, which was proposed independently in 1973 by Bernd Fischer of the University of Bielefeld and by Robert L. Griess, Jr., of the University of Michigan, lent itself to a different type of construction. In January, Griess, who is currently on sabbatical leave at the Institute for Advanced Study in Princeton, N.J., announced that he had constructed the group and that his construction had been carried out "entirely by hand," that is, without the aid of a computer. Griess has not yet made public the details of his construction, but it is widely believed he relied on a representation of F_1 as a group of rotations in a space of 196,883 dimensions.

F_1, the largest of all the sporadic groups, is a particularly interesting group. Called the monster because it has a staggering 808,017,424,794,512,875,886,459,904,961,710,757,005,754,368,000,000,000 (or $2^{46} \times 3^{20} \times 5^9 \times 7^6 \times 11^2 \times 13^3 \times 17 \times 19 \times 23 \times 29 \times 31 \times 41 \times 47 \times 59 \times 71$) elements, the group appears nonetheless to be a very natural structure. In particular it has embedded in it most (although not all) of the other sporadic groups. Moreover, although several of these smaller groups were constructed by means of a lengthy computer proof, Griess reports that their existence follows "almost trivially" from his proof of the existence of F_1.

In order to classify the finite simple groups it is necessary not only to make a list of their different types but also to prove that the list is complete. Over the

past 30 years hundreds of mathematicians have worked on the latter part of the problem. This unprecedented group effort, which has been described as a mathematical equivalent of the Manhattan project, has been carried out primarily by finite-group theorists in the U.S., Britain and West Germany. In 1972 Daniel Gorenstein of Rutgers University put forward a 16-step program for proving that any finite simple group must be either a member of one of the established infinite families or one of the 26 sporadics. Michael Aschbacher of the California Institute of Technology later proved a number of fundamental theorems that resulted in a modified version of the program that could be completed faster. Today only a few well-defined problems remain to be solved, and it is expected that the program will be completed in anywhere from six months to two years. In other words, the end is clearly in sight.

Completing the classification proof will not automatically settle the issue of whether F_1 and J_4 are indeed the last of the sporadic groups. The final proof will be extremely long (some 10,000 pages, according to Gorenstein) and so will certainly include some mistakes. Most mathematicians believe, however, that the classification program and the techniques employed to implement it are basically sound. They have faith that any holes in the various arguments can be patched. It is nonetheless possible that through such a hole one or two sporadic groups may have slipped. Only time will tell. Meanwhile the construction of F_1 and J_4 makes a significant contribution to mathematicians' understanding of one of the most unifying concepts in all mathematics: the group.

Microbroadcasting

In the office of the future, it is said, the clattering of the typewriter will be replaced by the meaningful silences of the computer display terminal and by the beeps, whirs and hums of other machines that manipulate or store information in electronic form. In general these devices must communicate with one another and with a central computer, which suggests that another characteristic of the office of the future may be a tangled web of cables underfoot. The cables are more than a mere impediment. They are expensive; installing them is still more expensive, and once they are installed it is difficult to move or rearrange any of the devices connected to them.

An alternative to such a "hard-wired" office is now under investigation at the Zurich Research Laboratory of the International Business Machines Corporation. It would enable computers, terminals and other electronic devices to communicate by broadcasting at infrared wavelengths. The system is de-

scribed by Fritz R. Gfeller and Urs Bapst of the Zurich laboratory in *Proceedings of the IEEE.*

In principle a computer and several remote terminals could be linked by radio-frequency signals. Each terminal would be equipped with a transmitter, a receiver and an antenna. The range of radio-frequency signals cannot be controlled precisely, however, with the result that neighboring computer networks might interfere with one another. There are many other possible sources of interference, including radiation from the terminals themselves. What is more, some part of the radio-frequency spectrum would have to be set aside for such purposes, and the spectrum is already crowded.

The use of infrared radiation would circumvent all these problems. Infrared radiation does not penetrate most materials, and so the signals could readily be confined to a single room; nearby networks could operate independently. The system would be immune to interference from most electromagnetic emissions.

The transmitter for an infrared data-communications link would be a light-emitting diode, a semiconductor device that emits infrared radiation in response to an applied voltage. The emitted radiation could be modulated directly by turning the diode off and on to represent the 0's and 1's of binary data; alternatively the diode could be switched off and on at a fixed frequency to generate a carrier wave, which would then be modulated by any of several methods, such as shifting the phase of certain pulses. The receiver is another semiconductor device, a photodiode that gives rise to a voltage when it absorbs light or infrared radiation. Amplifying and detecting circuits would recover the original signal from these voltages.

An essential feature of the infrared data link is that it does not depend on a direct beam to connect two devices. The radiation is diffuse, it is reflected by walls and the ceiling and ideally it permeates an entire room like light from a chandelier. Hence there is no need to maintain a clear line of sight between a transmitter and a receiver. Terminals and other devices could be placed anywhere in the room and in any orientation. Signals from the central computer would be broadcast by a large array of light-emitting diodes near the center of the room; each signal would be prefaced by an address designating a particular terminal and would be ignored by all other terminals. Signals in the other direction would be transmitted by light-emitting diodes mounted on the terminals and would be received by photodiodes in the central array.

The maximum speed with which information can be transmitted is determined in part by the size of the room. The interval between successive pulses

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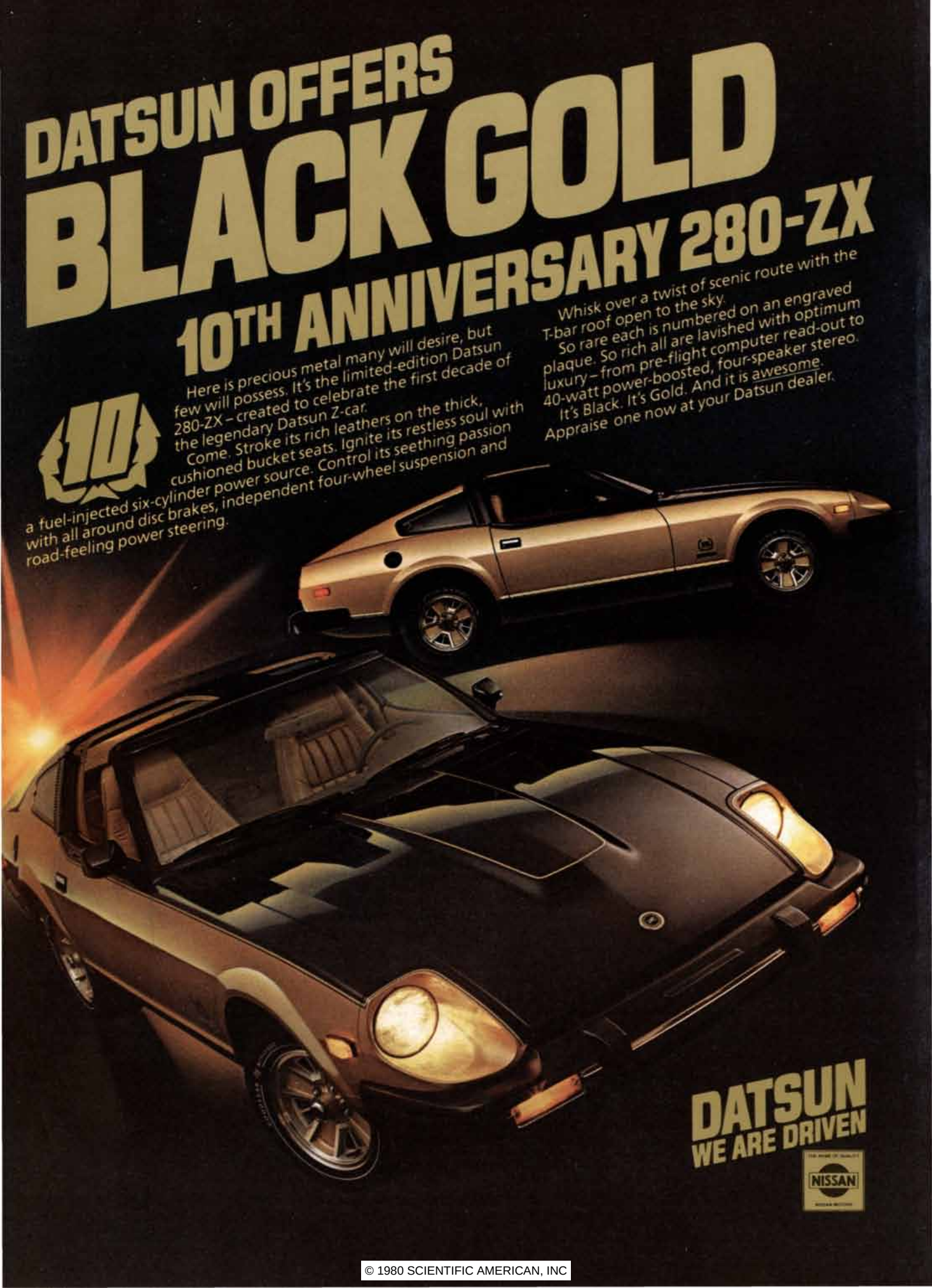

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must be long enough so that a pulse reflected from a distant wall reaches the receiver before the next pulse gets there by direct transmission. In practice a lower speed limit is set by noise introduced into the photodiodes by background illumination. The maximum practical speed is probably less than a million bits per second. Prototype senders and receivers built at the Zurich laboratory operate at 64,000 and 125,000 bits per second.

Having untethered a computer terminal, it becomes possible to make it truly portable. An infrared data link developed by Siemens AG of West Germany will be employed to connect a central computer with a hand-held data-input device, much like a hand-held calculator. The transmissions will have a range of about 20 meters and will carry information at a rate of 2,400 or 4,800 bits per second. The system is to be installed on a Volkswagen assembly line, where the hand-held terminal will report assembly defects to the computer controlling the line.

Disentangling Alliance

The DNA in a cell of the human body is more than four feet long, but it lies within a nucleus that is less than a thousandth of an inch in diameter. Most of the time, therefore, it seems to be a tangle. Yet when the cell divides, the DNA condenses into strands in duplicate copies and complete sets draw apart, one set for each daughter cell. Clearly the DNA was copied while it was apparently in the form of a tangle, and it was copied in a way that allowed the duplicates to segregate.

The study of bacteria, the principal experimental organisms of modern biochemical genetics, is of little help in understanding this process. To be sure, it is known that in bacteria the copying of DNA is engineered by enzymes—perhaps as many as 100—that form complexes that bind to the DNA, locally unwind it, synthesize new DNA using the old as a template and even correct mistakes. Moreover, evidence is accumulating that the copied DNA, and perhaps the enzyme complexes, binds to the inner face of the bacterium's surface membrane, no doubt in a way that facilitates the allocation of genetic material between the two daughter cells. The fact remains that the genetic material in a bacterium is far simpler than that in a higher organism: it consists of a single circular chromosome and smaller circular strands, and they are not confined in a nucleus.

In 1974 Ronald Berezney and Donald S. Coffey of the Johns Hopkins University School of Medicine reported that approximately 5 percent of the protein in a nucleus constitutes what appears in electron micrographs to be a rigid skeleton or scaffolding. They called this structure the nuclear matrix. Further experiments, conducted by Drew M. Pardoll, Bert Vogelstein and Coffey, now suggest a function of the scaffolding. The investigators propose that the DNA in the nucleus is attached at thousands of places to sites on the nuclear matrix, so that the genetic material is arrayed in thousands of loops. The sites are enzyme complexes and the loops are in motion through them, because it is there the loops are copied in a way that preserves the loops and keeps them attached to the matrix. Thus when the cell divides, it is duplicate copies of loops already joined to a scaffolding that are drawn apart to the daughter cells.

The experiments on which the Johns Hopkins workers base their hypothesis involved the brief exposure of rat cells or mouse cells to a radioactively labeled substance that is incorporated into DNA in the course of its synthesis. A subsequent treatment of the cells enables enzymes to digest the DNA, leaving only those parts that are tightly bound to the nuclear matrix. The DNA that is bound turns out to include much of the radioactivity, which means that it is newly made.

The Johns Hopkins workers acknowledge that their hypothesis leaves a number of mechanical details unexplained. For example, if a length of DNA is arrayed as a series of loops because it is attached at several places to enzyme complexes, and if loops are simultaneously in motion, the DNA may become unduly stretched. The investigators cite some numbers as a partial resolution. The genetic material in rat liver cells consists of from 10,000 to 15,000 loops. The nuclear matrix has a corresponding number of enzyme complexes. The complexes work at a rate that would make a copy of a loop in approximately half an hour, yet the part of the life cycle in which the DNA replicates is known to last for eight hours. On the average, therefore, only a sixteenth of the complexes need to be active at any one time, and only a sixteenth of the loops need to be moving.

Where Is Thy Sting?

A minor but fascinating puzzle of nature is how certain fishes can live safely in intimate contact with coelenterates that sting other fishes and digest them. Among the immune fishes is the clownfish *Amphiprion,* which in its natural habitat in the Pacific and Indian oceans finds shelter among the tentacles of various sea anemones, including those of the genus *Stichodactyla.* Over the years numerous hypotheses attempting to explain the immunity of the clownfish have been put forward. Now in a series of elegant experiments designed to test these hypotheses Roger Lubbock of the University of Cambridge has eliminated them all and come forward with an explanation of his own.

An experiment that had been done was to remove the skin from clownfish tissue and expose the tissue to an anemone. The anemone readily stung the tissue, indicating that what protects the fish is some factor associated with its exterior. One hypothesis was that the fish secretes some kind of protective substance. Another was that the sea anemone secretes substances that inhibit the response of its stinging cells, and that the fish becomes coated with these substances. A third hypothesis was that the anemones that do not sting the clownfish do not sting any other live fish either. A fourth was that the presence of the clownfish alters the anemone's behavior and prevents the stinging reflex.

Lubbock tested *Stichodactyla*'s predatory abilities and found it was prompt to seize and sting fishes other than the clownfish. He suggests that the observations indicating the anemones did not sting any live fish were made under poor aquarium conditions. He repeated the live-fish tests with a clownfish sheltered among the anemone's tentacles. The presence of the clownfish in no way inhibited the anemone's efforts to capture other fish species, a finding that disposed of the possibility that the clownfish alters the anemone's behavior.

The clownfish, like other fishes, is coated with a layer of mucus ("slime"). Lubbock found that the mucous coating of the clownfish was three to four times thicker than that of the other fishes used in the experiments. Could the thick coating result from a buildup of anemone mucus, along with the proposed inhibitory substance? Evidently not; the mucous layer was just as thick on clownfish kept in isolation for five months as it was on clownfish in daily contact with anemones. So much, then, for the hypothesis that the fish is protected by a substance secreted by the anemone.

Could the clownfish itself be secreting into its mucous coating a substance that inhibits the anemone's stinging cells? To test this possibility Lubbock mixed clownfish mucus with the mucus of fishes that were subject to attack by the anemones. When the mixture was presented to the anemone, its stinging response was as strong as before. Clearly there was no substance present that affected the anemone's stinging behavior.

What was left? Writing in *Proceedings of the Royal Society of London,* Lubbock reports a simple conclusion. It is not a matter of what is in the clownfish mucus but of what is not in it. The sea anemone's stinging cells are able to recognize that the protein in the mucus of fishes other than the clownfish is "foreign," and their response follows automatically. The thick mucous jacket worn by the clownfish, however, is chemically neutral, so that the stinging cells do not recognize it as being foreign, and therefore the fish is not stung.

Myelin

It wraps around nerve fibers and gives them electrical insulation. Its presence reconciles the brain's conflicting needs for compact size, complex circuitry, rapid signaling and modest use of energy

by Pierre Morell and William T. Norton

In all higher vertebrate animals the division of the tissue of the brain and the spinal cord into white regions and gray regions—white matter and gray matter—is plain on even casual inspection. The proportion of the white matter to the gray increases as one ascends the evolutionary scale, until in man more than 40 percent of the area of a cross section through the brain may consist of glistening white material. The nerves that course through the body are also a glistening white. Microscopic examination shows that the white matter consists of closely packed cylinders, most of which have a fatty white coating. These are axons: the fibers over which neurons, or nerve cells, transmit their signals. The fatty coating is myelin. The German pathologist Rudolf Virchow, to whom the naming of myelin is attributed, gave an early description of the substance in 1864. He derived the word myelin from the Greek *myelós,* marrow. The term reflects his observation that myelin is notably abundant in the marrow, or core, of the brain.

The pervasiveness of myelin has a ready explanation: it is an electrical insulator that speeds the conduction of nerve signals. In particular the velocity of signal conduction by a bare nerve fiber (one without a myelin coat) increases with roughly the square root of the fiber's diameter, so that for the rate to be doubled the caliber of the fiber must be four times larger. In contrast, the velocity of signal conduction by a nerve fiber sheathed in myelin increases with roughly the diameter of the fiber, so that a doubling of the rate requires only a doubling of the caliber. The saving in space is prodigious: at a mammalian body temperature of 37 degrees Celsius an unmyelinated fiber would have to be several millimeters in diameter to conduct at the speed (100 meters per second) of a myelinated fiber only 20 microns, or a fiftieth of a millimeter, in diameter. To put it another way, if the human spinal cord contained only bare nerve fibers, it would have to be several yards in diameter to maintain its conduction velocities.

An advantage in energy consumption is equally impressive. In a frog a myelinated nerve fiber 12 microns in diameter conducts signals at a velocity of 25 meters per second. So does the unmyelinated giant axon of the squid, but it is 500 microns in diameter and uses 5,000 times as much energy. For at least two reasons, then, it is impractical for a complex nervous system to lack a substance such as myelin: the energy and space requirements would both be too stringent. If myelin has a disadvantage, it lies in the very degree to which it is needed. The loss of myelin sheaths, or of the cells that produce them and wrap them around nerve fibers, is implicated in diseases such as multiple sclerosis.

Signal Conduction in Neurons

Suggestions that myelin is an electrical insulator date back to 1878, when the French pathologist Louis-Antoine Ranvier, in a book on the anatomy of the nervous system, drew an analogy between myelin and the protective sheathing of undersea telegraph cables. No doubt he was influenced by the wide interest in the transatlantic cables, the first of which was laid in 1866.

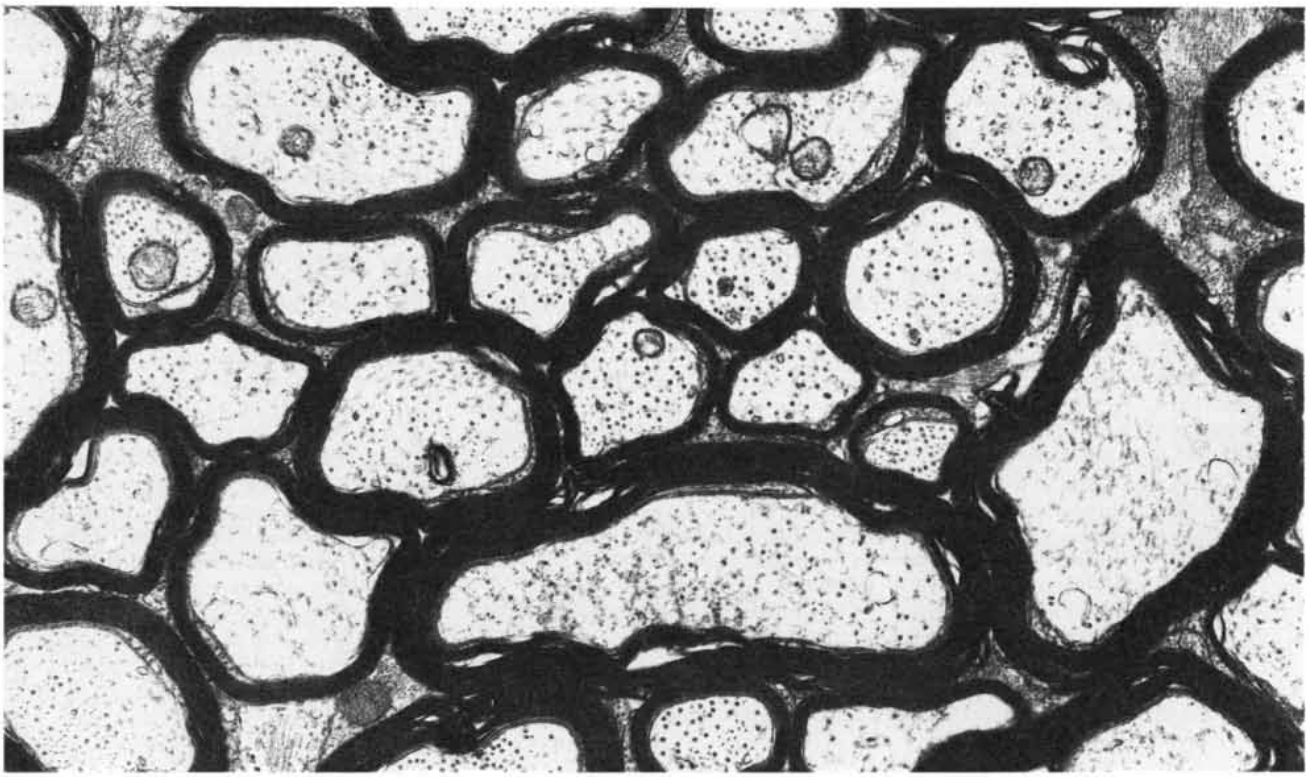
The mechanism by which myelin facilitates conduction, however, has no exact analogy in electrical circuitry. To begin with, a nerve cell consists of a cell body with various processes, or fibers. The major process, the axon, bears signals away from the cell. It can be remarkably long. Axons of neurons controlling muscles in the foot extend into the foot from cell bodies inside the spinal cord.

The membrane forming the surface of the neuron, including the axon and its endings, maintains a difference in voltage between the inside and the outside of the cell. It does so by concentrating potassium ions inside the cell while expelling sodium ions. Under certain conditions gateways in the membrane can be opened temporarily to allow an influx of sodium followed by an outflow of potassium, so that the voltage difference drops but then is rapidly restored. When a sufficiently large area of the cell-surface membrane is "depolarized" in this manner, the transient disturbance can propagate down the axon. That is the neuron's signal, often referred to as the nerve impulse.

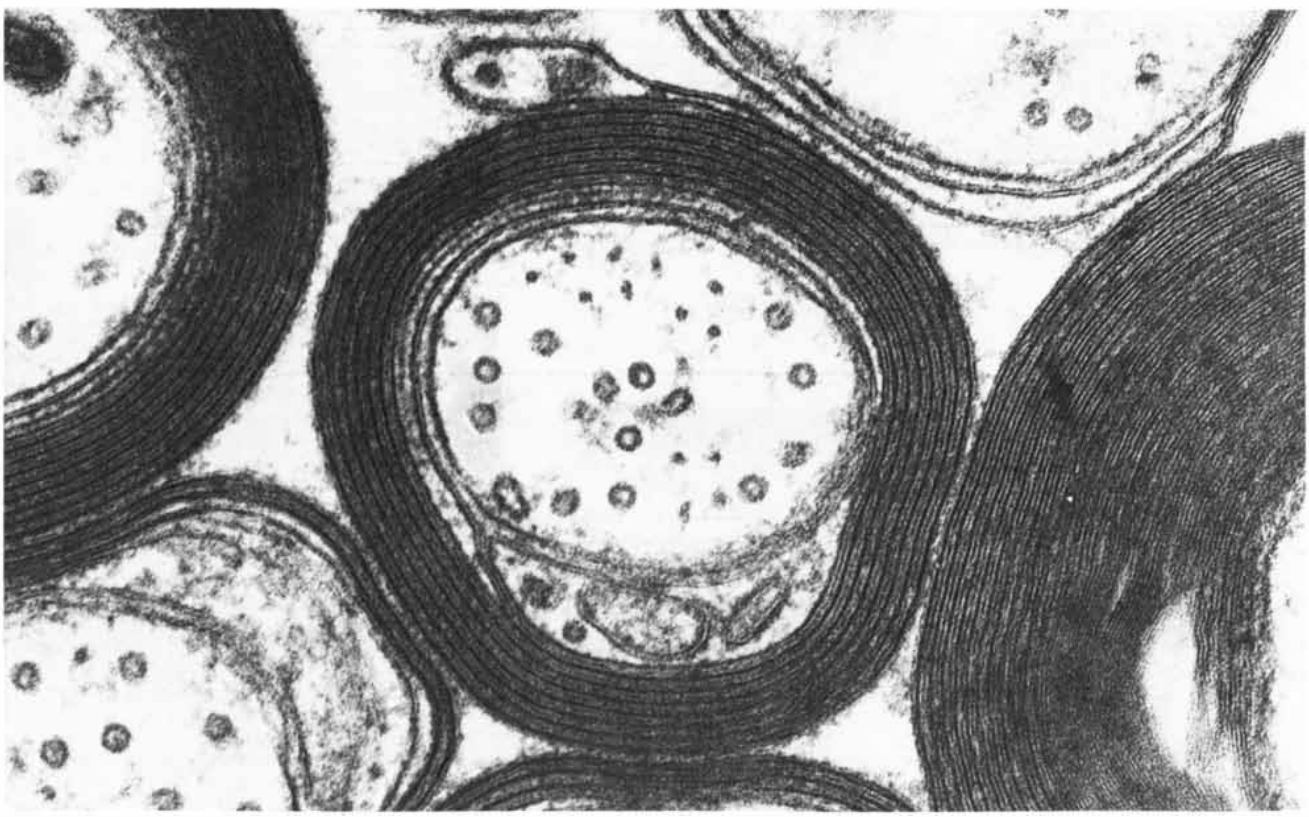
In an unmyelinated axon the impulse propagates by means of a local and temporary flow of ions, and thus of electric current, into the depolarized region of membrane and out through adjacent membrane. These local circuits depolarize the nearby membrane in a continuous, sequential manner. Hence the signal moves down the axon like a wave. The mechanism is called continuous conduction. At the end of the axon the depolarization triggers the release of a neurotransmitter, a substance that can depolarize the membrane of a neuron that receives it. If the axon ends on a muscle, the neurotransmitter can cause the muscle to contract.

In a myelinated axon the process of conduction is different. Here the axonal membrane is exposed to the extracellular environment only at the gaps called the nodes of Ranvier. (It was he who first described the gaps in 1871.) The remainder of the axonal membrane is covered by a myelin sheath, which has a much higher electrical resistance and a much lower capacitance than the axonal membrane itself. When the membrane is depolarized at a node of Ranvier, the local circuit generated cannot flow through the adjacent membrane. Instead it excites the membrane only at the next node. Because the excitation of the membrane jumps from node to node the conduction of signals is faster than it is in a fiber without a myelin sheath.

Moreover, in a myelinated axon a modest flow of sodium ions and potassium ions will serve to depolarize the small area of axonal membrane that is exposed at a node of Ranvier. Hence a modest amount of energy is involved in pumping sodium ions back out of the axon and potassium ions back in to repolarize the membrane. In an unmyelinated fiber the entire axonal membrane must depolarize and then repolarize. That is why the signal conduction in a



MYELIN SHEATHS of nerve fibers appear as thick, dark coats of the axons in this electron micrograph, which like the other electron micrographs in this article was made by Cedric S. Raine of the Albert Einstein College of Medicine in New York. The tissue is white matter. It comes from the optic nerve of a guinea pig, but it is typical of white matter from the central nervous system (the brain and the spinal cord) of any vertebrate animal: it includes axons of various diameters, with sheaths of various thicknesses. In general the wider axons have thicker sheaths. The axons with their sheaths lie in a matrix consisting of the processes of cells called astrocytes. One such process courses downward at the upper right. Others are cut in cross section. The magnification of the micrograph is 16,000 diameters.



SINGLE MYELINATED AXON from the central nervous system is shown at a magnification of 150,000 diameters. The beginning of the sheath is a loop of cytoplasm. It is actually a ridge, seen here in cross section. The loop compacts on itself to form a two-ply layer of myelin that spirals around the axon. The end of the sheath is an inner loop of cytoplasm. The tissue is from the spinal cord of a dog.

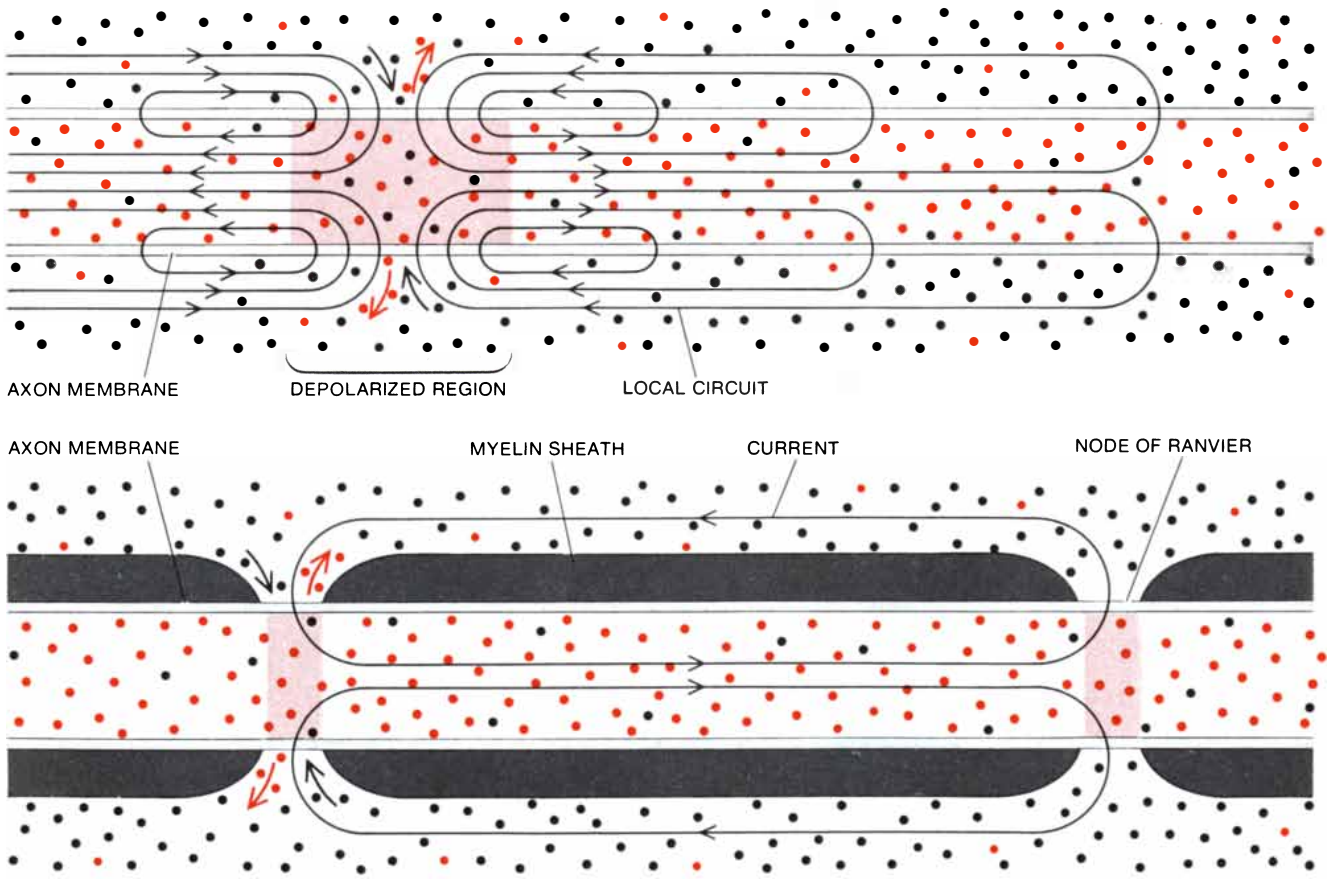
myelinated fiber is less demanding of energy. The form of signal conduction in a myelinated fiber is called saltatory conduction, from the Latin *saltare,* to leap.

The Form of the Sheath

Studies of the structure of myelin were first carried out on nerves whose position in the body makes them easy to dissect. In addition the axons in a nerve are arranged in parallel, as if they lay in a cable, so that the entire assembly, including the myelin sheaths, is in a known configuration. The ability of nerve fibers to reorient polarized light waves had been known since the 19th century. It was correctly interpreted as demonstrating that the molecules constituting myelin are arranged with a high degree of order. In 1913 Gustav Göthlin demonstrated that the reorientation was due primarily to an arrangement of lipids, because the optical properties of myelin changed drastically after the extraction of such molecules with alcohol. (Lipids are a structurally heterogeneous class of compounds defined by the property of being relatively insoluble in water but soluble in organic solvents such as alcohol and benzene.) An ordered arrangement of proteins also made a contribution. Another technique, the diffraction of X rays, was utilized in the late 1930's by Francis O. Schmitt, Richard S. Bear and their colleagues at the Massachusetts Institute of Technology to assign distances between the repetitive molecular arrays that appeared to constitute myelin. A model was proposed in which myelin had a stratified structure consisting of layers assumed to be lipid, each about 5.5 nanometers thick, alternating with more strongly diffracting layers assumed to be proteinaceous, each about three nanometers thick. The protein layers were themselves of two types, one type more diffractive than the other. They appeared to alternate in the overall stratified structure. Finally, each lipid layer was posited to be in fact a bilayer, two lipid molecules thick.

The model is consistent in many ways with the structure of surface membrane of mammalian cells in general, a structure that consists of a bilayer of lipids sandwiched between proteinaceous inner and outer faces. (The inner face bounds the cytoplasm of the cell; the outer face is exposed to the extracellular environment.) The reason for the similarity became apparent in 1954, when Betty B. Geren, who was then working at the Harvard Medical School, published electron micrographs demonstrating that in the peripheral nervous system myelin is not the product of the neuron with whose axon it is intimately associated. Indeed, the myelin does not come from neurons; it develops instead from the cell-surface membrane of the cells known as Schwann cells.

The arrangement in the peripheral nervous system was then rapidly clarified. A row of Schwann cells lies parallel to an axon, and each segment of myelin sheath between two nodes of Ranvier is supplied by a separate Schwann cell. More specifically, the membrane of each Schwann cell compacts on itself to form a flattened sheet that wraps around the axon repeatedly. As a result of this compaction each wrap of a myelin sheath is two plies of a cell-surface membrane. The occasional appearance of cytoplasmic compartments called Schmidt-Lanterman clefts within the myelin sheath is also clarified in this scheme; the clefts are ribbons of cyto-



CONDUCTION OF AN IMPULSE (a signal produced by a nerve cell) is diagrammed for a bare nerve fiber (*top*) and a nerve fiber sheathed in myelin (*bottom*). In both cases the impulse is a local and transient depolarization: a change in the membrane of the fiber so that sodium ions (*black dots*) flow in and then potassium ions (*colored dots*) flow out. In the bare nerve fiber a local current arises from the flow of ions that depolarizes nearby membrane. Hence the conduction is continuous. In the myelinated fiber the ions flow in and out mostly at the nodes of Ranvier, which are gaps in the myelin sheathing. The impulse "jumps" from node to node. If an impulse somehow were generated in the middle of an axon, it would spread along the fiber in both directions (a possibility suggested by this illustration). It is generated, however, at the cell body of a neuron. Thus it is conducted away from the cell body toward the terminals of the axon.

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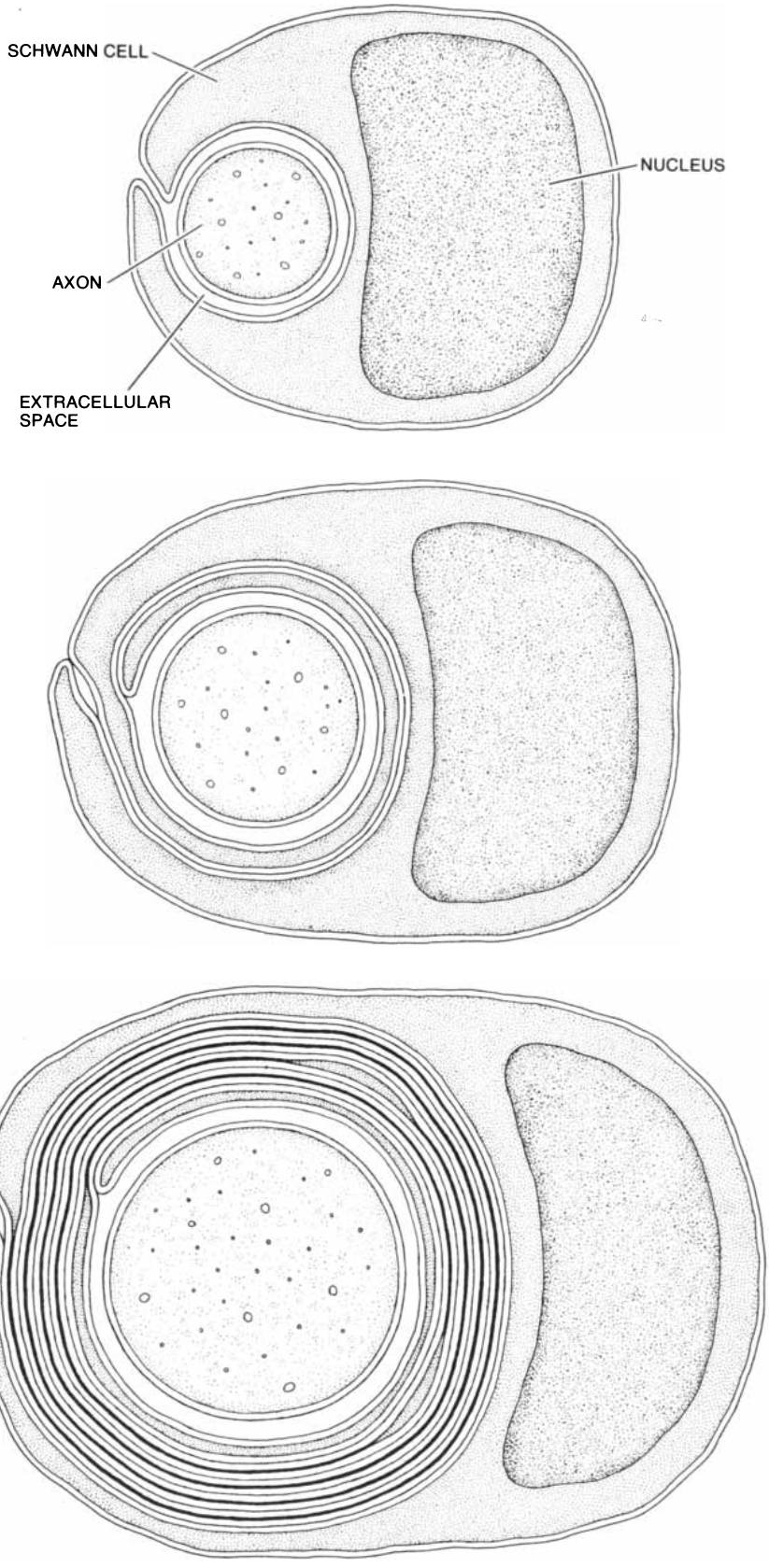

MYELIN SHEATH IN A NERVE is contributed to an axon by a file of cells called Schwann cells, which wrap their flattened surface membrane many times around the fiber. Although the actual mechanism is not yet certain, a likely one is depicted here in successive cross sections. The cell body of each Schwann cell is stationary and its flattened membrane burrows under itself so that it envelops the axon. As successive wraps are added and the axon grows in diameter the myelin membrane compacts. Each Schwann cell contributes one segment of myelin sheath; the gaps between the segments are the nodes of Ranvier. Only near the nodes does the sheath actually meet the axon. Elsewhere a slender extracellular space intervenes between the two.

plasm that remain where the compaction of Schwann-cell membrane is imperfect, and they lead back to the cell body of the Schwann cell.

The successive wrappings of membrane account for the multilayered structure predicted by Schmitt, Bear and their colleagues. They also account for the alternation of protein layers, and by that token for a pattern of dark and light lines that form concentric rings around an axon in electron micrographs of a myelin sheath in cross section. The dark lines result from the coming together of the proteinaceous inner faces of the membrane of a Schwann cell when the membrane compacts on itself. The inner faces abut so closely that they almost fuse. The lighter lines result from the coming together, in successive wraps around the axon, of the Schwann-cell membrane's outer faces. These too are proteinaceous, but they do not abut as closely, perhaps because their proteins are different from those of an inner face. Thus one can often distinguish a split in the lighter line.

Elucidation of the organization of myelin in the central nervous system (the brain and the spinal cord) was delayed by various technical difficulties, but eventually Richard P. Bunge and his colleagues at the Columbia University College of Physicians and Surgeons were able to infer its three-dimensional arrangement from the two-dimensional images of electron micrographs. Myelin in the central nervous system is different in some ways from myelin in nerves. In particular the cells supplying myelin in the central nervous system are oligodendroglia. They are a variety of what are called glial cells, which are satellites of neurons. Each oligodendroglial cell body sends out a number of processes that invest adjacent axons. Alan Peters of the Boston University School of Medicine has shown that for an oligodendroglial cell in certain parts of the nervous system the average number of these processes may be as high as 40. It is probable, however, that on any single axon each internodal region is myelinated by a different oligodendroglial cell.

Molecular Composition

The most conspicuous feature of the composition of myelin with respect to the composition of other cell-surface membrane (for example the cell-surface membrane of liver cells) is its high proportion of lipid to protein. Since a high concentration of lipid effectively excludes water and whatever is soluble in water, including sodium ions and potassium ions, the content of lipid in myelin contributes to myelin's function as an insulator.

The high concentration of lipid also makes myelin more buoyant than other membranes (a reflection of the fact that oil floats on water). This property facili-

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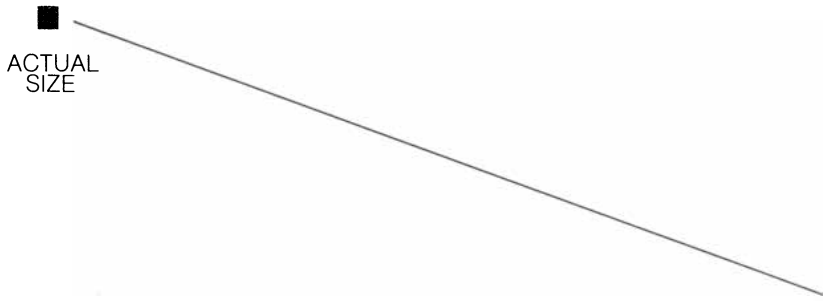

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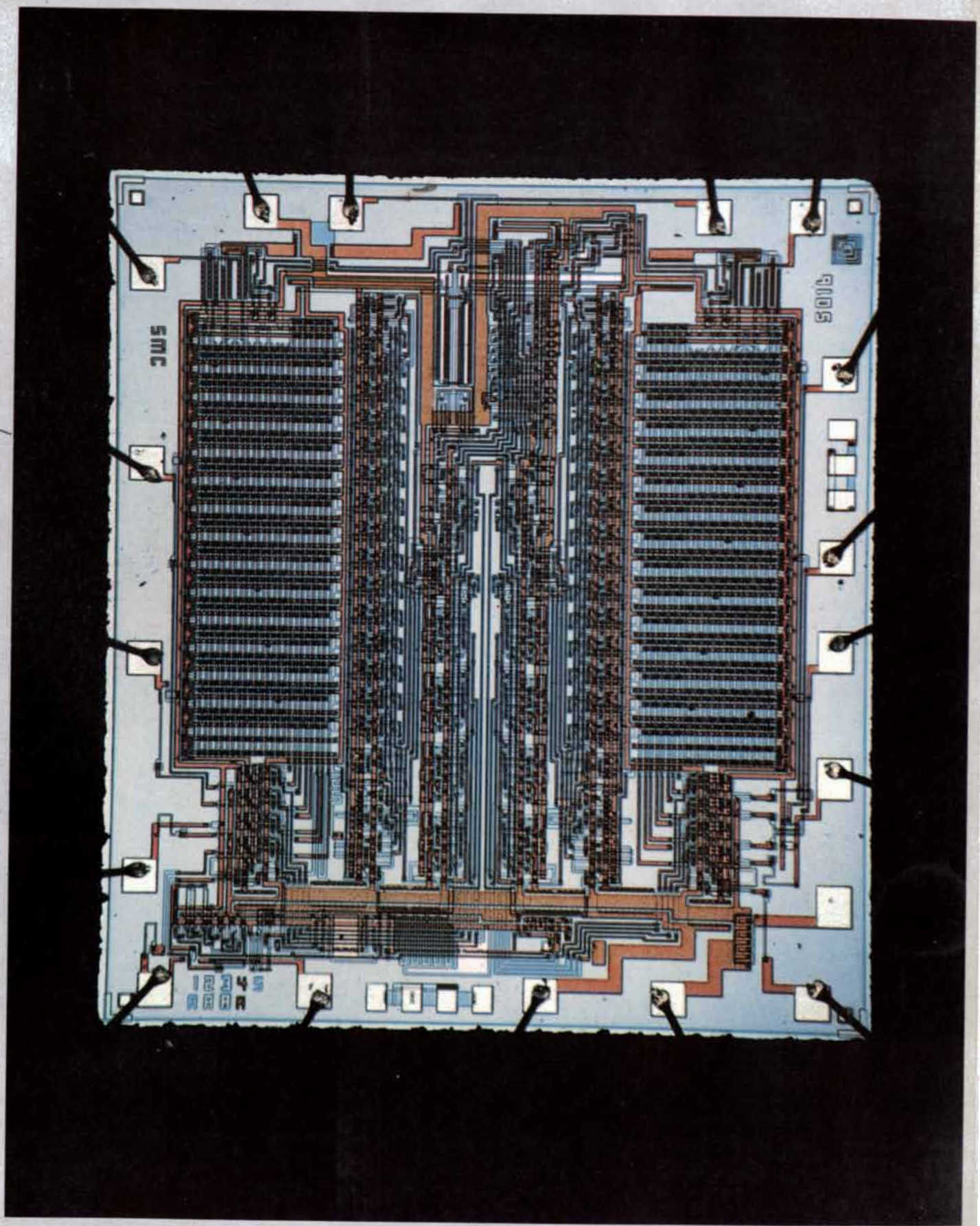

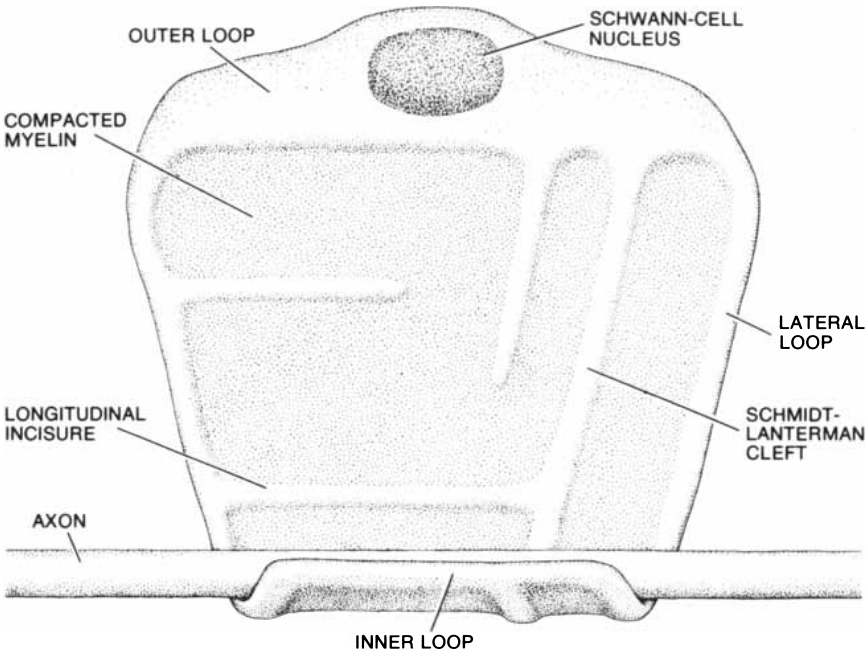

UNROLLED MYELIN SHEATH from an axon in a nerve shows cytoplasmic channels that remain in the sheath where the Schwann cell's membrane does not quite compact on itself. Channels that lead from the sheath back to the cell body of the Schwann cell are Schmidt-Lanterman clefts. These are always present in myelin outside the brain and the spinal cord.

tates myelin's isolation and makes possible more detailed studies of its composition. In one technique, a widely used version of which was developed by one of the authors (Norton) in collaboration with S. E. Poduslo, a brain homogenate is placed in the top of a centrifuge tube containing a gradient of sucrose. When the tube is spun in the centrifuge, each of the various particulate components of the homogenate is driven through the gradient until it reaches the solution whose density is the same as its own.

In this way it is possible to obtain a membrane fraction that under the electron microscope appears to consist almost exclusively of particles identifiable as myelin by the characteristic pattern of alternating dark and light lines. The lipids, which constitute some 70 percent of the dry weight of purified myelin from the central nervous system, can then be isolated and analyzed. As in other membranes, some of the lipid is cholesterol, some is phospholipid (a diverse category of lipids that are comparable because they all contain phosphorus atoms) and some is glycolipid (a diverse category of lipid molecules that each include a sugar). A glycolipid called cerebroside, which incorporates in its structure the sugar galactose, turns out to represent some 20 percent of the total dry weight of the myelin. Six percent of the dry weight of the human brain therefore consists of this kind of lipid. Cerebroside is found almost nowhere in the brain except in myelin sheaths.

The protein content of myelin also is distinctive. Most cell-surface membranes consist primarily of a heterogeneous collection of proteins, none of which quantitatively overshadows the others. In contrast, not only does myelin have much less protein than other cell-surface membranes but also there are many fewer types of protein. Among the missing proteins are those that facilitate the passage of ions through lipid bilayers; their absence contributes to the ionic impermeability of the myelin sheath. Furthermore, two proteins in myelin predominate. One of them is called myelin basic protein because of its solubility in an acidic solution. It accounts for about a third of the total myelin protein. The other predominant protein was identified some 30 years ago by Jordi Folch-pi and Marjorie B. Lees of the McLean Hospital in Belmont, Mass. It accounts for another third or more of the total, and it has the unusual property of being soluble in organic solvents. Because of this lipidlike feature it is called proteolipid protein.

Both proteolipid protein and myelin basic protein are thought to have structural roles. The proteolipid protein is presumed to organize the lipid bilayer; this is suggested by the lipidlike solubility of the substance and is supported by indirect evidence that the proteolipid protein is largely buried within the lipid bilayers of myelin. The basic protein may be involved in the tight compaction of inner membrane faces to form the dense line seen in electron micrographs. This hypothesis too is supported by the location of the protein; a number of experimental approaches have demonstrated that it is exposed primarily on the inner membrane face.

Several other proteins that are present in lesser quantity have also been isolated, and some have been partially characterized. One of them is a sugar-containing protein, hence the term myelin glycoprotein. Others have been identified as enzymes. Among the latter some are now known to catalyze the synthesis or degradation of the lipids in myelin. Presumably these are necessary for the assembly or the metabolic turnover of components of the membrane, topics to which we shall return. The presence of other enzymes is harder to explain. An example is carbonic anhydrase, an enzyme that catalyzes the interconversion of carbon dioxide and carbonic acid. Its presence suggests that in addition to being an electrical insulator myelin may play some active role, as yet unknown, in facilitating neuronal function.

Although the myelin of the peripheral nervous system has a concentration of lipid (about 80 percent) even higher than that of the central nervous system, the proportions of the various lipids are similar. In the peripheral nervous system, however, a single protein designated P_0 accounts for 55 percent of the total of myelin protein. Other proteins that have been characterized in myelin of the peripheral nervous system include P_1 (a protein probably identical with the basic protein of the central nervous system's myelin but present in small amounts in the peripheral nervous system) and P_2 (a basic protein unique to the peripheral nervous system).

Assembly of the Sheath

In the peripheral nervous system of a human infant the investment of axons with myelin sheaths is largely complete before birth, although myelination must continue during childhood to cover the expanding surface area of nerves, which grow along with the body. In contrast, the myelination of the human brain and spinal cord is far from complete at birth. It occurs at different times in different regions of the central nervous system. The mechanism by which an axon signals to an oligodendroglial cell that it is ready to be myelinated is not known in detail. Quite recently, however, Nancy Sternberger, Richard H. Quarles, Henry DeForest Webster and their collaborators at the National Institute of Neurological and Communicative Disorders and Stroke have demonstrated that at the time of myelination the glycoprotein mentioned above is concentrated at the place of contact between an axon and the outgrowing membrane of oligodendroglial cells. A logical (although unproved) assumption is that the glycoprotein plays some role in recognition between the two.

After recognition there is a rapid deposition of myelin around the axon. Much of the myelin is laid down over a time that in human beings may be several months for any one brain region. During this period the cell body of an oligo-

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In 1947, Heyerdahl set sail from the coast of Peru in the balsa log raft "Kon-Tiki." One hundred and one days later the "Kon-Tiki" made landfall in the Pacific Islands.

In 1970, Thor Heyerdahl's papyrus reed ship "Ra II" left Africa. Fifty-seven days later "Ra II" reached Barbados on the other side of the Atlantic.

During 1977-78, Heyerdahl built the reed ship "Tigris" in Iraq, and sailed it by way of Oman and Pakistan to the entrance of the Red Sea. Local war stopped further progress, but "Tigris" had shown that the three old-world civilisations of Sumer, the Indus Valley and Egypt could have communicated by sea.

"The oceans did not separate early civilisations," says Heyerdahl. "They linked them together."


Tigris

The success of Heyerdahl's expeditions is based on careful planning and strict accuracy in every detail.

"We have sailed precise replicas of the first ships built by early navigators," says Heyerdahl. "We have used their rigging and steering methods, survived on their food, and tested their simple navigation devices. But for accurate scientific plotting of our routes, and for obligatory radio contacts when entering modern ports and shipping channels, we needed what ancient man could do without: a thoroughly reliable, precisely accurate modern watch."

We are flattered to receive such a compliment especially from the world's number one international traveller.

The watches used by Thor Heyerdahl and his crew are made by Rolex.

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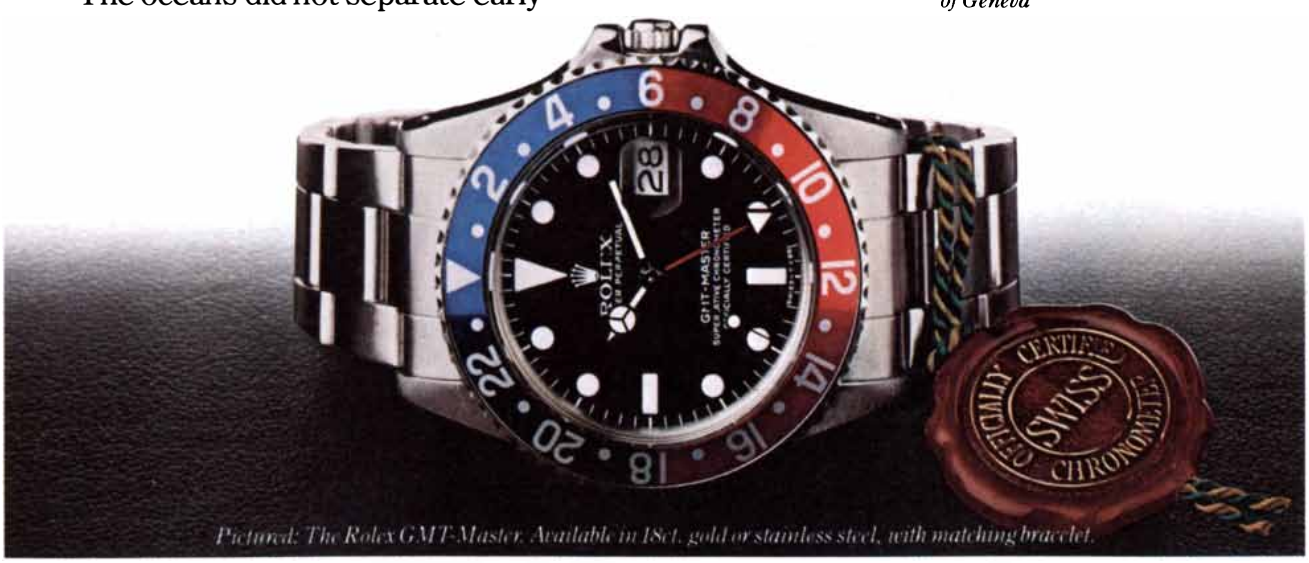

Pictured: The Rolex GMT-Master. Available in 18ct. gold or stainless steel, with matching bracelet.

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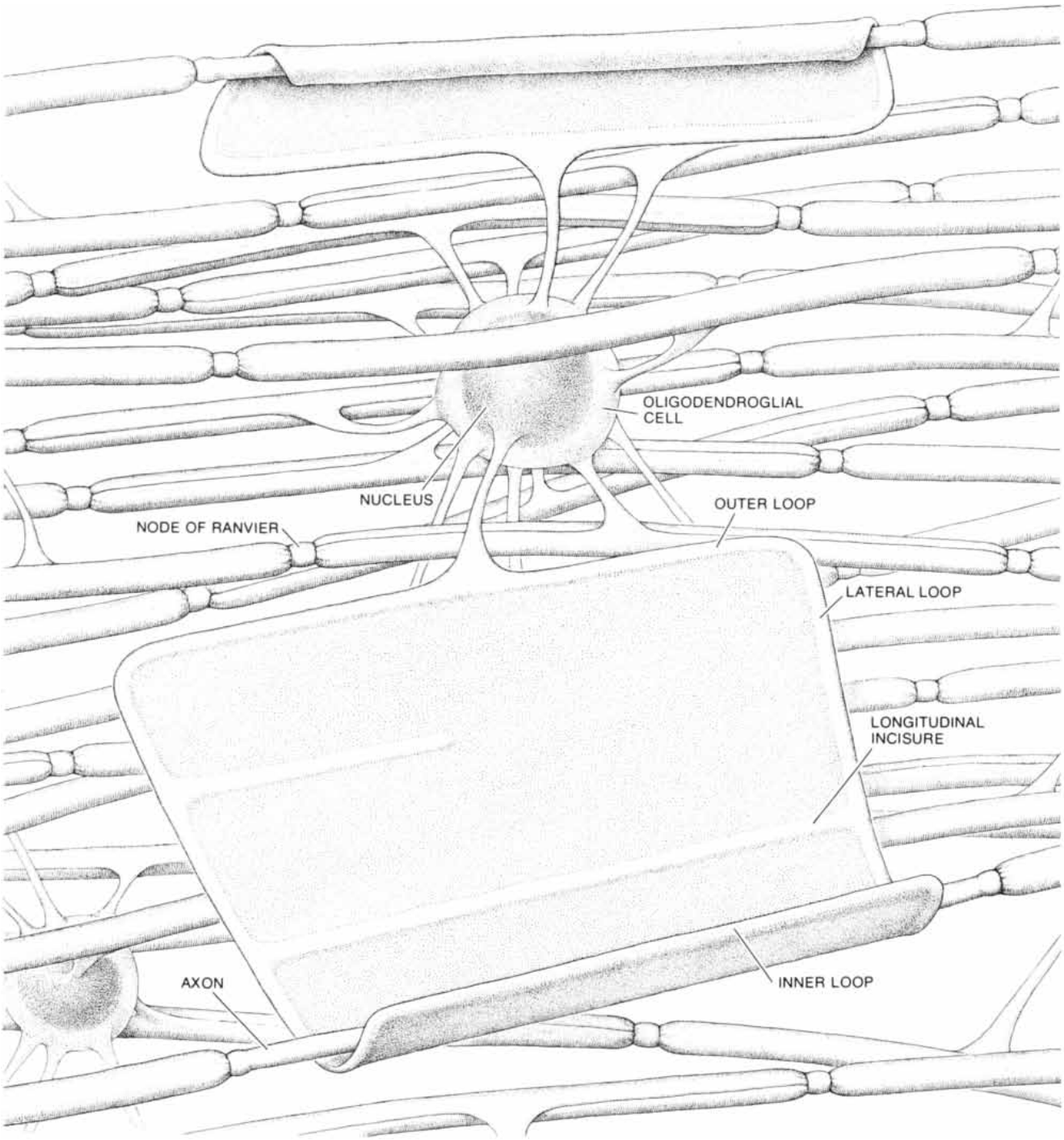
World headquarters in Geneva. Other offices in Toronto and major cities around the world.

dendroglial cell must synthesize several times its own mass in myelin each day. Marked interference with the general supply of nutrients, or with the supply of certain critical nutrients such as essential amino acids (those building blocks of protein that must be supplied in the diet because the body itself cannot synthesize them), may render the oligodendroglial cells incapable of meeting the metabolic demands placed on them. Such metabolic insult can result from malnutrition (either outright starvation or a severely unbalanced diet) or be secondary to some disease that interferes with eating or the absorption of food or with the synthesis of protein or lipid in the myelin-forming cells.

In any case severe metabolic insult during early development can result in an insufficiency of myelin at the appropriate time in the complex sequence of events in brain growth. Although some catching up is possible in later life, it is likely that in severe cases a permanent deficit results. It is impossible at present to separate the consequences of inadequate myelination from other results of starvation, but it seems a safe assumption that they are not beneficial. It should be emphasized that the situation during development is different from the one in maturity: a starving adult animal suffers no appreciable loss of any brain component.

In regard to the actual growth of the



MYELIN SHEATHS IN THE BRAIN (or in the spinal cord) are made by cells called oligodendroglia, which send out sail-like extensions of their surface membranes that provide segments of sheath for numerous axons. Two segments of sheath are depicted at least partially unrolled. The unrolling of the segment of sheath near the bottom of the illustration makes the channels of cytoplasm inside it visible. The analogues of Schmidt-Lanterman clefts are absent in the segment because such channels are not common in the central nervous system.

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And all are focused on one objective: helping the Bell System bring you the best possible telecommunications service at the lowest possible cost.

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Western Electric gave the laser its first application in industry. In 1965, scientists at our Engineering Research Center designed a laser operation that vaporized holes through the diamonds used as dies for drawing copper wire. It turned a five-day drilling job into a 90-second flash.

It may sound simple, but it wasn't. There's much more to working a laser than "ready... aim... fire". Years of exhaustive research preceded that first laser-drilled diamond.

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Even with these uses, Western Electric has only begun to tap the laser's potential for telecommunications.

More applications are on the way. And they will bring more savings, more and better products made with laser technology.

Using lasers to cut costs is just one innovation from the Engineering Research Center. The Center's research in manufacturing techniques is an important part of Western Electric's total commitment to using the latest and the best in technology to keep the cost of your phone service down.

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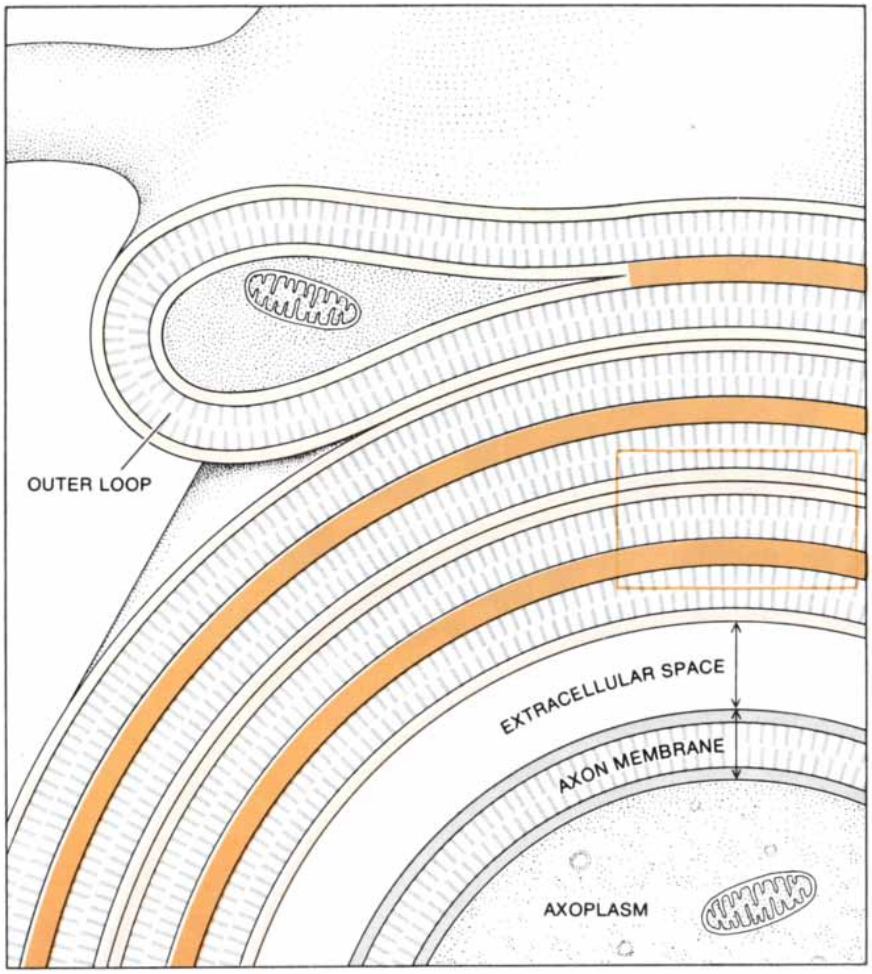
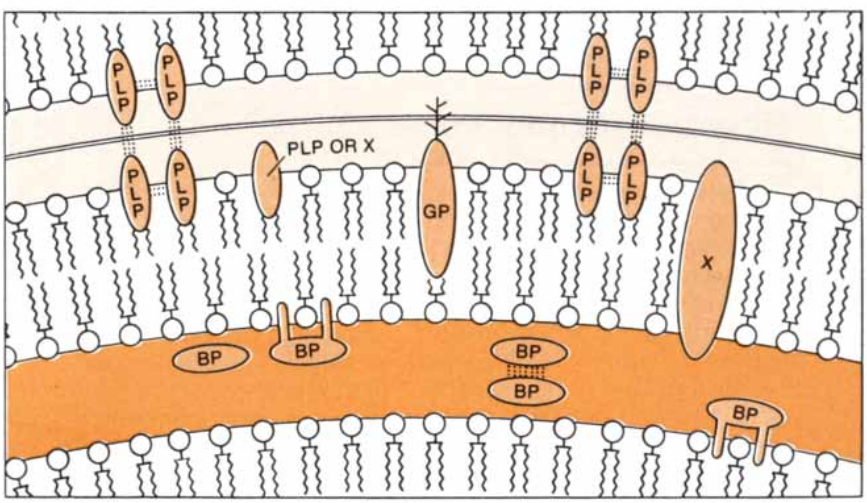


PATTERN OF DARK AND LIGHT LINES in electron micrographs of myelin is explained by the molecular structure of the membrane and by the way it sheathes an axon. At the top of the illustration the surface membrane of an oligodendroglial cell compacts on itself to form a two-ply sheet that wraps around the axon repeatedly. When the membrane compacts, its inner faces (which bound the cytoplasm of the myelin-forming cell) meet and almost fuse; they make a dark line. The outer faces of the membrane abut in successive wraps to make a lighter line; they do not fuse as closely. Both dark and light lines are protein. Between them are lipid layers.



CLOSER VIEW of myelin membrane in the central nervous system includes hypothetical positions of various proteins. The view, which is adapted from an illustration prepared by Peter E. Braun of McGill University, encompasses the rectangle in the top illustration on this page. Basic protein (*BP*) is a constituent of the dark lines that are apparent in electron micrographs of a myelin sheath. Proteolipid protein (*PLP*) is in the lighter lines, from which, however, it extends into the lipid layers. Glycoprotein (*GP*) is also a protein of the lighter lines. Other proteins (*labeled* X) remain to be characterized; some are known to be enzymes. The lipid layer is actually a bilayer: it is two molecules thick. Its structure is shown here in extreme simplification.

sheaths it is instructive to consider briefly what is known about the synthesis of surface membrane in more typical cells such as those that make up other body organs. Inside such a cell lipids and most of the protein components of membranes are synthesized and assembled into a membrane-precursor vesicle, or sac. The vesicle then fuses with the surface membrane and becomes a part of it. In a later step other proteins are added, primarily those exposed on the inner face of the membrane.

The crucial point is that in most cell types the membrane of precursor vesicles seems to become distributed at random in the growing cell membrane. In contrast, it would appear that myelin membrane must be assembled with a polarity, since it grows away from the cell body in a particular direction.

What is the location of the newly added myelin? Is it added near the cell body of the myelin-forming cell or at the growing edge of the sheath? Or is it added randomly in patches? The available evidence favors the first possibility. Robert M. Gould of the Institute for Basic Research in Mental Retardation has carried out experiments in which the incorporation of radioactively labeled molecules into growing myelin sheaths in the sciatic nerve, which innervates tissues in the leg, has been resolved by the electron microscope. When the labeled substance is the myelin protein P_0, radioactivity first appears in the cytoplasm of the Schwann cell, then in a region of its membrane close to the outgrowth of myelin and next in the outermost wrapping of the growing myelin sheath. After a period of days this band of radioactivity is buried under successive layers of myelin.

The findings leave undetermined the precise way an axon gets its sheath. Is newly formed myelin deposited by movement of the myelin-forming cell around an axon, with a trail of myelin left behind, or is myelin extruded from a stationary cell, so that the leading edge of the sheath is pushed around the axon? It should be noted that in the central nervous system an oligodendroglial cell has a constraint that does not exist for a Schwann cell. As a growing tongue of myelin loops around an axon the parent Schwann cell may move to give rise to a looseness in the spirals of the sheath so that the tongue can squeeze under the layers already deposited. An oligodendroglial cell, however, is anchored by the processes that connect it to many myelin sheaths. It therefore seems impossible in the central nervous system for myelin to be deposited by a cell body that shuttles around an axon. Here the newly formed myelin must push the many layers of already formed myelin in a spiral so that the tip of the sheath advances. How the requirement for looseness of the spiraling myelin sheath during growth is met by the oligoden-

DP Dialogue

Notes and observations from the IBM Data Processing Division that may prove of interest to the engineering community

This gas pumping station, near Houston, is in a pipeline operated by Houston Natural Gas Corporation. To estimate the reserve in a gas or oil field, the company sends instrument probes down a drill hole. Today, computation with APL has replaced extensive graphic analysis of this data, and geologists learn far more about each field.

More Oil for the Buck: HNG Takes a Closer Look at its Reservoirs

"Analysis of a gas or oil field is not a 'cookbook' kind of thing," says Michael A. Roberts of HNG Fossil Fuels Company. "I can't simply crank the instrument readings into the computer and sit back to wait for the results. I watch the progress of the calculation and make computing decisions as the program runs. The course of the analysis is different for each field."

Roberts is senior geological engineer for HNG Fossil Fuels Company, a subsidiary of Houston Natural Gas Corporation specializing in exploration and production of oil and gas. Using APL, an IBM user-oriented computer language, he analyzes some 100 existing or potential fields around the world each year, in order to estimate the reserve of oil and gas contained in each.

To do so, Roberts uses a number of physical measurements: an instrument probe is sent down a drill hole, and senses a number of variables, such as induced electric potential in the surrounding formations and the resistivity of fluids in the reservoir rocks. The readings at each depth are analyzed by the IBM 3031 Processor at the company's headquarters in Houston.

A great deal can be learned about the material at each depth from such measurements, and from calculations on them, Roberts notes. For example, if sandstone is encountered, the geologist can calculate porosity from its acoustic response. Then he can apply this porosity factor to the computed volume of the formation, to estimate the volume of crude petroleum in the field.

Other measurements help him forecast the viscosity of the crude, its expansion and shrinkage that will be encountered during production, and the volumes of associated gas.

Formerly, Roberts explains, many of these calculations were done by manipulating a chart, called a nomograph, of physical relationships. "This graphical method was tedious and less accurate," he says. "And with the computer, if we don't have a good handle on one variable, we can run a sensitivity analysis and establish a range of probable values for the reservoir volume.

"We get a better picture of what's in an oilfield, so the money to get it out is better spent. Today the person who needs the power of the computer accesses it directly. APL bridges the communication gap; it gets the tool to the user."

You Ate 0.459 Gram of Phenylalanine Yesterday

Health professionals at Louisiana State University can determine the exact amount of each of 100 different nutrients in any list of foods, with the help of a computer. For example, a hospital dietitian can submit a series of planned menus, and receive back a complete analysis of the number of calories, the quantity of fat, carbohydrate, protein, and other nutrients from Vitamin A to phenylalanine (one of the amino acids).

Conventionally, a dietitian does such analyses with a desk calculator and a reference table. If one item of a menu is changed – say, a peach is substituted for a pear in a dessert – the entire list must be recalculated.

Insights into Disease

The nutrition data base at LSU is also very useful in studying the relationship between diet and disease, explains Dr. Prentiss E. Schilling, head of the department of Experimental Statistics at the university's Baton Rouge campus. "We can enter a person's food intake for 24 hours – items and quantities – and receive back a calorie count and the quantity of each nutrient," he says.

"In one project, a study of atherosclerosis, the researchers are measuring plaque formation in the coronary arteries of individuals, and comparing it to their eating histories by recording all food prepared in each subject's home for one month. Then the system converts each history into a complete nutritional profile."

The nutrition data base is maintained by the International Dietary Information Foundation, Dr. Schilling notes, which collects its information from laboratories in the food industry as well as government and academic sources. Currently stored in the university's IBM 3033 Processor is the complete analysis of over 3,000 basic foods and recipes.

Food Industry Aided

"Our system is very useful to the food industry," Dr. Schilling points out. "Frequently, a processor must reformulate a product, as ingredients become available – substituting, say, palm oil for soy oil in baked goods. And this significantly changes the nutritional analysis. We enter the revised recipe and receive back a printout of a complete table of nutrients, with the quantity of each constituent stated in the appropriate unit of measure. This provides the basis of the nutritional labeling most packaged foods are required by law to carry."

Under the direction of Dr. Prentiss E. Schilling, a data base in an IBM computer at Louisiana State University keeps track of the proportion of every known nutrient in more than 3,000 foods.

This technician is taking a sound signature to identify and isolate noise sources. Deere controls noise while developing machines that operate with increased power and speed.

John Deere Breaks New Ground in Farm Tractor Design

Designing a farm tractor becomes a much tougher challenge year by year. Customers demand comfort as well as increased productivity, which means better control of noise, vibration and temperature, along with a wider range of power. And the government is imposing new noise and emission regulations.

Mike Mack of Deere and Company explains: "We have to accommodate a variety of farming practices and cultures, while holding down the proliferation of models and parts." Mack is director of the Product Engineering Center in Waterloo, Iowa, where Deere designs its farm tractors, engines, and hydraulic and electronic systems.

"Without interactive computing, product development would be far costlier and take much longer," he continues. "We would have to build more prototype models for test and would often still not achieve the same product quality."

Adds Kenneth H. Huebner, manager of engineering analysis: "A good example of this is gear design. We must find a good compromise between surface-compressive stress and beam stress. Calculating the best geometry is tedious and repetitive: manually, you may have time for only three or four iterations. The computer does it hundreds of times, giving us a more nearly optimal design."

The center has been striving to bring the computer directly to the engineer, Huebner explains, by installing over 100 online terminals, and adopting APL, an easily learned IBM programming language for end users.

Engineers can now access the full power of the IBM System/370 Model 168 computer by drawing on a library of some 600 prepared engineering programs, documented and following a set of standards that make them widely used. The Center holds training seminars, and the number of active users has risen from five to over 200 in less than two years.

"A technique called finite element analysis has helped us reduce the weight of parts while meeting structural requirements," he notes. "This results in considerable savings on large parts.

"Another valuable tool is the IBM Continuous System Modeling Program (CSMP). By simulating a hydraulic system or transmission, it eliminates many test models we would otherwise have to build.

"While these computer programs can't be expected to describe the physical product with absolute precision," Huebner points out, "they are good at reflecting change, clearly showing the sensitivity of important performance parameters to variations in the design."

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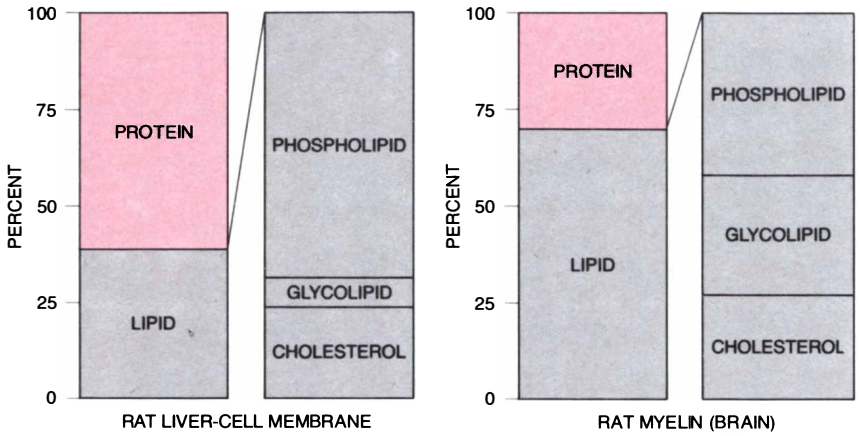
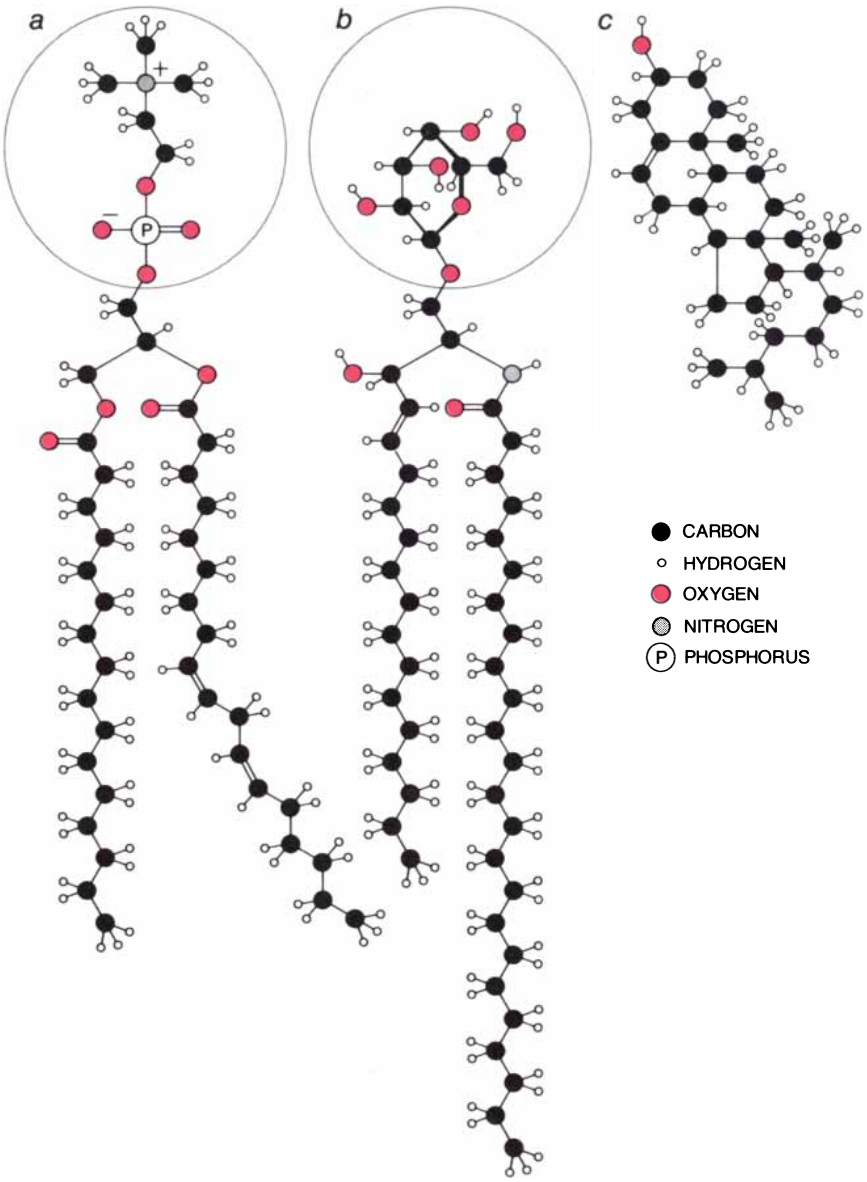


MOLECULAR CONTENT of myelin and that of a more typical cell-surface membrane are compared by weight. The typical membrane is of liver cells in the rat; the myelin is from the brain of a rat. In myelin lipids are dominant over protein. The lipids are of three distinct types.



THREE LIPIDS IN MYELIN are diagrammed; they represent the different classes of lipids shown in the bar graphs at the top of the page. Phosphatidyl choline (*a*) is a phospholipid: a lipid that includes phosphorus atoms. Cerebroside (*b*) is a glycolipid: it includes a sugar, here galactose, in its structure. A double bond between carbon atoms bends a tail of phosphatidyl choline. In the tails of glycolipid double bonds are not common. The third molecule (*c*) is cholesterol.

droglia is a puzzle that is now taxing the ingenuity of electron microscopists.

Replacement of Molecules

The question also arises whether there is turnover of proteins and lipids in the fully formed myelin sheath, as there is in more typical cell-surface membrane. The replacement rate of a particular membrane component is determined by introducing into the vicinity of the cell that synthesizes the membrane a radioactively labeled compound. Typical experiments involve the use of a radioactive amino acid, which is incorporated into protein, or of radioactive glucose, which is metabolized into products that are incorporated into lipid. Consider a constituent of myelin that is labeled in this manner. It is inserted into the membrane over a period of minutes or hours. In time, however, the total radioactivity in the membrane declines because the molecules, or the membrane fragments containing them, are removed and new membrane components are added that are not radioactive. The time in which the radioactivity declines by half is the time in which half of the molecules are replaced. That is the metabolic half-life of the lipid or the protein.

Actual calculations are somewhat more complicated because corrections must be included for any increase in the amount of membrane that takes place during growth. Moreover, some of the membrane turnover may be accomplished when entire pieces of membrane form vesicles and reenter the cytoplasm of the cells, probably to be replaced by newly assembled segments of membrane. Many components of the old membrane may be reused in this process. Still, it is now clear on the basis of work by a number of research groups (including the laboratory of Marion E. Smith at the Stanford University School of Medicine and the laboratory of one of the authors, Morell, at the University of North Carolina School of Medicine) that the components of myelin do turn over, although more slowly than the components of other membranes in the brain. This greater metabolic stability was originally proposed by Alan Davison of the University of London Institute of Neurology. Most of the lipids in myelin have half-lives of several weeks. Some of them, such as cerebroside, have half-lives of several months. The turnover of the myelin proteins is also very slow: for much of the myelin basic protein and proteolipid protein the half-life is several months. These results, it should be said, are obtained with experimental animals, usually with rats. The turnover of myelin in the human nervous system may be even slower.

One wonders, of course, how the molecules in myelin can be metabolized at all, when the bulk of the myelin membrane is highly compacted between ad-

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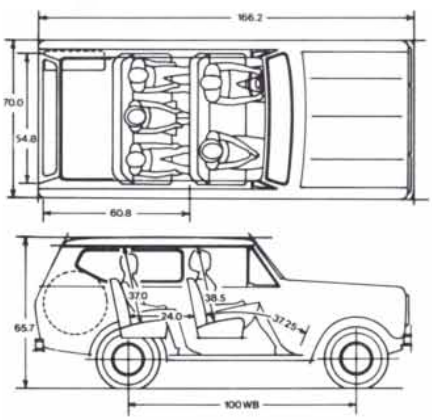

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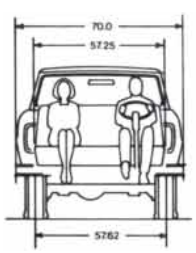

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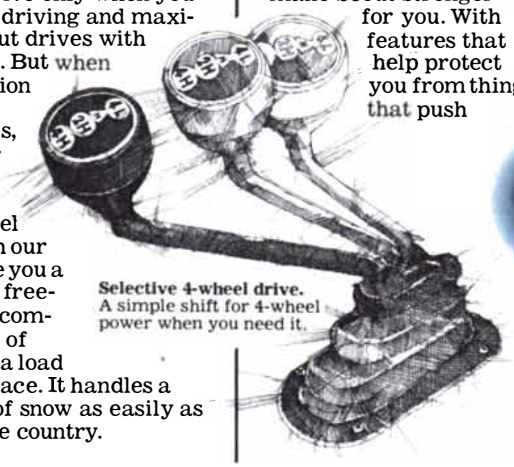

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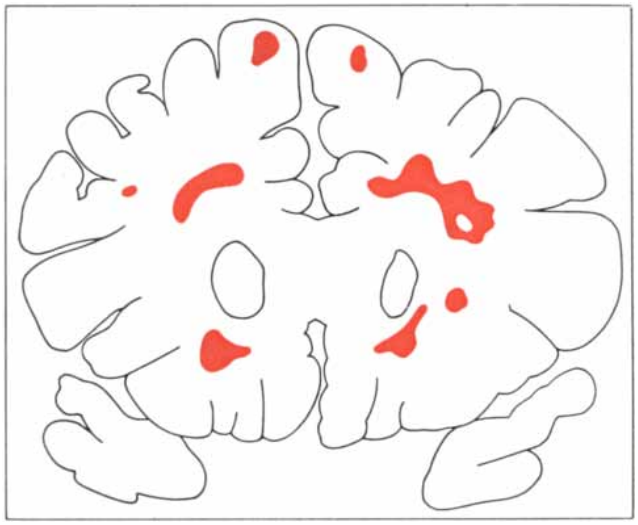

BRAIN of a 60-year-old man who died of multiple sclerosis, a disease of myelin, 14 years after the condition was diagnosed has pathology that is visible even in a cross section that has not been stained. Two large, more or less symmetrical holes in the section are the chambers in the forebrain called the lateral ventricles; the surrounding white matter is discolored in places where axons have lost their myelin sheaths. Other such regions, which are called plaques, are scattered throughout the white matter. The map at the right shows locations of the plaques. The brain was photographed at the Albert Einstein College of Medicine by Cedric S. Raine and Dikran S. Horoupian.

jacent layers of myelin. On looking at an electron micrograph one sees no obvious mechanism by which any given part of the compacted myelin membrane can bud off into the cytoplasm of the myelin-forming cell. Nor can myelin membrane be discarded to the outside of the cell. Occasional views of the myelin sheath in cross section, however, reveal the channels of cytoplasm that lead from the cell body that made the myelin sheath into the compacted regions. Perhaps they contain the intracellular machinery for metabolizing the constituents of myelin. If such a cytoplasmic finger is not really fixed in time and space (as is the case when it is trapped for electron microscopy) but is a dynamic structure constantly in motion, one can imagine a local reprocessing that takes place in this compartment.

A related possibility is that components of the myelin membrane may diffuse to an outside edge of the sheath, where the compaction of the membrane is imperfect and leaves a cytoplasmic channel called the lateral loop. It is likely that the lipid components of the sheath are freer to diffuse than the protein components. (The latter may be arranged in a framework that limits their mobility.) In this view the lower turnover rates of certain lipids might be related to a tighter binding to protein.

Multiple Sclerosis

Since myelin facilitates the conduction of the nerve impulse, one would expect that the loss of myelin sheaths or injury to them would have deleterious effects on the functioning of the nervous system. This indeed is the case. It is particularly true in the central nervous system, because oligodendroglial cells do not regenerate after injury. In contrast, damage to the Schwann-cell population of a nerve is often reversible because new Schwann cells form.

The role of damage to myelin in causing functional deficits is complicated by the fact that in many diseases of myelin there is also damage to neurons. In fact, the severe injury or death of neurons causes disruption of myelin and the death of oligodendroglial cells; this is called secondary demyelination because the primary event is damage to the neurons. There are, however, a number of disorders in which damage to myelin or to oligodendroglial cells is an initial event. It is those conditions, in which the myelin-forming cells are uniquely vulnerable and the nerve cells and axons remain relatively intact for long periods of time after the initial injury, that we shall consider here.

The most prevalent and best-known of the diseases in which myelin is destroyed and nerve cells are spared is multiple sclerosis. In the U.S. the disease is fairly common: it is estimated to affect about 250,000 people. It is diagnosed in young adults, usually between 20 and 40 years of age. The incidence is higher in females than in males. The symptoms vary; examples are difficulty in seeing, muscle weakness, lack of coordination and spasticity. All of them, however, reflect alterations in nervous-system function. The symptoms may vanish or become less severe, followed by exacerbations. The usual course is cyclical, with progressively increasing disability, but there are many variations. For these reasons multiple sclerosis is difficult to diagnose in its early stages.

Evidently the symptoms of multiple sclerosis are caused by the development of multiple sclerotic (scarlike) plaques in the white matter of the central nervous system: plaques that frequently are visible to the unaided eye at autopsy. Under the microscope the plaques are seen to be devoid of myelin and oligodendroglia, but the axons running through them look fairly normal. The myelin and the oligodendroglia have been replaced by cells known as reactive astrocytes, which form a hard, interlaced matrix. Around the edges of each plaque are macrophages and lymphocytes (white blood cells that destroy foreign material). In active plaques, where the destruction of myelin is still in progress, the macrophages have myelin debris inside them. Stephen Cohen, Robert M. Herndon and Guy M. McKhann, working together at the Johns Hopkins University School of Medicine, and John Whitaker of the University of Tennessee have recently shown that exacerbations of the disease are accompanied by an increase of myelin basic protein in the cerebrospinal fluid, which surrounds the brain and the spinal cord. This further supports the proposed relation between the symptoms of the disease and the breakdown of myelin.

Most investigators believe the symptoms are caused by the failure of axons in the plaques to conduct impulses properly after they have lost their myelin insulation. In fact, it appears that such axons cannot conduct at all. There is speculation (and some evidence) that if an axon has lost its myelin only in small regions, the properties of the demyelinated axon membrane change after a time, so that a slow conduction may be restored in the demyelinated region by the continuous-conduction mechanism. (Some axons never become myelinated and operate by the continuous-conduction mechanism exclusive-

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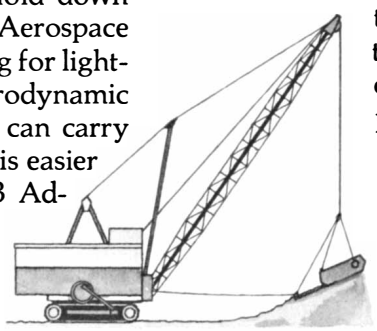

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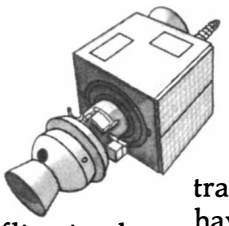

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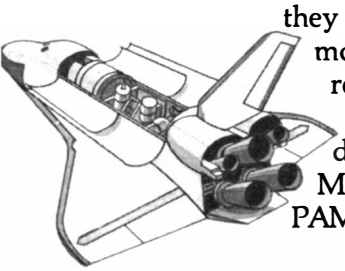

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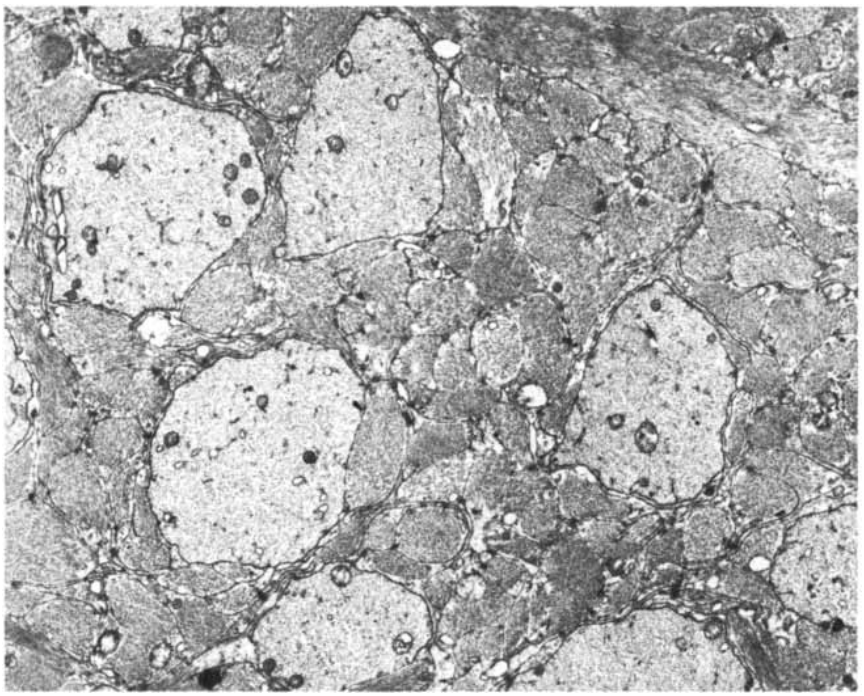
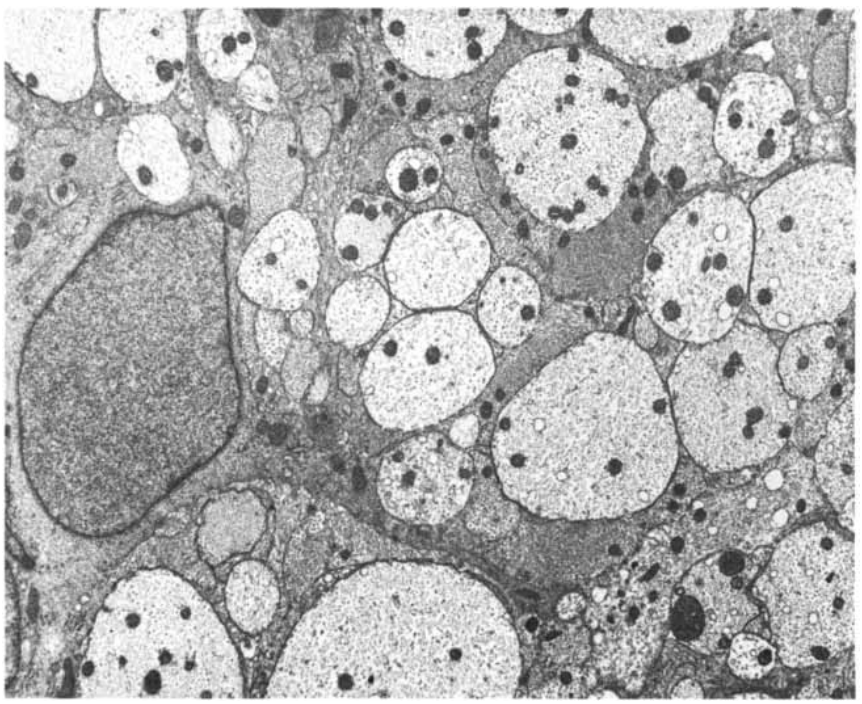


DISEASED REGION of white matter is shown in an electron micrograph of plaque tissue taken at autopsy from the spinal cord of a man who died of multiple sclerosis 20 years after the disease was diagnosed. Cross sections of five axons appear, and parts of a few more. They have lost their myelin sheaths and are embedded in a matrix of abnormal astrocyte processes that produce hardening (sclerosis) of the plaque. One such process courses diagonally at the upper right corner; the others appear in cross section. The minute dots in each such process are filaments cut in cross section. As a comparison with the normal tissue shown in the top illustration on page 89 will suggest, their density is abnormally great. The magnification is 8,000 diameters.



EXPERIMENTAL DISEASE that mimics multiple sclerosis is experimental allergic encephalomyelitis. Like multiple sclerosis, the chronic form of the disease causes axons to lose their myelin and lie embedded in a matrix of abnormal astrocytes. The nucleus of such an astrocyte is at the left. The tissue is taken from the spinal cord of a guinea pig that received a single subcutaneous injection of emulsified white matter and developed an immune reaction to myelin in its own nervous system. The injected material also included an adjuvant: a preparation of dried bacterial membrane that stimulates the immune system nonspecifically. The animal became paralyzed eight weeks after the injection, recovered partially and then relapsed more severely. It was sacrificed 16 weeks after the injection. The magnification is 8,000 diameters.

ly.) That may be why some symptoms of multiple sclerosis remit.

Another possible reason for partial recovery of function is partial remyelination. This may involve the synthesis of myelin by undamaged oligodendroglial cells. Oligodendroglial cells cannot, however, increase in number, and so they have no capacity to remyelinate plaques of any significant size. In plaques that lie in the spinal cord not too far from a nerve a special case has been observed: remyelination by Schwann cells that penetrate into the cord from the peripheral nervous system. Might it be possible to encourage Schwann cells to migrate to plaques farther in the interior of the spinal cord or the brain? At the moment almost nothing is known about how the Schwann cells migrate, nor is there any assurance that remyelination of axons is indeed related to any recovery of function.

Although the cause of multiple sclerosis is obscure, several plausible hypotheses exist. There is evidence suggesting a virus infection. Other evidence shows that the disease has a higher incidence in people with a particular genetic makeup. Moreover, most immunologists would agree that the lesions in the nervous system are consistent with a cellular immune reaction, in which the body destroys its own tissue. The most comprehensive hypotheses include all three of these factors. Such hypotheses propose that a virus infects the brain early in life and that susceptibility to the virus is partly a function of genetic background. Lymphocytes and macrophages then invade the brain, but in the act of destroying the virus they destroy the brain's myelin too. Another possibility is that brain proteins, including those in myelin, are released by the virus infection or by the immunological reaction to the virus and eventually reach the general circulation. Ordinarily these molecules are strictly compartmentalized in the nervous system, and so the immune system, having never encountered them before, might make antibodies against them. The antibodies would then destroy the normal proteins in myelin as if they were foreign invaders.

Experimental Diseases

Let us be somewhat more specific about the evidence bearing on the cause (or causes) of multiple sclerosis. Support for a viral etiology comes from epidemiological studies that correlate the incidence of the disorder not so much with the geographical location where the disease was first diagnosed but with where the patient lived as an adolescent. This pattern is compatible with infection by a virus at an early age and expression of the virus after a latent period of many years. Other "slow virus" disorders have been characterized in recent years. There are also reports that one or

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another research group has found evidence for viruses in the brain of multiple sclerosis patients. Such reports have not yet been confirmed, but further efforts can be expected.

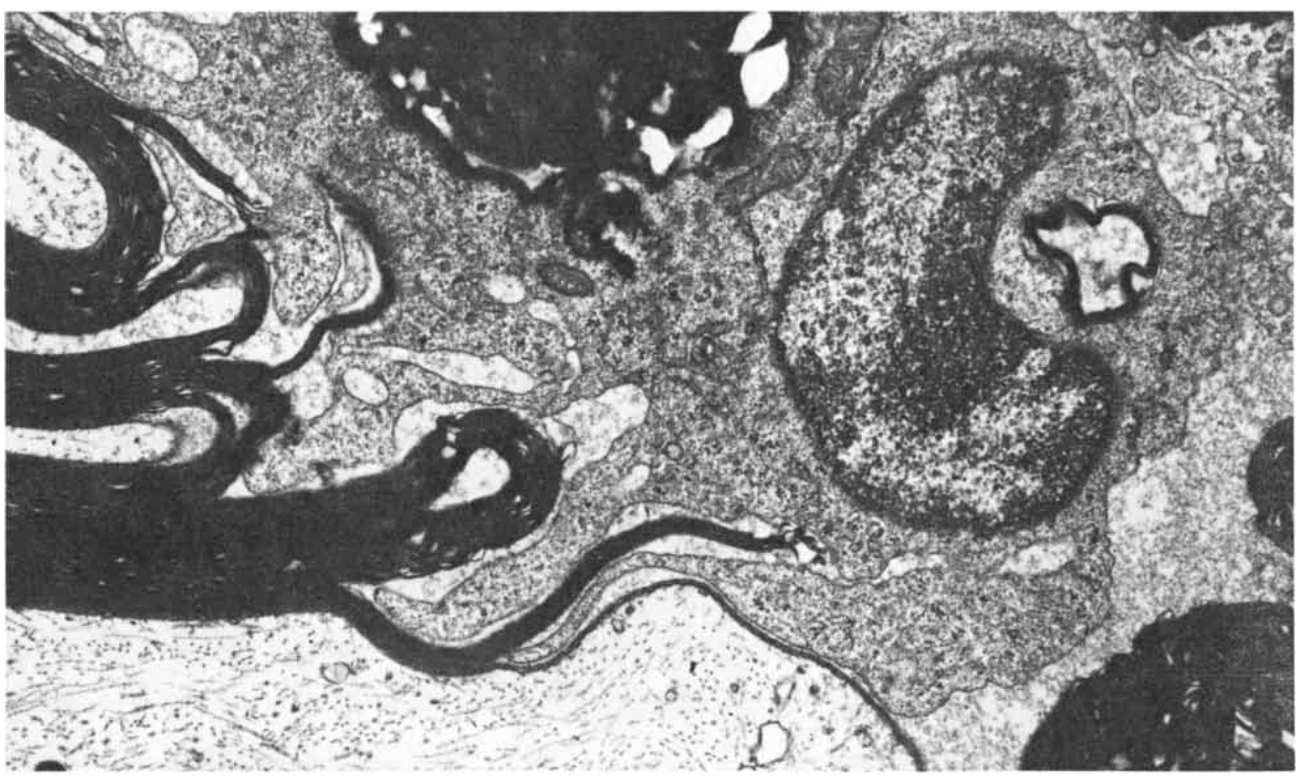
Support for a genetic predisposition to the disease comes from studies in which individuals have been typed according to the presence or absence of certain cell-surface marker molecules. The distribution of these markers in the population was initially studied in connection with the problem of determining compatibility for tissue transplantation, but the typing for certain markers turned out also to have a slight statistical correlation with the increased incidence of certain diseases, including multiple sclerosis.

Finally, support for an immunological etiology is based on the relation between the brain lesions observed in multiple sclerosis and those observed in a disorder called experimental allergic encephalomyelitis, or EAE. EAE has a long and curious history. In the 1880's Louis Pasteur and his colleagues developed a way to modify rabies virus for use as a vaccine while the virus was still in the stage of incubation. Many patients were helped by their treatment, but a significant number had an adverse reaction that led to paralysis and even death. The reason is now known. The modified rabies virus was originally cultured in the brain and the spinal cord of rabbits; thus it was injected into a patient along with representative molecules of the rabbit nervous system. Antibodies might be raised against not only the modified virus but also other components of the mixture. One of these components is evidently the same in rabbit myelin and in human myelin, and so if the human rabies victim was unfortunate enough to have a strong immune reaction, his own lymphocytes would penetrate into his brain and spinal cord, primed to destroy his own tissue.

This accidental disease of human beings is called EAE when it is duplicated in animals by injecting them with an emulsion of brain tissue along with an adjuvant, a bacterial-membrane preparation that stimulates the immune system nonspecifically. The particular protein responsible for the disease—the one at which the immune reaction is directed—was isolated from brain tissue in the late 1950's by the research groups of Marian W. Kies at the National Institute of Mental Health and of Elizabeth Roboz Einstein at the University of California School of Medicine in San Francisco. It was later shown to be myelin basic protein.

Although there are many similarities in the symptomatology and pathology of EAE and multiple sclerosis, there are also many differences. For example, classical EAE fails to show the cycle of remission and relapse characteristic of multiple sclerosis. Furthermore, a therapy that reverses the course of EAE has not yet proved to be useful in the treatment of multiple sclerosis. That therapy is the injection into the bloodstream of myelin basic protein without the addition of an adjuvant. It is the injection, in other words, of the substance that caused the disease. The further injection seems to make the immune reaction spend itself outside the brain.

In connection with immunology the P_2 protein of myelin in the peripheral nervous system is also of importance: when it is injected into animals along with an adjuvant, it can cause an immunological disease. The disease is called experimental allergic neuritis, or EAN; it consists of demyelination and loss of Schwann cells in peripheral nerves. EAN is much like the human disorder Guillain-Barré syndrome, which occasionally occurs as a sequel to certain virus infections. (In the U.S. a number of cases of Guillain-Barré syndrome were brought on a few years ago as a by-product of the "swine flu" vaccination program.) Both EAN and the Guillain-Barré syndrome cause paralysis, and either one can be life-threatening if it interferes with breathing. If appropriate life-support measures are maintained, however, Schwann cells multiply and remyelinate the damaged nerves. Recovery in human cases of Guillain-Barré syndrome is often complete, although



MYELIN IS DEVOURED by a macrophage, a white blood cell, in the nervous system of a rabbit that developed experimental allergic encephalomyelitis after a single subcutaneous injection of white matter and an adjuvant. In the rabbit the disease is acute: it consists of a single episode of an untoward immune reaction. At the left pseudopods of the macrophage lift layers of myelin from an axon. Cytoplasm of the axon appears at the bottom left, under the disrupted sheath. One large fragment of myelin, already pried from the sheath, lies above and at the left of the nucleus of the macrophage. Another is at the right of the nucleus. The magnification is 25,000 diameters.

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residual effects on the control of fine muscle movement are not uncommon.

Sometimes damage to myelin is clearly unrelated to any immunological or viral etiology. It can result, for example, from exposure to certain toxins. The germicide hexachlorophene is notorious in this respect. It was used extensively in hospitals to prevent the spread of staphylococcal infections in infants, and it was included in some deodorant soaps and other proprietary products. The compound can enter the skin and then be carried in the blood to the brain, where it is concentrated in myelin. Several cases of poisoning in which myelin sheaths had become swollen and disrupted were eventually traced to hexachlorophene, which has since been withdrawn from general use. Certain trialkyl tin compounds, which are employed in industrial processes, and acetyl-ethyl-tetramethyl tetralin, a synthetic fragrance at one time used in certain cosmetics, have also been shown to damage myelin preferentially. Moreover, recent work with young animals during their period of rapid myelin formation has shown that relatively low levels of exposure to lead or organic tin compounds can cause a profound and probably permanent deficit of myelin.

Still another group of diseases of myelin consists of developmental disorders due to biochemical defects called inborn errors of metabolism. One such disease, fortunately quite rare, is globoid-cell leukodystrophy. Here the biochemical defect is the inability to break down cerebroside. The normal metabolic turnover of cerebroside is slow, but if it cannot be degraded, it will eventually accumulate. The myelin-forming cells become stuffed with the material. Eventually they die. The name of the disease refers to the accumulation of cerebroside as crystalline or tubular deposits in swollen (globoid) cells. The explanation of the disease is consistent with the metabolic experiments on the normal turnover of myelin constituents.

Our description of myelin and of the myelin-forming cells has placed emphasis on what is known, but the efforts to understand myelin conform to the adage that good experiments raise more questions than they answer. Knowledge of the way myelin-forming cells are attracted to the axons of neurons and triggered to deposit myelin, of how myelin is synthesized and assembled and of how it is metabolized are just approaching the point where one can ask specific questions about the mechanism involved. Along with the increase in knowledge about normal myelin comes information of importance to an understanding of diseases in which myelin is affected. The application of this knowledge to the design of specific therapies for myelin disorders is the obvious, if distant, goal of many research programs.

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The Chemical Evolution of the Earth's Mantle

Clues to the nature and timing of the mantle's differentiation are gained from precise measurements of the isotopic ratios of certain trace elements in rock samples from continental and oceanic crust

by R. K. O'Nions, P. J. Hamilton and Norman M. Evensen

According to the prevailing plate-tectonic theory of geophysics, the oceanic crust, which represents more than two-thirds of the earth's solid surface, is being constantly created at the mid-ocean ridges by flows of lava from the earth's interior. This veneer of basaltic rock, averaging less than a thousandth of the earth's radius in thickness, rides along on top of the considerably denser mantle for as much as thousands of kilometers to a subduction zone, where it plunges downward, returning to the deep recesses of the mantle. The thicker, lighter continents, which account for the remaining third of the globe's surface area, are literally islands of stability amid this shifting scene. Whereas the oldest-known parts of the oceanic crust are about 200 million years old, an area of the continental crust has been found to be close to 3.8 billion years old: almost 20 times older. Yet old as the continents are, they are apparently not primordial features of the earth but rather secondary features that have formed and evolved during the earth's lifetime. Indeed, they appear to be accreting even today. Recent advances in geochemistry offer a clearer view of how the continents have arisen out of material of the mantle and, by inference, how and when the earth as a whole became differentiated into its present multilayered structure.

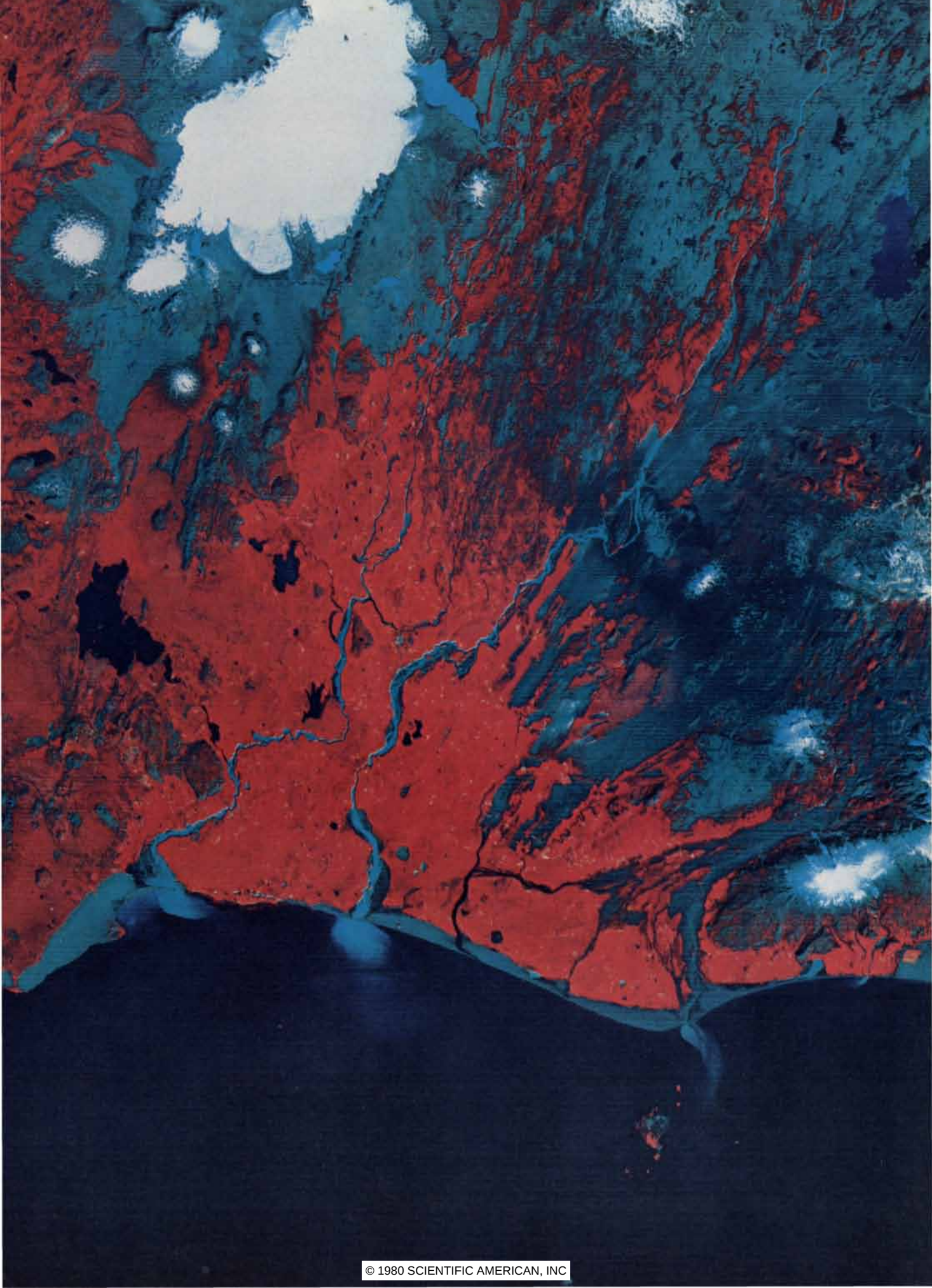
The continental crust has a chemical composition very different from that of the rest of the earth. Although the continents make up only .4 percent of the earth's mass, they have concentrated within them disproportionately large shares of the earth's inventory of certain elements. Among the most notable of these elements are the heat-producing radioactive isotopes of potassium, thorium and uranium; a significant fraction of each of these elements now resides in the continents. Within the past two decades it has been demonstrated on the basis of the systematic radiometric dating of continental rocks that the continents themselves must have grown more or less continuously over the course of geologic time. In the early 1960's Patrick M. Hurley and his colleagues at the Massachusetts Institute of Technology were able to show that the continents are the product of many separate episodes of chemical differentiation, and a great deal of evidence has since been adduced in support of this conclusion [see "The Oldest Rocks and the Growth of Continents," by Stephen Moorbath; SCIENTIFIC AMERICAN, March, 1977].

The outstanding questions concerning the role of the earth's mantle in producing the continents include the following: How much of the mantle is involved in the formation of the continents? Do the mantle-derived lavas that have erupted at the surface come from previously differentiated mantle or from undifferentiated mantle? Over what part of the earth's history have the continents developed and at what rate? How much early continental material has been recycled back into the mantle?

The search for satisfactory answers to these questions involves the difficult task of deciphering from a very incomplete geologic record the comparative distributions of various elements between the mantle and the continental crust as a function of time. In a situation where much of the material of interest is securely out of reach one must resort to the use of geochemical "tracers" to reconstruct some record of the chemical fractionation and differentiation that has taken place. The most recent and successful work of this kind has exploited the nonradioactive decay products of radioactive trace elements with half-lives comparable in duration to the age of the earth. These naturally occurring "parent-daughter" associations include the parent isotopes potassium 40, rubidium 87, samarium 147, thorium 232, uranium 235 and uranium 238, together with their respective daughter isotopes calcium 40 (or argon 40 in the case of electron capture by potassium 40), strontium 87, neodymium 143, lead 208, lead 207 and lead 206 [*see illustration on page 123*].

One feature common to all these elements is that their ionic radii are much larger than those of the most abundant constituents of the mantle, such as magnesium, aluminum, silicon and iron. The large ionic radii of the trace elements, together with their propensity to substitute for other ions in the comparatively open silicate structures of the rocks of the earth's crust, has led geochemists to refer to them as large-ion lithophile elements. In spite of the comparatively low abundance of the large-ion lithophile elements in the earth, three of them—potassium, thorium and uranium—are responsible for most of the earth's internal heat production. The degree to which these trace elements are concentrated selectively in the continental crust can be appreciated by comparing their abundances in the continental crust with their abundances in the earth as a whole [*see top illustration on page 124*]. Because the trace elements have larger ionic radii than magnesium, silicon or iron, which make up most of the dense rocks

MATERIAL FROM THE MANTLE is exposed in the form of newly created oceanic crust in this Landsat image of southern Iceland. The entire island is part of the Mid-Atlantic Ridge system. Here the crest of the ridge, an intensely active volcanic zone, runs southwest-northeast. In this false-color image, made in the summertime, the dark gray areas correspond to the most recent lava flows and the red areas are somewhat older lava beds covered with vegetation. Large white shapes are glaciers. Circular white spots are snow-capped volcanoes. The small islands at the bottom include Heimaey and Surtsey, both sites of volcanic eruptions in recent years.



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*Manufacturer's suggested retail price for GS Model shown. S Model $7495. Slightly higher in California. Actual prices established by dealers. Taxes, license, freight, optional equipment and any other dealer charges are extra. (Wide alloy wheels shown $275-$295.) All prices subject to change without notice.

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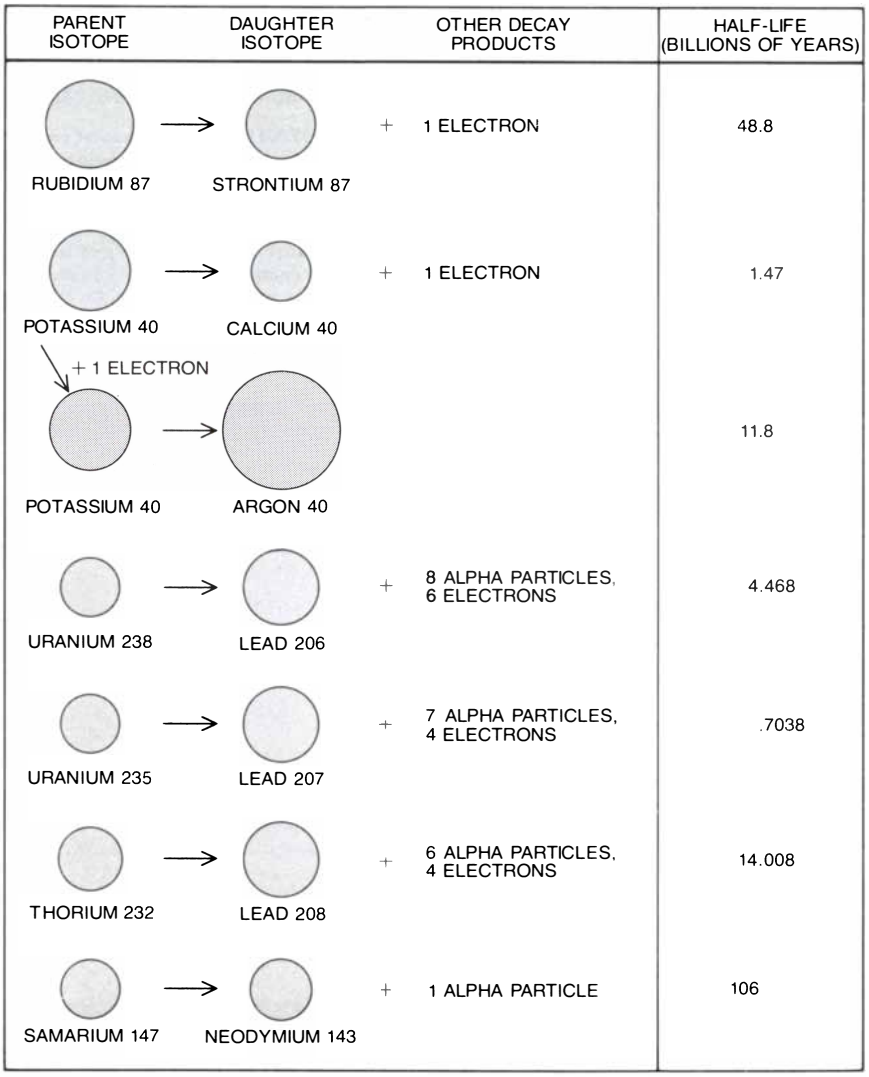
of the mantle, they do not substitute readily in these rocks.

How does the abundance of a particular daughter isotope reflect the fractionation history of a part of the earth? Consider the abundance of the daughter isotope lead 206 at a given time and place within the earth. Some of the lead 206 will have existed from the time of the earth's formation, but it will have been augmented by additions from the decay of the parent isotope uranium 238. The exact amount of lead 206 present will reflect changes in the ratio of uranium to lead as a function of time. If, for example, the fractionation history of uranium and lead is such that at some time in the past one part of the earth had a high uranium/lead ratio and another part had a low uranium/lead ratio, then after a certain elapsed time the relative abundance of lead 206 in the first part would be expected to be greater than that in the second. The difference is conveniently illustrated by expressing the abundance of lead 206 with respect to the abundance of an isotope of lead that has not received radiogenic additions, namely lead 204. Thus the fractionation history of uranium and lead in the earth is recorded in the variability of the lead 206/lead 204 ratio from time to time and place to place.

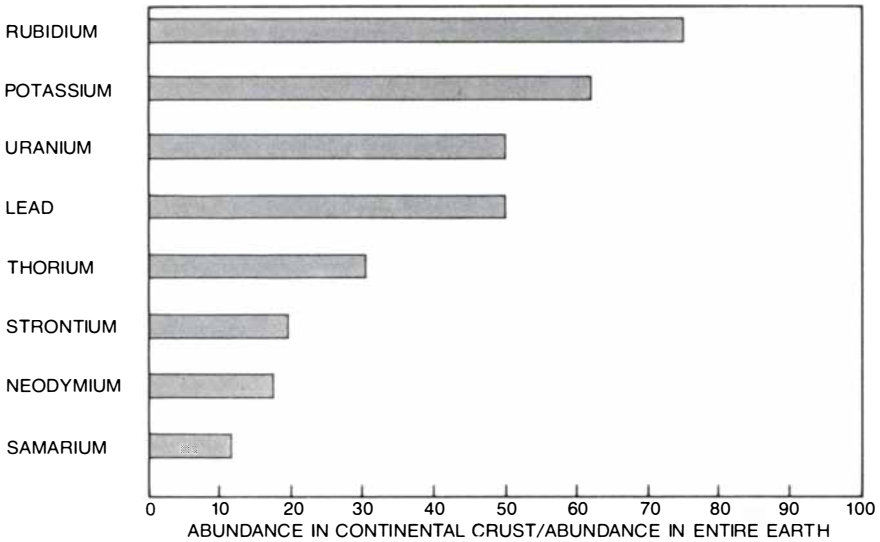
In a similar way the ratios of lead 208 to lead 204, of lead 207 to lead 204, of neodymium 143 to neodymium 144, of strontium 87 to strontium 86 and of argon 40 to argon 36 will respectively reflect the fractionation histories of the thorium-lead, uranium-lead, samarium-neodymium, rubidium-strontium and potassium-argon parent-daughter associations. Because the half-lives of the parent isotopes are all comparable to the age of the earth the present isotopic ratios of argon, strontium, neodymium and lead can be taken as a reflection of parent-daughter fractionations that have taken place over the entire history of the earth. The daughter of a parent isotope with a much shorter half-life, such as xenon 129, the decay product of iodine 129, which has a half-life of 16 million years, can reflect only the fractionation of iodine and xenon that occurred in the first couple of hundred million years after the formation of the earth. Parent-daughter associations with such short half-lives are of limited value for studying processes that have occupied a large fraction of the earth's history, such as the growth of continents.

The selective removal of large-ion lithophile elements from the mantle and their concentration in the developing continental crust are processes that involve relative fractionations in the abundances of these elements. For example, the continental crust develops with a higher ratio of rubidium to strontium and a lower ratio of samarium to neodymium than exist in the mantle; in both cases the continents selectively concentrate the element with the larger ionic radius of the pair. As a result the continents evolve with a greater relative abundance of strontium 87 and a lesser relative abundance of neodymium 143 than the mantle, a phenomenon that is recorded in a higher strontium 87/strontium 86 ratio and a lower neodymium 143/neodymium 144 ratio in the continents compared with the residual mantle. In principle, therefore, isotopic studies of new additions of material to the continents at various times can provide information about the previous differentiation history of the source from which the sample was extracted. Similarly, the present isotopic composition of mantle-derived samples will in principle yield information about the mantle's prehistory.

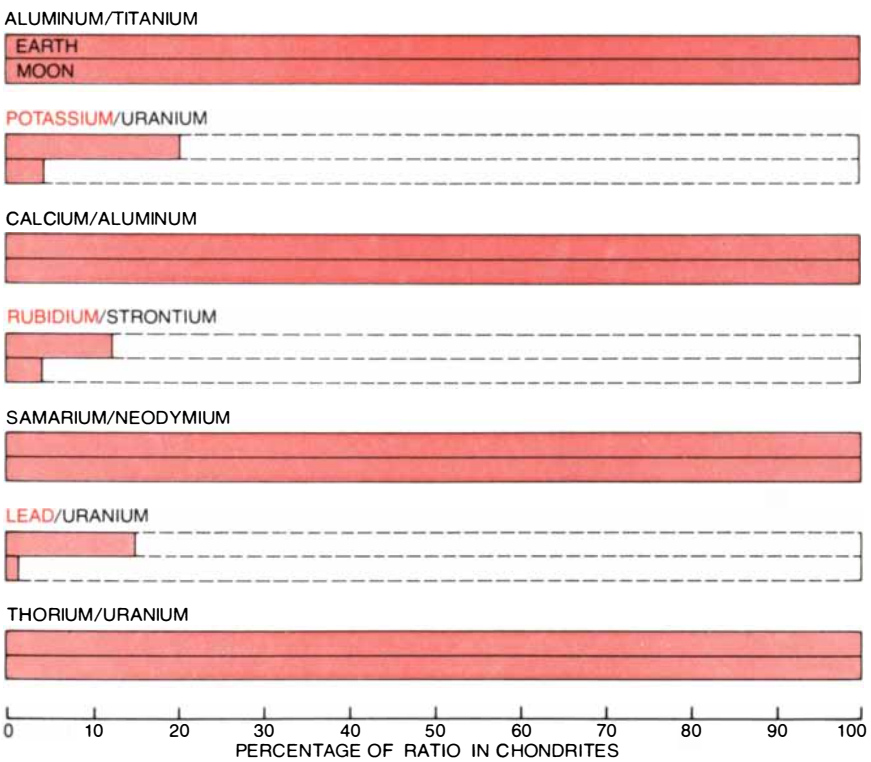
This article is primarily concerned with recent developments in geochemistry that furnish insights into the nature and timing of the processes that have produced the earth's present chemically differentiated character. Before



LARGE IONIC RADII of an assortment of radioactive trace elements and their respective major decay products are crucial to the effectiveness of these isotopes as geochemical probes. The ions constituting each "parent-daughter" association are drawn to the same scale at the left. (The smallest of these isotopes, samarium 147, has an ionic radius of .964 angstrom unit.) As the column at the right shows, each of the parent isotopes has a half-life on the order of (or greater than) the estimated age of the earth (4.55 billion years). Potassium 40 can decay by either capturing or emitting an electron, leading to different daughter isotopes. With the exception of calcium, all the parent and daughter isotopes shown are present in trace amounts in the earth (one part per million or less). Each of the trace elements has an ionic radius larger than that of the much commoner elements silicon, aluminum, magnesium, calcium and iron, which in the form of oxides make up most of the earth's mantle. The large ions do not fit into the dense crystal structures of the mantle minerals, which generally accommodate only the more abundant smaller ions. As a result the larger ions migrate to the crust, where they reside in less dense crystal structures. The largest ion, that of argon 40, can escape into the atmosphere, which is about 1 percent argon. This argon is almost entirely the product of the decay of potassium 40.



ABUNDANCES OF SOME LARGE-ION TRACE ELEMENTS in the continental crust, estimated by S. R. Taylor of the Australian National University, are given as a function of their estimated abundances in the earth as a whole. The elements with the largest ionic radius tend to exhibit the greatest degree of enrichment in the crust. In spite of the insignificant mass of the crust compared with that of the mantle, a significant fraction of the earth's total inventory of these large-ionic-radius elements resides in the crust. Because of the propensity of such elements to substitute for those with smaller ionic radii in the comparatively open silicate structures of the crustal rocks, they are referred to by geochemists as large-ion lithophile elements.



THE EARTH AND THE MOON APPEAR TO BE DEPLETED in certain volatile trace elements (*colored type*) when the ratios of pairs of elements are compared with corresponding ratios in carbonaceous chondrites, a class of meteorites that are considered to be representative of the average composition of the solar system. (Ratios are used for this purpose rather than average abundances, because they can be determined with greater precision.) When both elements are refractory, and hence would presumably have condensed together at high temperatures out of the primordial solar nebula, their ratio is identical in the earth, the moon and the chondrites. The ratio of volatile elements to refractory ones is found to be lower in the earth than in the chondrites, however, and it is lower still in the moon. The volatile elements would have condensed out of the cooling solar nebula later than the refractory ones; the earth and the moon appear to be depleted in this volatile fraction. (Here lead refers to primordial lead and does not include lead produced since the earth's formation by decay of uranium and thorium.)

getting into the details it will be helpful to compare the abundances of some of the elements in the earth that are relevant to our story with their estimated abundances in the primordial solar nebula and also in the moon, the only other sizable object in the solar system for which appropriate data are currently available.

The inner, terrestrial planets, such as the earth and Mars, have in general retained a much smaller complement of the most volatile elements (hydrogen, for example) from the solar nebula than the outer, giant planets, such as Jupiter and Saturn. Furthermore, recent planetary explorations have uncovered significant differences in composition among the earth, Mars and the moon. Much of the ensuing discussion will be concerned with the abundances and isotopic ratios of potassium, argon, rubidium, strontium, neodymium, samarium, lead, thorium and uranium, all of which are trace constituents not only of the earth but also of the other terrestrial planets. For comparative purposes magnesium, aluminum and silicon, which are major constituents of both the earth and the other terrestrial planets, will also enter the discussion. As far as these particular elements are concerned the meteorites known as carbonaceous chondrites are considered to represent the best approximation of their abundances in the primordial solar nebula.

The first point to be noted from a comparison of this type is that the abundances of most of the elements named are roughly the same in the earth, the moon and the carbonaceous chondrites. In contrast, potassium, rubidium and lead are apparently less abundant in the earth and the moon than in the chondrites, the extent of the depletion being greater in the case of the moon. The relative depletion of potassium can be demonstrated on the basis of the measured potassium/uranium ratios of terrestrial, lunar and chondritic samples. The relative depletion of rubidium and lead can be demonstrated on the basis of the known isotopic compositions of the strontium and lead in these three materials.

Lawrence Grossman of the University of Chicago has calculated that in a gas of the same composition as that of the sun calcium, aluminum, strontium, neodymium, samarium, uranium and thorium would all be quite refractory, condensing at temperatures higher than 1,350 degrees Kelvin, whereas potassium, rubidium and lead would all condense at lower temperatures, the least refractory of these being lead, which would condense at about 520 degrees K. It is beyond the scope of this article to review the possible mechanisms by which this fractionation of elements of differing volatility could have occurred in the earliest stages of the solar system; it is sufficient here merely to note that

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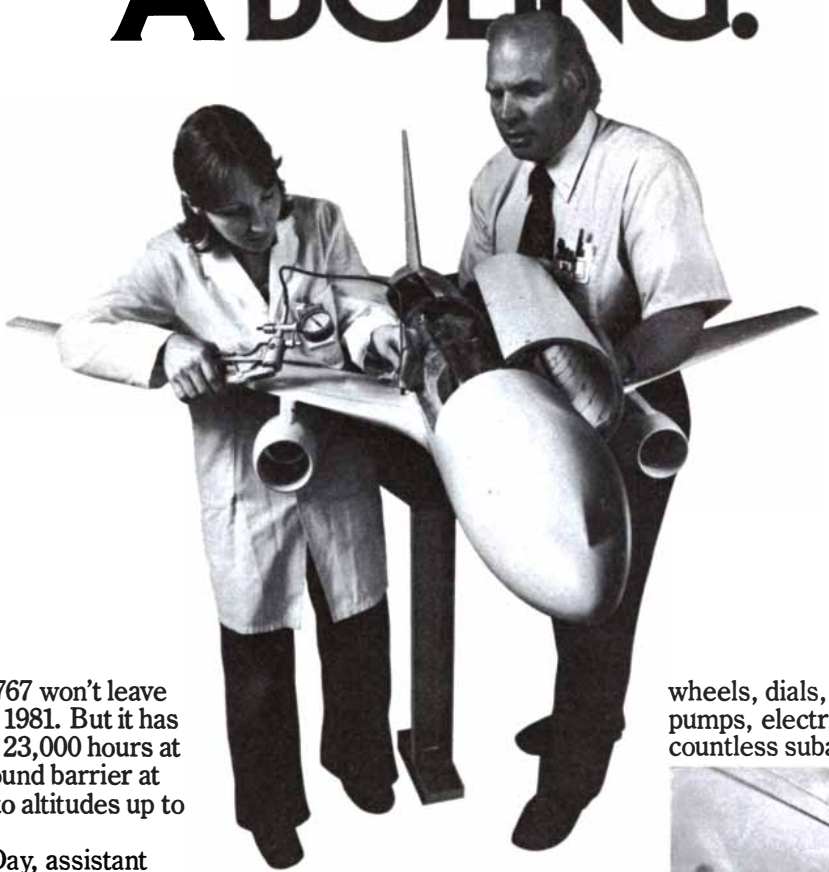

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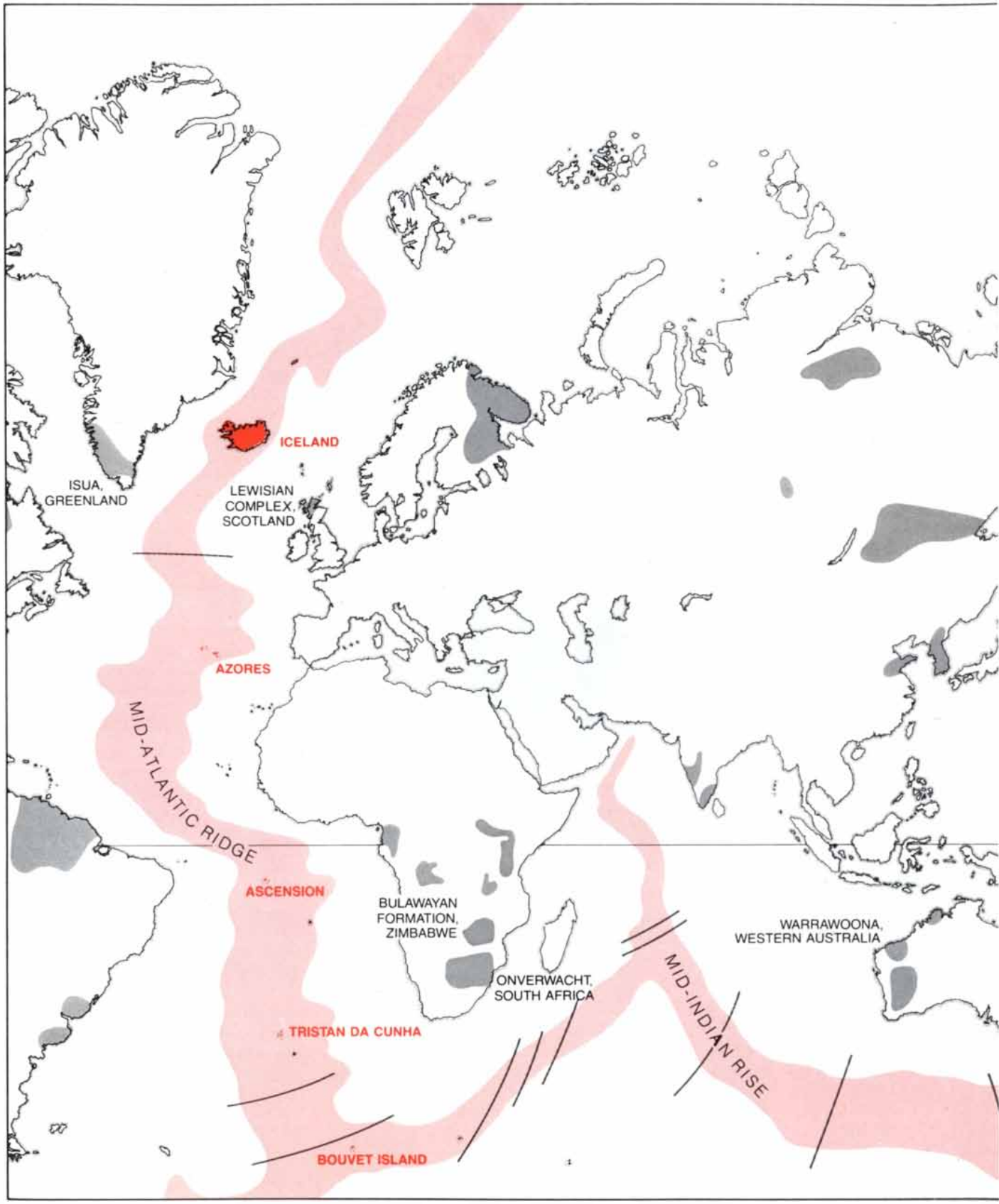
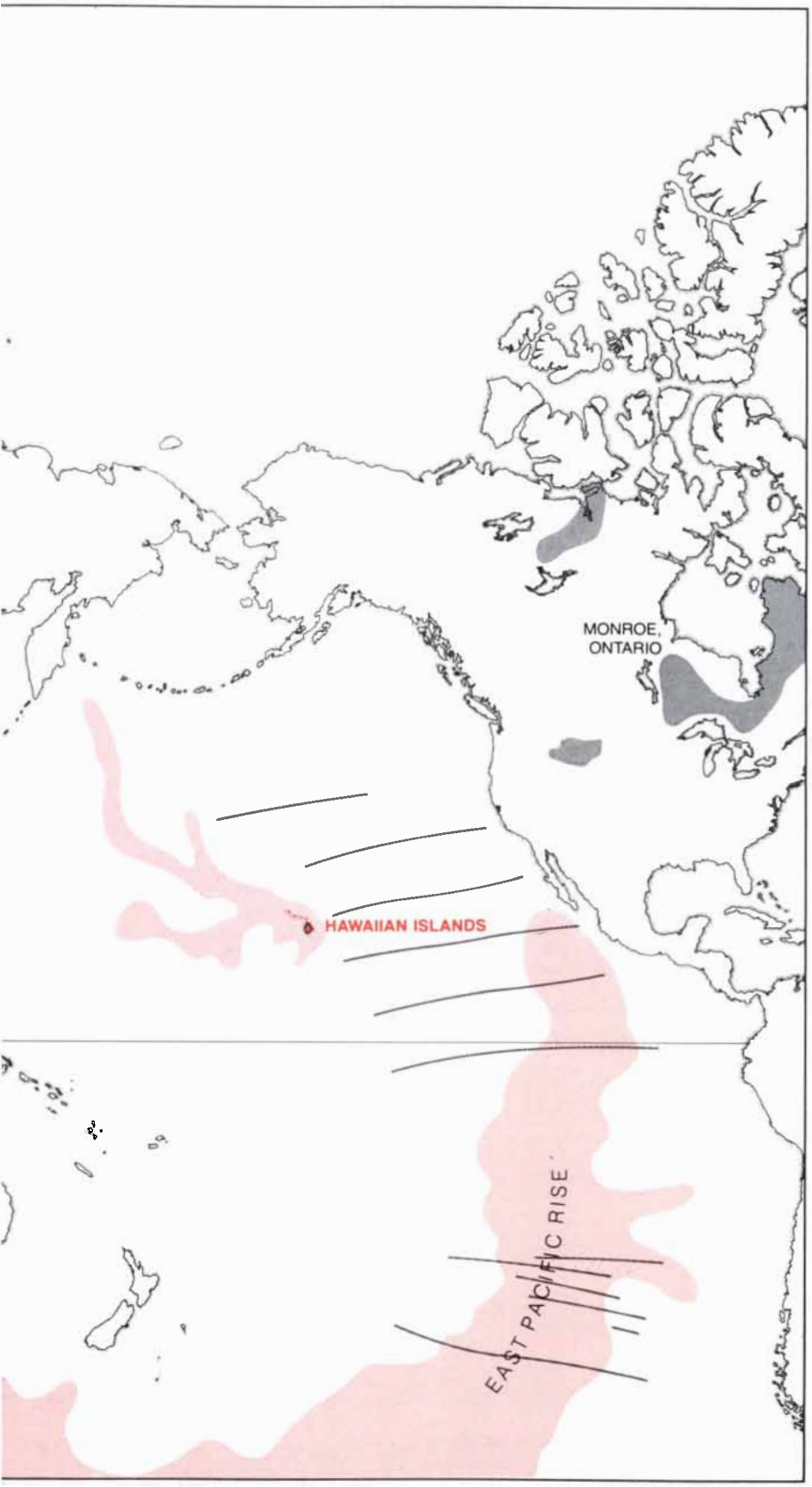


ROCK SAMPLES analyzed in the investigation of the isotopic ratios of large-ion lithophile elements in the continental crust and the oceanic crust are located. Parts of the continental crust more than 2.5 billion years old are in gray; in general they are found in the most ancient, tectonically stable "shield" regions of the continents. Rocks from the named regions have figured specifically in the recent determination of the early isotopic history of the earth. The colored areas include the youngest parts of the earth's crust: the mid-ocean ridges, where new crust is created by the flow of lava from the mantle. Isotopic analyses of these lavas indicate they are derived from mantle

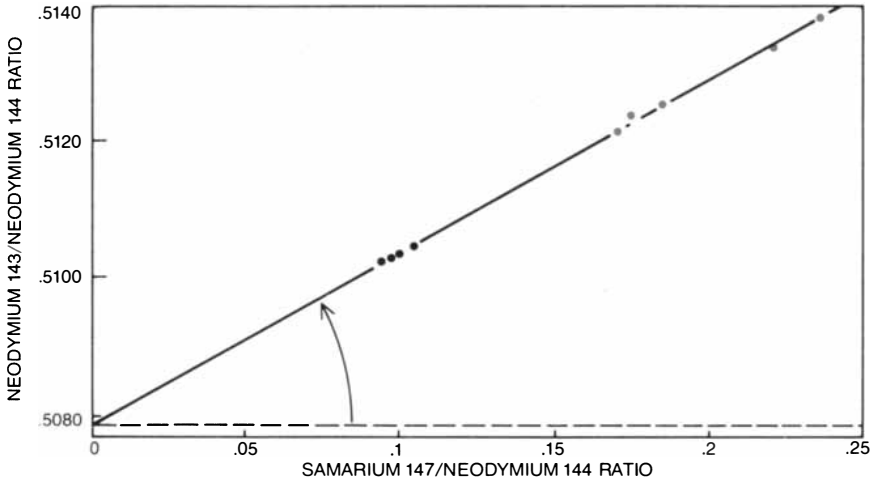


material that is depleted in the very elements (particularly in the heat-producing radioactive trace elements potassium, thorium and uranium) selectively concentrated in the continental crust. The oceanic islands, marked in solid color, have emerged as a result of particularly voluminous flows of lava. Analyses of rocks from these islands suggest that the rocks are derived from mantle material less depleted than that responsible for the rest of the mid-ocean ridges.

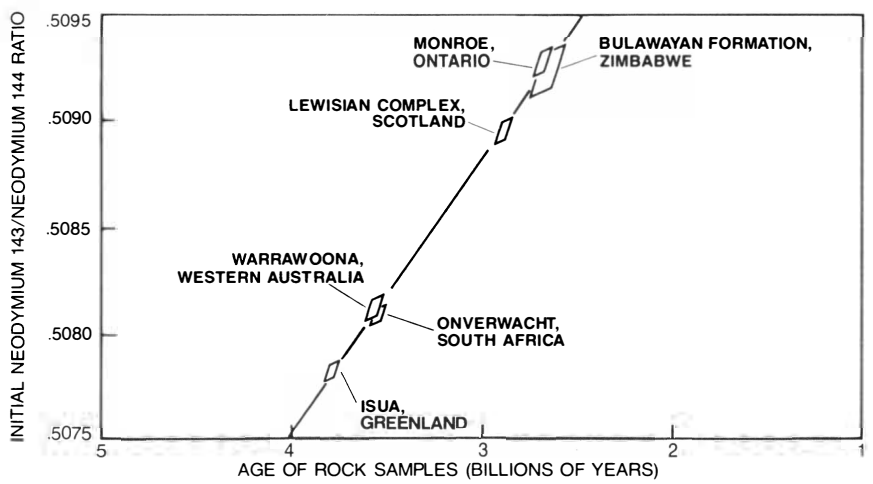
the earth and the moon appear to have formed with an assortment of refractory elements present in roughly chondritic proportions, but with a marked (and in the case of the moon an extreme) depletion in the more volatile elements. (The notion that the earth has a chondritic composition was popular for many years among geophysicists investigating terrestrial heat flow because of the coincidence of the conductive heat loss from the earth and the average rate of heat production in the chondritic meteorites. It now appears, however, that the ratios of the refractory elements thorium and uranium, two of the main heat-producing elements in the earth, to the more volatile potassium, the third important heat-producing element, in the earth differ greatly from those in the chondrites.)

Having considered briefly the abundances of some elements in the entire earth in the context of the composition of the primordial solar nebula, let us now turn our attention specifically to the differentiation of the earth itself. We shall first consider the progress that has been made in extracting isotopic data from some of the older parts of the continents. The prime objective of such investigations is to derive the values of the strontium 87/strontium 86, neodymium 143/neodymium 144, lead 208/lead 204, lead 207/lead 204 and lead 206/lead 204 ratios for the source region of a given segment of continental crust and to compare these values with the predicted isotopic ratios for undifferentiated mantle at that time.

Since 1975 considerable progress has been made in exploiting the samarium-neodymium system for the solution of problems in geochronology and in utilizing neodymium 143 as a natural tracer of geological processes. The rubidium-strontium and uranium-lead systems have been exploited successfully for two decades or more, but the application of the samarium-neodymium system was impeded by technical difficulties involved in the extraction of samarium and neodymium from rock samples and in the isotopic analysis of these elements to the required degree of precision. Because samarium 147 decays very slowly, extremely small differences in the abundance of neodymium 143 must be determined. Precise mass-spectrometric techniques now exist for such measurements, largely because of the pioneering efforts of Gerald J. Wasserburg and his colleagues at the California Institute of Technology. In 1975 Guenter W. Lugmair of the University of California at San Diego published the first precise isotopic analyses of the samarium-neodymium system in an achondritic meteorite and a lunar sample. Subsequently C. J. Allègre and his colleagues at the Univer-



ROCKS FROM ISUA, an ancient metamorphosed volcanic deposit in western Greenland, are dated by means of measurements of their samarium/neodymium and neodymium-isotope ratios. Assuming that the rocks formed originally from a part of the mantle with a uniform ratio of neodymium 143, the daughter isotope of samarium 147, to neodymium 144, an isotope that is neither generated nor consumed by radioactive decay, then the neodymium 143/neodymium 144 ratios of the rocks will increase with time, at rates that are proportional to their samarium 147/neodymium 144 ratios. Basic igneous rocks (*colored dots*) form with higher samarium 147/neodymium 144 ratios, closer to the original mantle value, than the more acid, silica-enriched rocks (*black dots*). In a plot of neodymium 143/neodymium 144 against samarium 147/neodymium 144, such as this one, all the dots would originally lie on the broken horizontal line. As the rocks evolve and develop higher neodymium 143/neodymium 144 ratios with time, the faster growth of the neodymium 143/neodymium 144 ratio in rocks with higher samarium 147/neodymium 144 ratios will cause the line to pivot upward at the right. The slope of the resulting line, called an isochron, indicates how long the rocks have followed their separate evolutionary paths since forming from a homogeneous reservoir. The age of the Isua samples determined by this method is 3.77 billion years, more than four-fifths of the age of the earth. Any disturbance that added or removed samarium or neodymium during that time would tend to destroy the linearity of the isochron. Only a hypothetical rock with a samarium 147/neodymium 144 ratio of zero would display no change in its neodymium 143/neodymium 144 ratio and so would preserve the original value of this ratio at the time the rocks formed. Since rocks with samarium 147/neodymium 144 ratios much lower than those shown here are not likely to form, the initial neodymium 143/neodymium 144 ratio of the Isua rocks is obtained by extrapolating the isochron to zero on the samarium 147/neodymium 144 axis. The initial ratio found in this way is an indicator of the isotopic composition of the mantle at that time (3.77 billion years ago). Similar measurements can be made with other parent-daughter associations, but the proportions of most such elements change in the course of metamorphism and therefore do not yield as accurate dates or initial isotopic ratios by the isochron technique.



EVOLUTION OF THE RATIO of neodymium 143 to neodymium 144 in the mantle can be followed by plotting the ages of rock samples from six ancient regions of the continental crust against their initial neodymium 143/neodymium 144 ratios, derived by the isochron technique. The symbols in this case are parallelograms within which there is a 95 percent probability that the true value lies. All the age determinations summarized here were obtained by the authors, except for the dating of the rocks from Monroe Township in Ontario, which was carried out by Alan Zindler and Stanley R. Hart of the Massachusetts Institute of Technology. The fact that the points lie close to a line representing the growth of the neodymium 143/neodymium 144 ratio in meteorites with a characteristically chondritic samarium 147/neodymium 144 ratio is evidence that the mantle formed with a chondritic samarium/neodymium ratio.

sity of Paris, Donald J. DePaolo and Wasserburg at Cal Tech, and our group, which was then at the Lamont-Doherty Geological Observatory of Columbia University, published the results of neodymium-isotope studies for a range of terrestrial samples and demonstrated the utility of the neodymium-isotope approach for investigating a variety of geological problems.

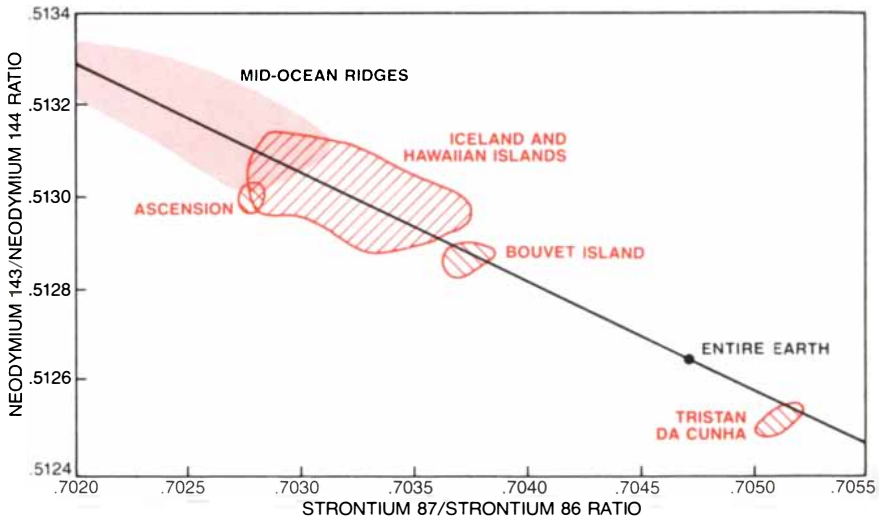
The samarium-neodymium system has been extremely valuable in studying the oldest components of the continental crust because of its survival through various alteration processes. The ratio of rubidium to strontium is often disturbed by weathering and other processes that affect volcanic rocks after their eruption, making the observed strontium 87/strontium 86 ratios difficult to interpret. In contrast, the work done so far has shown that the samarium/neodymium ratios are much less likely to be disturbed. This fortunate attribute of samarium and neodymium has enabled us to obtain precise samarium/neodymium ages and initial neodymium 143/neodymium 144 ratios for some old parts of the continents [*see top illustration at left*]. In particular we obtained samarium/neodymium ages for some supracrustal rocks (that is, rocks deposited on preexisting crust) discovered at Isua in Greenland that are among the oldest-known rocks on the earth. Although the samples we studied were altered considerably since their original extrusion as lava, they have yielded a precise age of 3.77 billion years, which is in excellent agreement with the date obtained by Allègre's group in Paris, based on the analysis of the uranium/lead ratio in samples of zircon (zirconium silicate) from the Isua site. In addition to determining the time the Isua samples formed we also established the neodymium-isotope ratio of their source region with high precision. Precise samarium/neodymium ages and initial neodymium-isotope ratios have also been obtained by the authors from the Onverwacht group in South Africa (3.54 billion years), the Warrawoona group in Western Australia (3.56 billion years), the Lewisian complex in Scotland (2.92 billion years) and the Bulawayan formation in Zimbabwe (2.64 billion years).

The ages and the initial neodymium-isotope ratios of these rocks may be plotted against one another and compared with the evolution of the neodymium-isotope ratio from 4.55 billion years ago in material that has a chondritic samarium/neodymium ratio, as deduced from the analysis of meteorites. One obtains a line corresponding to a samarium/neodymium ratio of .31, which is the current best estimate of the cosmic-abundance ratio. The fact that the data for terrestrial samples more than 2.5 billion years old plot close to this line indicates that the source region

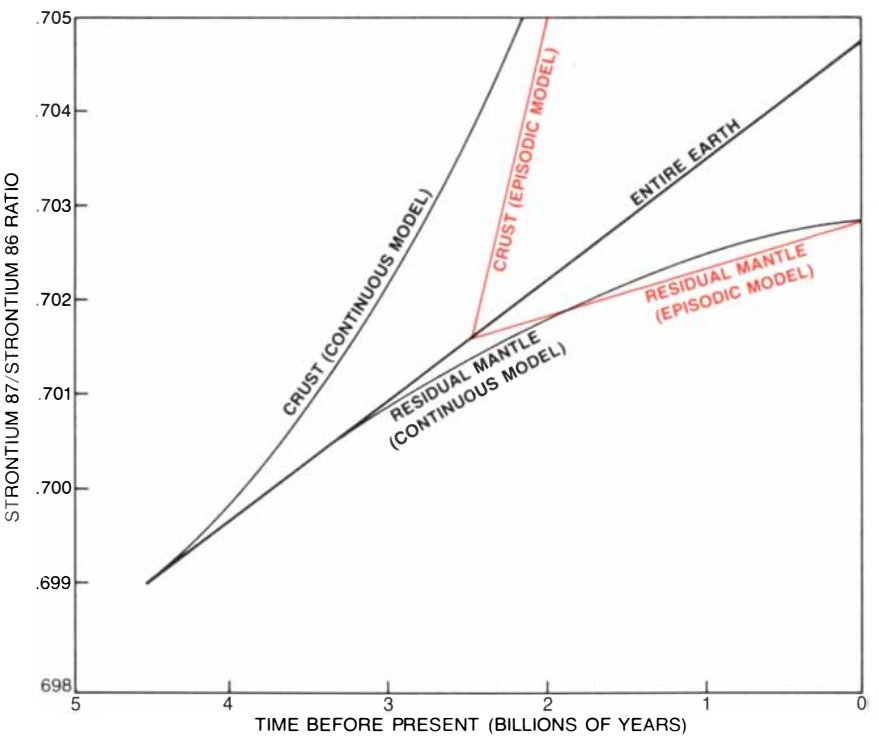
of early crust and by inference the earth as a whole had a samarium/neodymium ratio indistinguishable from the cosmic-abundance ratio. The separation of continental crust leaves the residual mantle with a higher ratio of samarium to neodymium than the earth as a whole; hence the average neodymium-isotope ratio of the present mantle cannot lie on the extrapolated portion of the line but must lie above it. Furthermore, the results obtained are consistent with the apparent absence of continental rocks older than the Isua samples. The separation of large amounts of continent before about 3.8 billion years ago, if it had occurred, would be identifiable from the initial neodymium-isotope ratios of basic volcanic rocks erupted in more recent times and preserved in the continents.

Armed with the knowledge that undifferentiated mantle should always have had a ratio of samarium to neodymium equal to the cosmic-abundance ratio, we have been able to make a precise estimate of the present isotopic composition of neodymium in undifferentiated mantle. For the purpose of identifying those parts of the mantle that have donated material to the growth of the continents a survey of the neodymium-isotope composition of the upper mantle would clearly be of considerable value. With the exception of xenolithic (literally "foreign rock") fragments of mantle that are occasionally brought to the surface by kimberlite pipes and some basalt formations, direct sampling of the upper mantle is impossible. As a result it has been necessary to glean information from differentiation products of the mantle, namely the basaltic lavas erupted in the ocean basins and continents. Most recent basalts have been erupted along the mid-ocean ridges, which are the sites of plate generation and sea-floor spreading, but basalts are also erupted in smaller quantities in intraplate locations and along island arcs.

Until the start of the Deep Sea Drilling Project only a comparatively small number of basalt samples had been recovered from the ocean floor, but over the past decade the situation has changed dramatically. The Deep Sea Drilling Project has now entered an international phase of ocean drilling with the participation of France, West Germany, Japan, Britain and the U.S.S.R., and samples have been recovered from a large number of sites in the Atlantic, Indian and Pacific ocean basins. Many additional dredge samples have been obtained from mid-ocean ridges. Probably the most noteworthy of these dredging operations is the systematic and closely spaced dredging along the northern Mid-Atlantic Ridge organized by Jean-Guy Schilling of the University of Rhode Island. In addition to



NEGATIVE CORRELATION is observed when measurements of the neodymium-isotope ratio are plotted against measurements of the strontium-isotope ratio for young basaltic rock samples obtained from mid-ocean ridges (*light color*) and oceanic islands (*dark color*). During the formation of the continental crust the mantle was more depleted in rubidium than in strontium and in neodymium than in samarium. Subsequently the neodymium 143/neodymium 144 ratio increased more rapidly and the strontium 87/strontium 86 ratio increased less rapidly in depleted mantle than in undepleted mantle. The mantle underlying the ridges was apparently more depleted than that from which the oceanic islands formed. Assuming that undepleted mantle has a samarium/neodymium ratio characteristic of chondrites, one can calculate the present neodymium 143/neodymium 144 ratio of the entire earth. If undepleted mantle lies on the anticorrelation line, its present strontium 87/strontium 86 ratio and therefore its present rubidium/strontium ratio can also be determined. As depleted mantle evolved chemically away from the point for the entire earth the continents evolved in a complementary manner. The point for typical continental crust would lie off the bottom right-hand corner of the graph.



TWO MODELS OF CRUSTAL EVOLUTION are compared in terms of the evolution of their strontium 87/strontium 86 ratios in the crust and the mantle. In the continuous model crust has been produced continuously from the time of the earth's formation, and the crust and the mantle evolve with strontium-isotope ratios that are increasingly different from the ratio of the earth as a whole. In the episodic model it is assumed that the present crust formed 2.5 billion years ago. In actuality older regions of crust are known. Even for this extreme case the evolution of the mantle is quite similar in the two models, since the mantle is a much larger reservoir of strontium than the crust. Curves representing the two models in terms of the evolution of their neodymium-isotope ratios would be even more similar, since samarium and neodymium are less strongly fractionated between the crust and the mantle than rubidium and strontium.

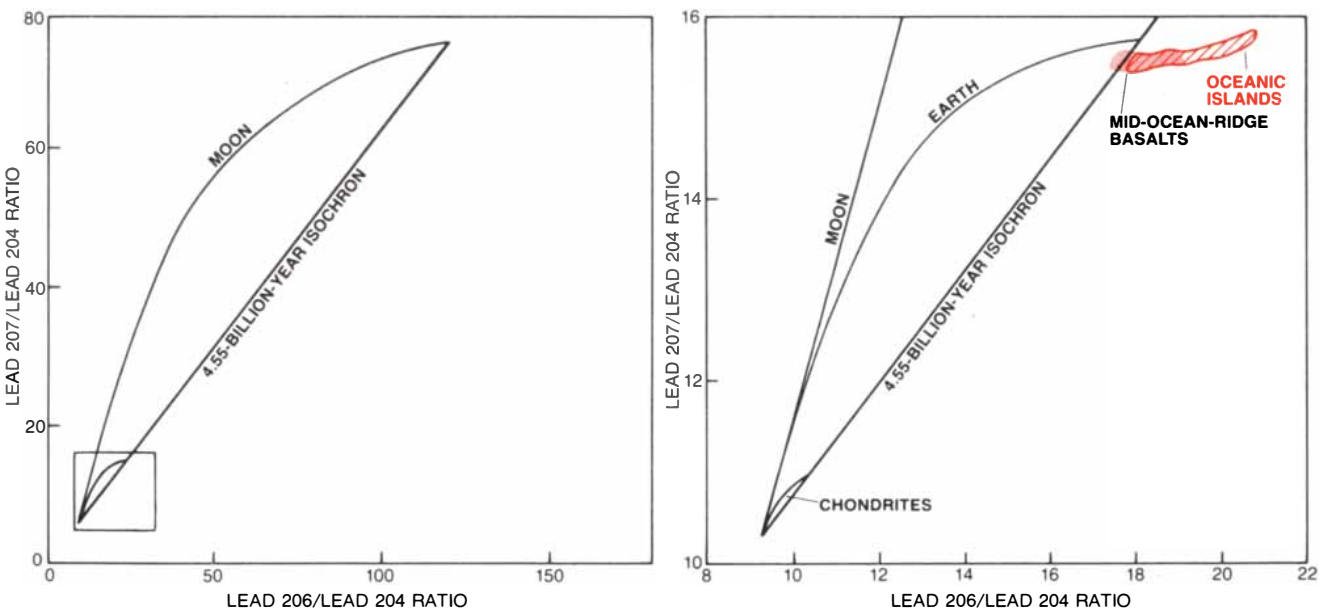
the advances made in ocean-bottom sampling, oceanic islands, particularly Iceland and the Hawaiian Islands, have been further sampled.

The most important advances in understanding the prehistory of the source regions of oceanic basalts have again come from isotopic analyses of strontium and neodymium made over the past few years. The analyses obtained for oceanic basalts exhibit a small range of strontium 87/strontium 86 and neodymium 143/neodymium 144 ratios and are compared with the current best estimates of the same isotopic ratios in the earth as a whole (or in undifferentiated mantle). The ocean-ridge basalts from the Atlantic, Indian and Pacific oceans have isotopic ratios of strontium and neodymium that are respectively lower and higher than the values for the earth as a whole. The lower strontium-isotope ratio requires that the source region of the ocean-ridge basalts have evolved with a lower ratio of rubidium to strontium than the earth as a whole or undifferentiated mantle, whereas the higher neodymium-isotope ratio requires that the samarium/neodymium ratio in the source region be higher than it is in the earth as a whole.

The movement of certain elements from the mantle to the crust has influenced the subsequent isotopic evolution of the mantle. The strontium 87/strontium 86 and neodymium 143/neodymium 144 ratios of recent mid-ocean-ridge basalts seem to be entirely consistent with the hypothesis that components with a higher rubidium/strontium ratio and a lower samarium/neodymium ratio than the earth as a whole have been removed and now reside in the continents. It is not possible to specify unequivocally from these data alone, however, whether the depletion of the mantle has been a continuous phenomenon or an episodic one. Nevertheless, it is clear that the ocean floor created at mid-ocean ridges is derived from a mantle that bears in its isotopic composition the evidence of previous depletion in large-ion lithophile elements.

The comparative uniformity of the isotopic composition of strontium and neodymium in mid-ocean-ridge basalts contrasts with the greater variability of these ratios in oceanic-island basalts. In some instances, such as the volcanic island Tristan da Cunha, the basalts have strontium 87/strontium 86 and neodymium 143/neodymium 144 ratios that are very close to our estimates of the values for the earth as a whole, implying that their source has not evolved in the same way that the sources of the mid-ocean-ridge basalts have and may have suffered far less depletion in crustal constituents in the past. It should be emphasized, however, that the volume of volcanic rock erupted on Tristan da Cunha is quite small compared with that erupted at the mid-ocean ridges. Elsewhere in the ocean basins basalts from islands such as Iceland and the Hawaiian Islands have strontium- and neodymium-isotope compositions that are intermediate and overlap those of the mid-ocean ridges.

In short, there is a strong negative correlation between the strontium- and neodymium-isotope compositions of oceanic basalts, indicating a general coherence of parent/daughter ratios during the extraction of the components now residing in the continental crust. Because the samarium/neodymium ratio and therefore the neodymium 143/neodymium 144 ratio of the earth as a whole at present are reliably established the correlation of the strontium- and neodymium-isotope ratios enables us to estimate the strontium 87/strontium 86 ratio in the earth as a whole. Comparison of measured isotopic ratios of neodymium and strontium in volcanic



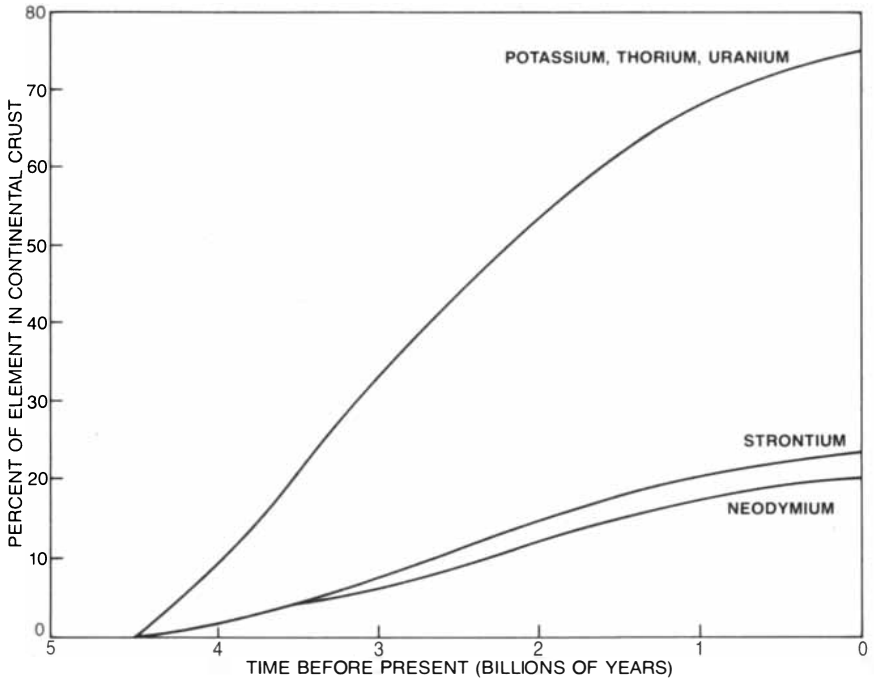
EVOLUTION OF LEAD in the mantle is plotted in the graph at the left and the enlargement at the right in terms of the relative abundances of two isotopes, lead 206 and lead 207, that have been produced at different rates during the earth's history (because of the different proportions and half-lives of the two uranium isotopes that generate them). The two axes of this graph relate the ratios of the two radiogenic lead isotopes to the ratio of lead 204, an isotope whose abundance does not vary with time. On the assumption that a reservoir of homogeneous lead, plotting as a single point on the diagram, was split into several portions with differing ratios of uranium to lead, the lead composition of each portion would evolve with time toward the upper right of the diagram, since both ratios would be increasing. The evolution would be along a growth curve that would depend on the uranium/lead ratio of each portion. At any given time the positions of all the portions along their respective growth curves would lie on a straight line passing through the original lead composition. The slope of the line would be related to the age of the system. In this case the original composition is taken to be that of primordial lead, as measured in iron meteorites with very low uranium/lead ratios. If this ratio was uniform throughout the primordial solar nebula, it would be the point of origin for the growth curves for the earth, the moon and the chondrites, whose uranium/lead ratios differ widely. At present the compositions of these bodies would plot along a line passing through the primordial-lead point with a slope corresponding to the age of the solar system. The compositions of oceanic basalts plot to the right of this line, called the geochron. Samples that appear from an analysis of their strontium- and neodymium-isotope ratios to have come from the most nearly undepleted mantle plot farthest from the geochron in the lead/lead diagram, indicating the evolution of lead in mantle is more complex than that of strontium and neodymium.

rocks with their predicted values for the earth as a whole provides a fine tool for the recognition of depleted-mantle source regions. The variability of isotopic compositions in oceanic basalts bears witness to the fact that the continental crust has not been extracted uniformly, and that the mantle, or at least the part of it under the oceans and efficiently sampled by mid-ocean-ridge volcanism, is depleted in large-ion lithophile elements that now reside in the continental crust.

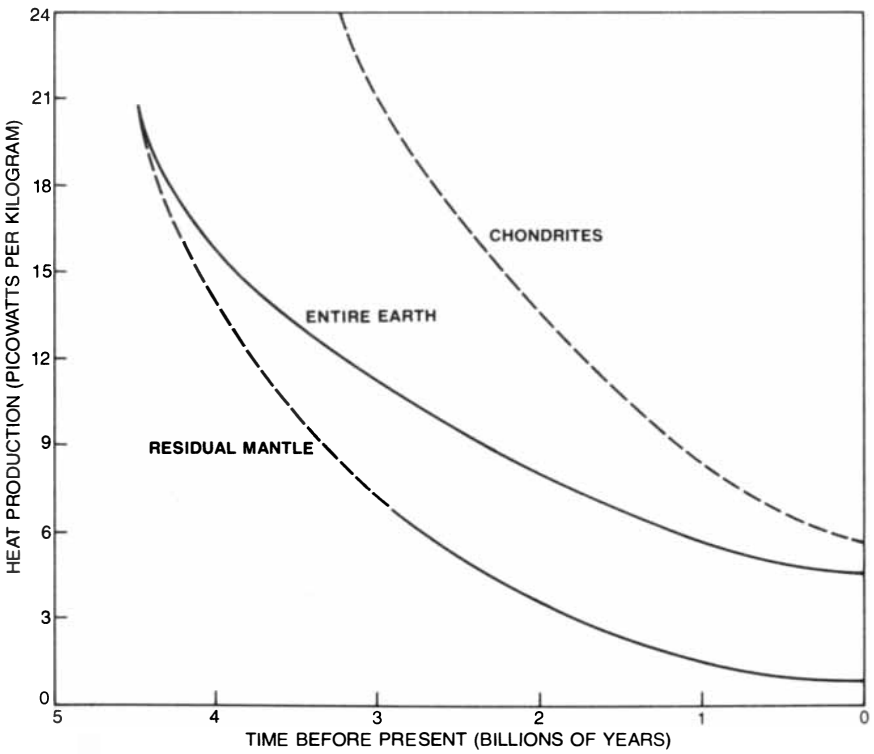
Evidence for this depletion process was deduced by the late Paul W. Gast in 1968 from considerations of the abundances of trace elements in oceanic basalts. The heterogeneous nature of the upper mantle is also evident from lead-isotope measurements. When these measurements are compared with the predicted average lead-isotope compositions of carbonaceous chondrites, the earth and the moon (assuming that the earth, the moon and meteorites all had the same lead-isotope composition 4.55 billion years ago), one finds that at present the carbonaceous chondrites and other meteorites plot close to a line with a slope corresponding to an age of 4.55 billion years, and one would expect that the bulk earth and moon should also plot close to this line. The relative positions of carbonaceous chondrites, the earth and the moon along this line indicate that the uranium/lead ratio for the moon is greater than the uranium/lead ratio for the earth is greater than the uranium/lead ratio for carbonaceous chondrites, which is consistent with the observation of lower abundances of relatively volatile lead compared with refractory uranium in the earth and the moon.

The lead-isotope compositions of oceanic basalts plot to the right of the 4.55-billion-year line, demonstrating that the suboceanic mantle is inhomogeneous with respect to the isotopic ratios of lead as well as those of strontium and neodymium. Oceanic-island basalts exhibit a greater range of lead-isotope compositions than mid-ocean-ridge basalts, as is also true of their strontium- and neodymium-isotope compositions. At present the existing data for lead, strontium and neodymium isotopes in oceanic basalts are inadequate for a full evaluation of the relations among them. It does seem, however, that a somewhat more complex model must be invoked in order to accommodate the known variations in the lead-isotope ratios. Whereas we have discussed the isotopic data for strontium and neodymium in terms of two reservoirs (the mantle and the continental crust), three reservoirs appear to be required to explain the variations in the lead-isotope ratio.

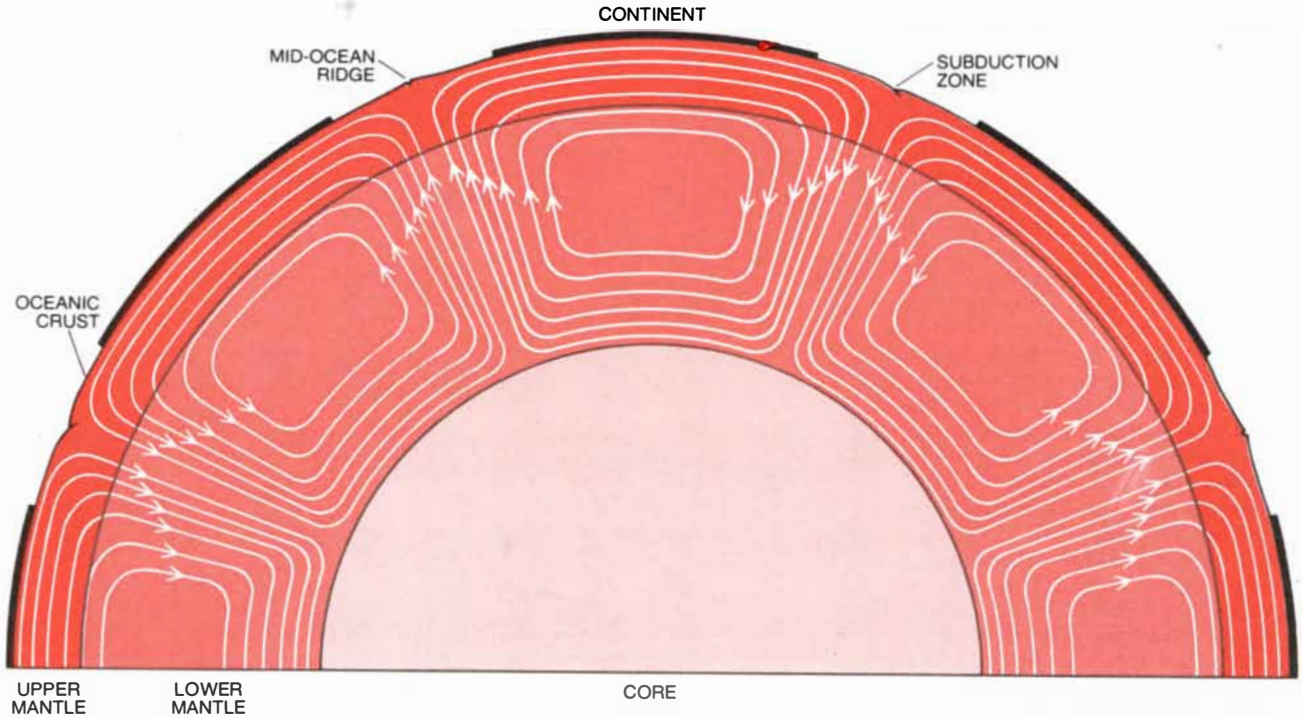
One of our primary goals in exploiting naturally occurring isotopes as tracers in continental- and mantle-derived

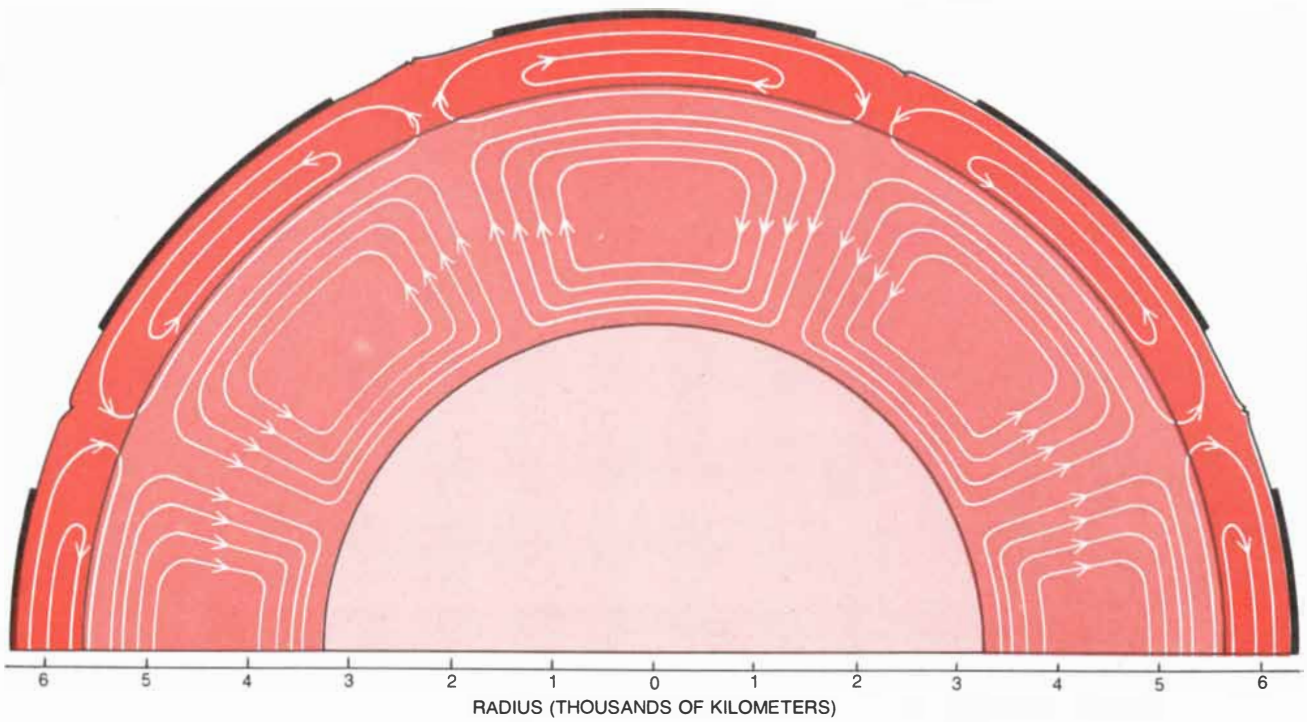


SELECTIVE CONCENTRATION of several large-ion lithophile elements originally present in the mantle but now residing in the continental crust is shown as a function of time. The curves are derived from calculations in which only half of the mantle is assumed to generate continental crust. The vertical axis gives the percent of the original inventory of each element that is present in the crust at any given stage of the earth's history. Heat-producing elements potassium, thorium and uranium have evidently been efficiently extracted from the mantle.



DECLINE IN HEAT PRODUCTION over geologic time is traced for the earth as a whole, the residual mantle (the mantle remaining after the formation of the continents) and the chondrites. All the curves are declining, since the abundances of the heat-producing elements decrease through the same processes of radioactive decay that produce the heat. The heat production in the residual mantle lags increasingly behind that in the earth as a whole as the continents are progressively extracted from the mantle. Heat production in the chondrites is initially high, but it falls off more rapidly than in the earth. This phenomenon is attributable to the fact that chondrites have a higher ratio of volatile potassium to refractory uranium than the earth has; heat from potassium is produced by the radioactive decay of potassium 40, which has a shorter half-life than uranium 238, the isotope that gives rise to most of the heat from uranium.





IMPORTANT CONSTRAINT is imposed on the convection that could have occurred in the mantle during most of the earth's history by the finding that no more than half of the mantle and possibly as little as a third can be as depleted in large-ion lithophile elements as the basalts erupted at mid-ocean ridges are. Assuming that the entire mantle is in some kind of convective motion, convective cells cannot operate throughout the full depth of the mantle (*top*); convection in the upper mantle must be decoupled from that in the lower (*bottom*).

material is to evaluate the timing and the rate of supply of materials from the mantle to the continental crust, and further to determine the proportion of mantle involved in the processes that have generated the continental crust. This task essentially involves an attempt to determine the comparative abundances of elements in the crust and some portion of the mantle as a function of time. The problem cannot be tackled solely by investigations of either mantle-derived rocks or the continental crust. Instead observations and deductions made from the sampling of materials from both mantle and continental crust must be made mutually compatible with some hypothesis.

The problem was first taken up seriously by Richard L. Armstrong of the University of British Columbia in 1969. In this early attempt to simulate the dynamic nature of continental evolution the continents were considered to have formed in a single episode some four billion years ago and to have been subsequently recycled and exchanged chemically with the mantle in the course of a large number of discrete events. Armstrong's model was able to reproduce some of the features of the isotopic chemistry of the mantle known at that time, but the model is not consistent with what is now known about the pattern of crustal growth.

Recently we modeled the isotopic evolution of the mantle on the basis of the following three assumptions about continental evolution: (1) There is apparently very little continental crust more than 3.8 billion years old. (2) The continents have grown more or less continuously for the past 3.8 billion years. (3) The growth rate of the continents achieved a maximum between 2.5 and three billion years ago (a deduction that follows from the age-distribution pattern in the continents).

A precise knowledge of the abundances of the large-ion lithophile elements in the continental crust is clearly critical to such models. The abundances of these trace elements (particularly the heat-producing radioactive ones) in the continents, however, are much harder to estimate than might be expected, because of their inhomogeneous distribution in the continents. For example, it has become clear from heat-flow studies and geochemical sampling that potassium, thorium and uranium are much more concentrated in the upper part of the crust than in the lower parts.

Acceptable models must also reproduce the isotopic characteristics of the residual mantle and the continents. Our main concern at first was to reproduce the strontium- and neodymium-isotope characteristics of mid-ocean-ridge basalts, because these must by virtue of their large volume provide the best estimate of the isotopic composition of the suboceanic upper mantle. In addition they are generated from the most depleted part of the mantle currently sampled by volcanism. The models we have investigated have assumed continuous differentiation, with the vigor of material transport in the mantle having declined as a function of time parallel to the decline of heat production in the earth. The delay in the stabilization of continental material until approximately 3.8 billion years ago is presumably a result of highly efficient recycling early in the earth's history.

The most important conclusion to emerge from such a model is that no more than half and possibly as little as a third of the mantle can be as depleted in large-ion lithophile elements as the part that supplies basalts at mid-ocean ridges. This conclusion, which is consistent with the findings of DePaolo and Wasserburg at Cal Tech, imposes a major constraint on the nature of the convection that could have occurred in the mantle during a large portion of the earth's history. It is difficult to see how cellular convection operating throughout the mantle could have operated to produce depletion in only a limited portion of it. If the entire mantle is indeed involved in some kind of convective motion, as most geophysicists believe, the convection in one portion of it (presumably the upper mantle) must be efficiently decoupled from the convection in the other (presumably the lower mantle). The portion of mantle that has been involved in the formation of the continents has become generally depleted in large-ion lithophile elements, but it is much more depleted in the heat-producing elements potassium, thorium and uranium than it is in strontium, neodymium and samarium.

This last point can be demonstrated by plotting the percent of large-ion lithophile elements originally in the mantle but now residing in the continents as a function of time [*see top illustration on page 131*]. About 70 percent of the potassium, thorium and uranium originally present in what is now the residual mantle has been transported to the continents. Thus the intrinsic heat production in this residual mantle has declined faster than if chemical differentiation of the continents had not occurred. In spite of the fact that the residual mantle now has a small intrinsic heat production, it continues to operate as the major heat sink of the earth during the creation and cooling of plates generated along the mid-ocean ridges. The heat dissipated during this process arises in part from the radioactive decay of trace elements in less depleted parts of the earth (perhaps in the lower mantle), augmented by some poorly defined yet significant amount of heat released by the cooling of the entire earth.

The Kinematics of Plant Growth

Like a flame or the wake of a boat, the form of a plant changes slowly but the components are in continual flux. The motions of the components can therefore be analyzed in terms of fluid flow

by Ralph O. Erickson and Wendy Kuhn Silk

The beauty of plant form has delighted and inspired poets, artists and scientists throughout recorded history. The conical shape of the spruce tree, the gracefully irregular form of the oak, the nearly perfect radial symmetry of many flowers, the mathematical regularity of a pine cone or a sunflower head and the characteristic shape of a maple leaf or an ivy leaf are part of the collective human consciousness. It is perhaps less immediately obvious that the forms, or at least the dimensions, of many parts of a plant are continually changing throughout the plant's life. A photograph made of a bean plant today will show slight differences from one made yesterday or tomorrow. An analysis of these changes reveals developmental regularities that are as striking as the symmetries of the mature form.

If one carefully observes a growing plant, one soon discovers that a leaf or a branch on the lower part of the stem (or a tag attached there) may not change its position even though the height of the plant may be increasing at a considerable rate. The reason is that the growth is limited to the region of the apex, that is, growth in length occurs only near the tip of the stem. A leaf or a mark placed below that tip but still in the growing region will change its position with respect to both the tip and the ground.

From this simple observation it is clear that growing plant tissues are simultaneously increasing in size and changing their position in relation to other parts of the plant. It is also clear that if one were interested in the behavior of cells in the growing region, it would not be possible to determine the rate of change over time of a cellular variable at a fixed position in space, since the cell would move during the time needed to make the determination. A method of analysis is required that is subtle enough to take into account both the displacement and the expansion of tissue elements.

It is also important to consider both aspects of growth (the displacement and the expansion of tissue elements) in studying a plant under the microscope and in studies of the chemical composition and the metabolism of growing tissue. In such studies the tissue is usually killed for the purpose of the study, so that direct observations of its growth are not possible. Nevertheless, indirect methods can often be found to interpret the analytical results in terms of the processes taking place in the growing tissue.

The problem of studying a system in which the elements are both moving and expanding (or contracting) arises also in the study of the behavior of a compressible fluid. We propose that an analogy can be made between the growth of a plant and the flow of a fluid. In each case one can assume the existence of a continuous medium (the fluid or the growing tissue) containing a field of local velocities that can differ from one another within the medium and with time. On the atomic scale a fluid is not a continuum, but at the microscopic scale and at larger ones the assumption of continuity is justified on statistical grounds. The assumption has made possible many important generalizations in fluid dynamics.

Plant tissues are far more complex than the fluids of classical mechanics. A plant tissue consists of several kinds of cells that are themselves highly complex. Many plant organs, however, are made up of rather large numbers of cells that to some extent show continuous gradations of size and other properties. Furthermore, the walls of the cells are cemented together in a polyhedral network that appears to expand in a coordinated way. The course of growth over time also appears to be continuous, as can be seen in time-lapse motion pictures, multiple-exposure photographs and streak photographs. (A streak photograph is made with a camera in which the lens is left open and the film moves at a constant speed.)

If we may draw an analogy between fluid flow and the growth of plant tissue, the mathematical methods of classical analysis are at our disposal, as they are in fluid dynamics. We expect that important generalizations about the morphogenesis of plants will emerge. Powerful methods for analyzing experimental data will also be available. It is interesting to note that a variety of striking and well-characterized flow patterns are recognized in fluid dynamics, among them streamlines, wakes, vortexes and standing waves, all of which are related in highly specific ways to the conditions of flow and to constraints on the flow. We expect by analogy that some well-known structures or patterns of plant morphology can be related to and probably explained by the characteristics of the growth processes that give rise to them.

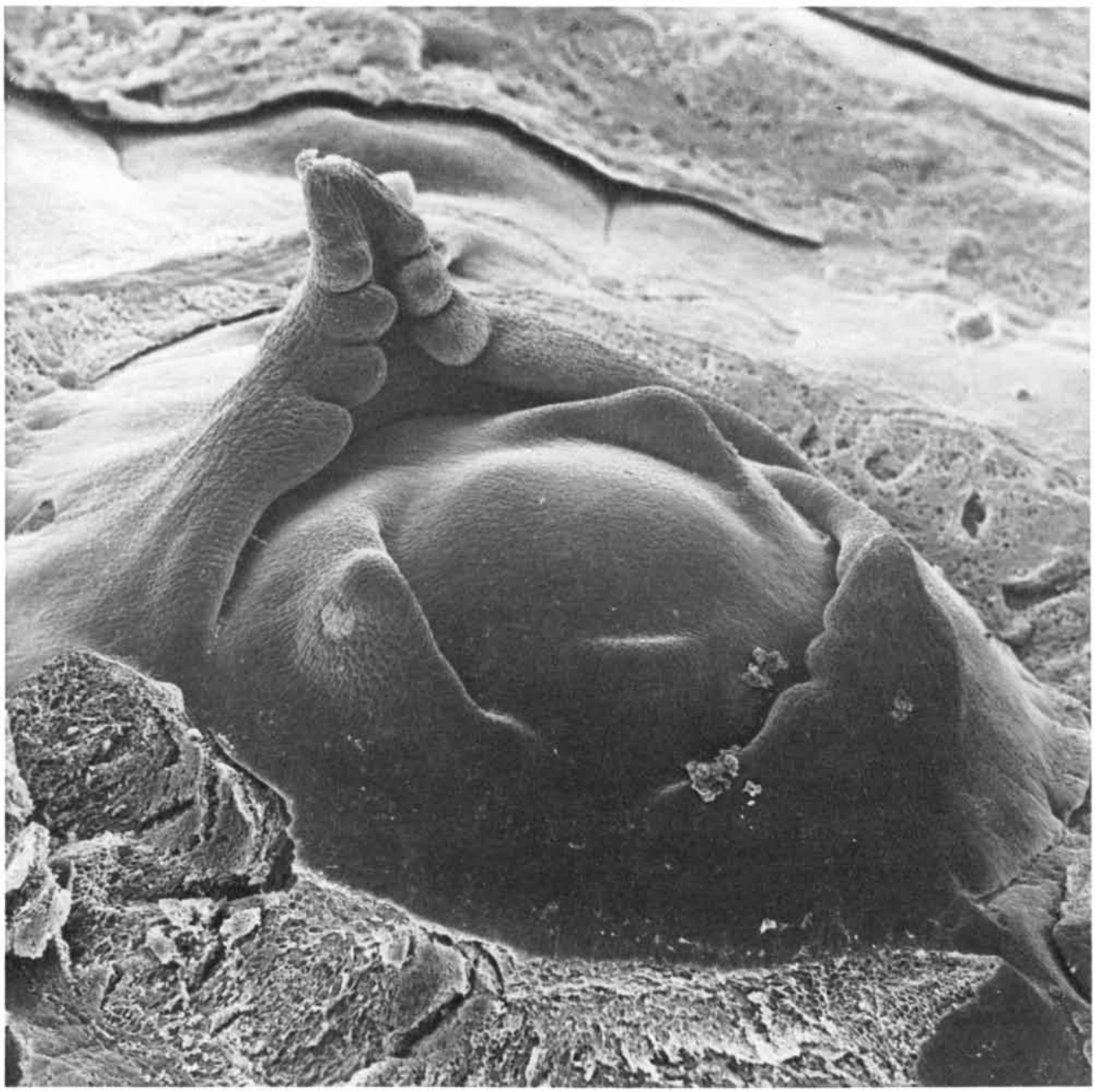
In fluid dynamics an important distinction is made between spatial changes and material ones. Spatial, or local, changes occur at a fixed position in space; material changes pertain to the physical elements (the molecules) of the fluid. One can appreciate this distinction by considering a waterfall or the wake of a boat. Its appearance and dimensions can be described in spatial terms, and the description may be valid over a period of time. The material elements—the molecules of water—are, however, continuously carried through the structure. Experimental data are for practical reasons usually obtained in local terms, that is, with reference to defined coordinates: geographical landmarks for a waterfall and, in our second example, the dimensions of the moving boat. If a variable that is a function of position and time is measured, its spatial rate of change can be determined. If the local velocities of the fluid are known, the material rate of change can also be determined.

Pursuing our analogy, we would argue that it is also important to make a careful distinction between local and material changes in studying the morphogenesis, growth and physiology of

plant tissues. It is experimentally most feasible to make a measurement at, say, four millimeters from the tip of a shoot and to analyze the data in those terms. The available data suggest that this is a valid and illuminating way to characterize the growth process.

Biologists also ascribe great significance to the cellular organization of tissues. Cells can be said to be the material elements of an organism. Both the structure and the function of the organism are explained to a large extent in terms of the structure and function of its cells. The material specification of change in growing tissue should then correspond closely to cellular changes. In the analysis of plant development both local and material aspects should be considered. Unfortunately most cellular studies are based on fixed tissues and so are interpreted in the absence of information about growth velocities or with intuitive assumptions being made about growth. We shall illustrate the importance of considering the expansion and the displacement of tissue elements and both the material aspects and the spatial aspects of growth in a few examples and shall point out some general relations suggested by these studies.

The point is well illustrated in root growth, which has been analyzed in detail by photographing the surface cells of living roots at half-hour intervals (as was done by Richard H. Goodwin and

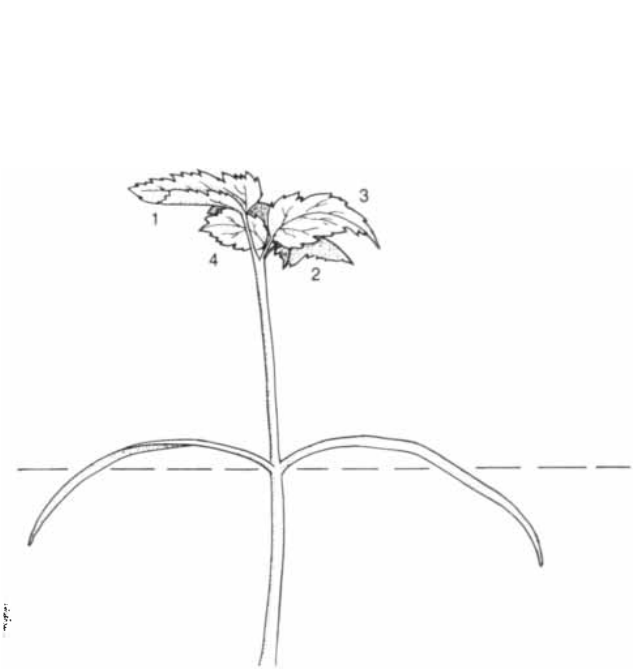


APEX OF A CELERY PLANT, the point where the new leaves of the plant originate, is visible as the central domelike structure in this scanning electron micrograph made by Roger D. Meicenheimer of Washington State University. The apex is ringed by ridgelike structures, each of which is a young leaf. The nearer a leaf is to the apex, the younger the leaf is. New leaves appear at equal time intervals (an interval termed a plastochron) if the temperature is constant. The micrograph, in which the enlargement is 130 diameters, was made by cutting the leaves away from a stalk of celery until the apex was revealed. The preparation was then dehydrated and shadowed with gold.

Charlotte J. Avers at Connecticut College) and by refined marking experiments that we have done. In the marking experiments the root of a corn seedling was marked by brushing it with a suspension of lampblack and then it was put in a moist chamber at a temperature of 25 degrees Celsius. Its image was focused on the slit of the streak-photograph camera. With the lens open continuously, the film moving and the light continuous but dim a streak photograph was made, recording the downward displacement of marks throughout the growing region of the root over a period of time. When the camera is calibrated for time and scale, such a photograph is a detailed, automatic plot of the growth of the root. Time is plotted horizontally and the distance along the root is plotted vertically. The slopes of the streaks represent the velocities of displacement and can be measured with a protractor.

It is convenient to consider a transformation of this plot in which the origin of the length axis is taken to be the tip of the root; one then measures velocities of displacement from the tip rather than downward velocities. Defining the origin as the tip is in conformity with the histology (tissue organization) of the root, since the cells of the root originate from initial cells at the tip of the meristem: the growing area. When velocities of displacement are plotted against distance from the tip of the root, they are seen to increase from zero at the tip to a maximum of almost two millimeters per hour about nine millimeters from the tip. (Nine millimeters marks the upper limit of the growing region.) This maximum velocity of displacement is identical with the growth rate usually cited for a whole root.

A streak photograph also contains information about the expansion of elements of root length. In a graph of



GROWING COCKLEBUR PLANT (*Xanthium pensylvanicum*) is portrayed on the basis of time-lapse photographs made in a growth chamber. The plant is shown as it looked at 10:00 A.M. on days 13, 15, 17 and 19 after the seed was planted. The leaves are numbered so that a given leaf can be identified in each drawing. The cotyledons, or seed leaves, near the bottom of the plant are arbitrarily placed at the same level in each drawing. Each plant was potted in a mixture of vermiculite and washed granite chips and watered daily with a

displacement velocities v. distance from the tip the slope of the curve at each point gives the rate of change of velocity with position. This is the velocity gradient; we call it the relative elemental rate of elongation. It is also called the local strain rate and can be regarded as the divergence of velocity in one dimension. In a typical plot the relative elemental growth rate rises from zero at the tip of the root to the remarkably high value of 40 percent per hour at about four millimeters from the tip, falling again to zero at about nine millimeters.

It is instructive to compare this analysis with classical root-marking experiments. In 1758 the French engineer and agriculturist Henri Louis Duhamel du Monceau, writing on the structure of trees, told of inserting fine silver wires into the roots of walnut seedlings and observing after several hours that the wires closest to the tip were widely separated, whereas the ones originally placed a few millimeters from the tip maintained their relative positions. In about 1860 the German botanist Julius von Sachs marked off successive one-millimeter segments of broad-bean roots with India ink and measured them after they had grown for 24 hours at a temperature of 20 degrees C. His findings, which have often been cited, were that the first 10 segments grew a total of 22.8 millimeters, distributed as follows (beginning at the tip): 1.5, 5.8, 8.2, 3.7, 1.4, 1.1, .4, .3, .2 and .2. In other words, the second and third segments had elongated the most and segments farther from the tip showed a progressively smaller increase in length. The root as a whole was growing at almost one millimeter per hour.

Many generations of botany students have repeated von Sachs's experiment and have been asked to conclude that the root tip, where mitotic (dividing) cells can be seen under the microscope,

mineral-nutrient solution. The growing lights (banks of fluorescent lamps) were on daily from 8:00 A.M. to midnight, except at intervals of 17.36 minutes when they were turned off briefly and photographic lights were turned on so that an exposure could be made. The photographic lights came on at the same interval during the daily eight-hour period of darkness. Since the cocklebur is a short-day plant and will flower only if it receives at least 8.5 hours of continuous total darkness each day, the growth of the plants was entirely vegetative.

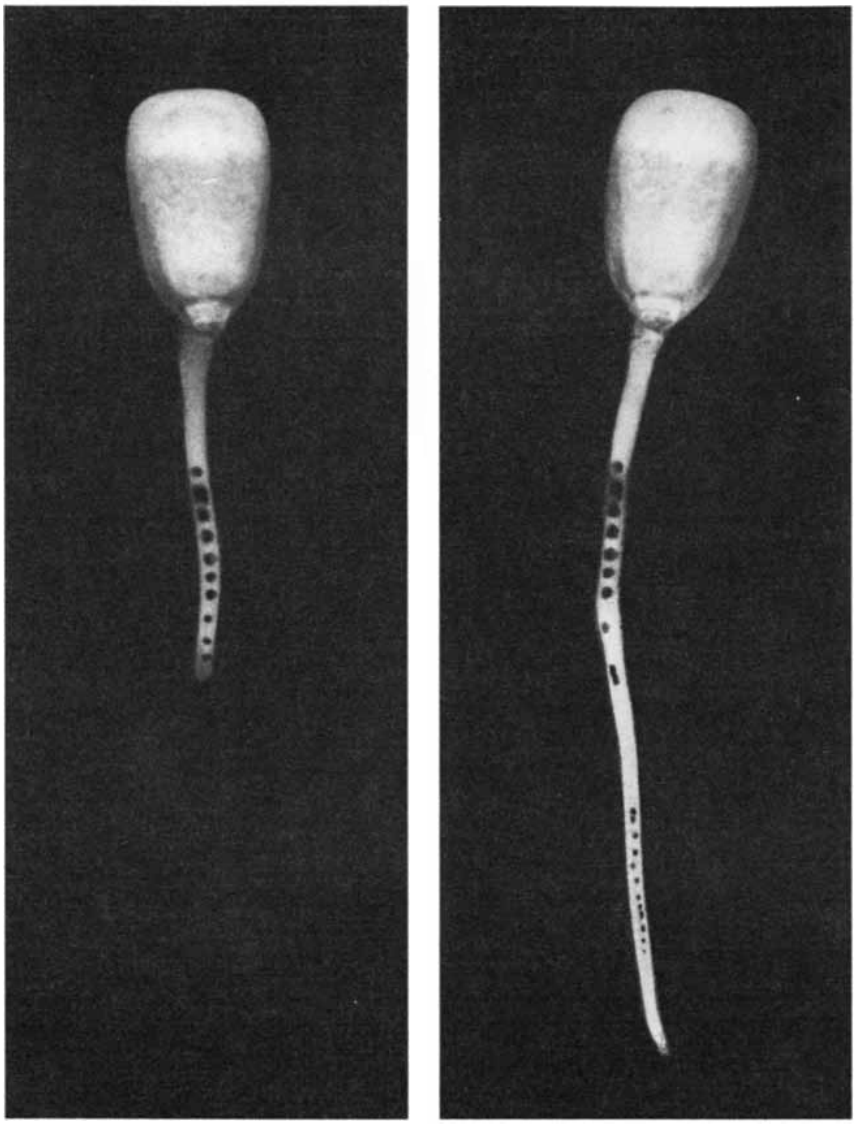
is growing the most rapidly. One finds a great discrepancy, however, between this conclusion and the conclusion from a streak photograph. If von Sachs's experiment were done on a corn root, the positions of the marks after 24 hours would suggest that the growth rate is greatest in the second millimeter behind the tip, which is about 40 cell lengths from the place where the elongation is at the maximum rate. The region of maximum local strain rate is well beyond the region of cell division.

The discrepancy is explained by the fact that in the classical experiments the increase in length of a marked segment (a material increment) was ascribed to the initial (spatial) position of the segment, thus attributing to the initial position growth that in fact took place farther from the tip. Moreover, both the long duration of the experiment and the relatively great length of the segments would have made it difficult to achieve good estimates of either instantaneous velocities or the behavior of elements of length if a rigorous analysis had been attempted.

A corn root grows linearly, that is, at a nearly constant overall rate, for many hours. Streak photographs made at different times during the linear-growth period show essentially identical relations of displacement velocities and relative elemental rates to distance from the tip. Borrowing a term from fluid dynamics, one can say that growth is steady, meaning that local growth rates are invariant with time. Steady growth was probably implicitly assumed by the people who did the classical root-marking experiments. It is probably also true that plant anatomists have intuitively assumed steady growth in presenting an illustration of a longitudinal section of a root as representing root structure in general, without citing the length or age of the root.

Classical morphologists also realized that the course of cellular development is evident from such a longitudinal section. Distance from the apex corresponds to developmental age. Hence it is possible to infer the history of a given cell by examining younger cells closer to the tip and to predict the fate of the cell from the characteristics of older cells farther from the tip.

An implication of steady growth is that one should distinguish between the spatial and material specifications of variables. For example, local growth rates are invariant with time, whereas each material element expands more rapidly and then less rapidly with time as it is displaced from the root tip. Similarly, there are spatial and material aspects of morphology. Particularly when growth is steady, the growing region of the root can be said to be a spatial or geometrical structure; it can be described or diagrammed in terms of zones of cell division, cell differentiation and so on at fixed distances from the tip. On the other hand, the material elements (the cells) of which the region consists are continually being displaced; they can be said to flow through the growing region.

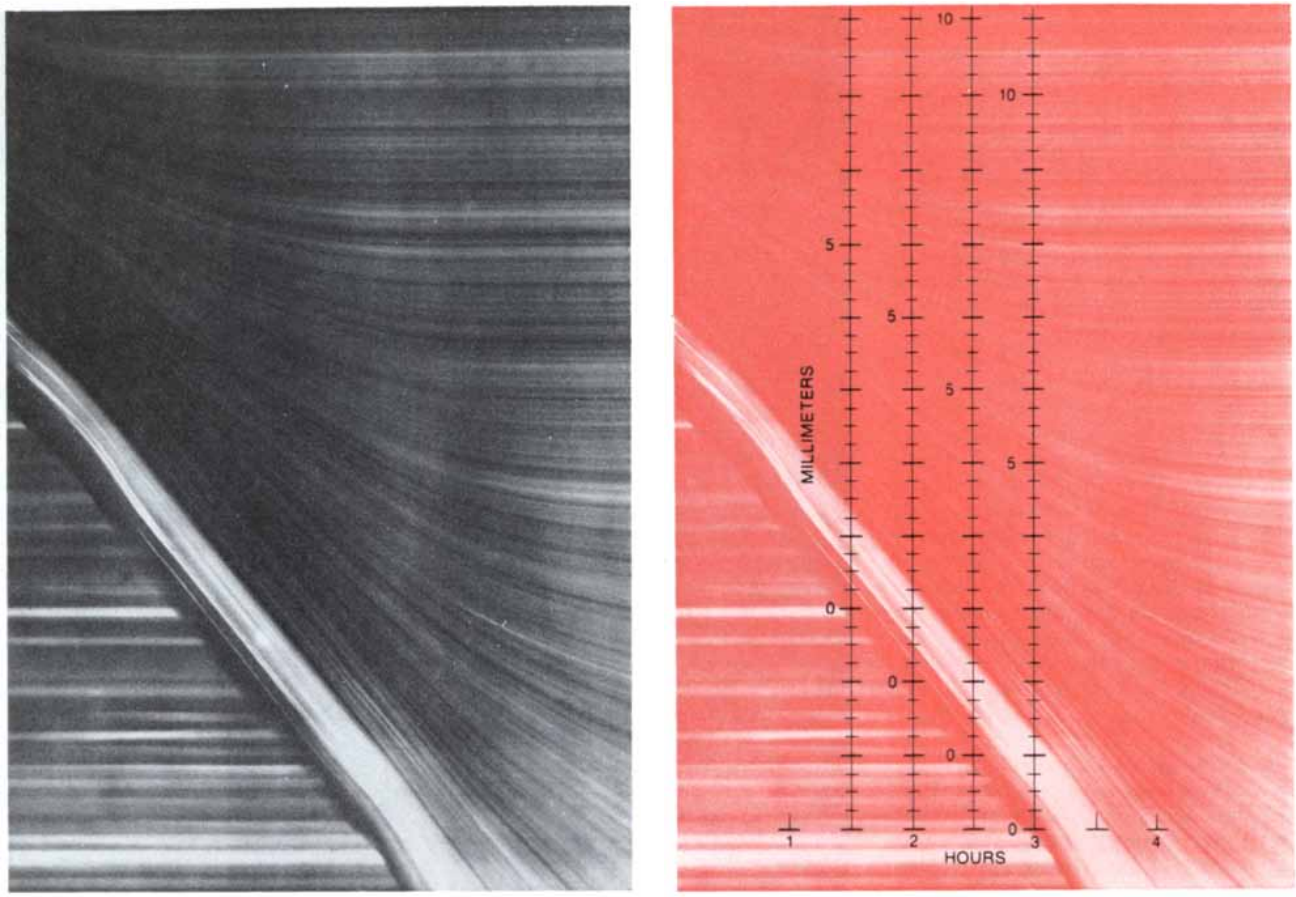


CORN SEEDLING is shown in photographs made just after its root had been marked at 10 intervals of one millimeter (*left*) and 14 hours later (*right*). It can be seen from the second photograph that the ink marks have expanded and been displaced. The marks separate during the growth of the root, and it is evident that the greatest separation is between marks that were originally near the tip. The classical interpretation of root growth was based on such experiments.

If the distribution of the relative elemental growth rate is known, one can evaluate the rates of many developmental processes. For example, the relative rate of cell division can be subtracted from the local relative elemental growth rate to obtain the relative rate of change in average cell length in the moving material element. In this way one can see that the steady distribution of cell lengths in the root is the result of the simultaneous processes of cell division and local expansion.

Another spatial or geometrical structure appears during the germination of the seeds of many broad-leaved plants. In a young seedling the tip of the stem often grows with a pronounced bend or hook, which is thought to protect the apical meristem from damage as the seedling pushes up through the soil. Once out of the soil the stem usually straightens. If the seedling is grown in dim light, however, the hook can be maintained for a long time after the stem emerges from the soil and continues to grow.

A simple marking experiment reveals that the hook is another example of a plant organ composed of changing ele-



GROWTH OF CORN ROOT is recorded in a streak photograph. The root was brushed with a suspension of lampblack and put in a moist chamber mounted in front of a camera in which the lens was open continuously and the film was moved at a steady rate past a vertical slit. The black spots on the growing root appear as streaks in the resulting photograph. At a given moment, as is shown by each of the vertical scales, zero indicates the tip of the root. Distances along the root are indicated by the scale of millimeters. The velocities of the displacement of marks at the given moment are shown by the slopes of streaks that intersect the vertical line. Growth is nearly constant.

ments. A mark placed on the apical side of a hook flows through the bent region and can be seen on the straight basal portion within eight hours. The mark is, of course, firmly attached to cells on the surface of the stem. This observation implies that each element of a stem first curves and then straightens as it is displaced from the apex of the stem. At any one time the hook is composed of some elements that are curving (on the apical side of the hook) and others that are decreasing in curvature (on the basal side).

Observations of the distribution of growth rates are consistent with this model. A stem element curves if one side of the stem grows faster than the other; a curved segment straightens if the inner surface grows faster than the outer. If *A* represents a point on the apical side of the hook and *B* a point on the basal side, one finds that the relative elemental growth rate decreases from outside to inside the hook at *A,* where elements are increasing in curvature, and decreases from inside to outside the hook at *B,* where elements are straightening. Thus a stable structure is created by a rather complex distribution of the growth rate. The structure has a steady local curvature but the material curvatures are changing with time.

We have discussed growth largely with respect to displacement along an axis such as the longitudinal axis of a root. The measurements are one-dimensional. A start has been made toward analyzing growth in two dimensions, but an analysis of three-dimensional growth in the terms we have described has scarcely been tried.

In broad-leaved plants the growth of the leaf blade can be described well in two dimensions, since its growth in thickness is slight compared with its increase in area. The pattern is quite different from that of a cylindrical organ such as a root. A leaf is determinate, that is, it attains a predictable size and then stops growing. Furthermore, its symmetry is likely to be bilateral rather than radial. With a leaf a given change in outline can be produced by gradients in direction as well as by gradients in the magnitude of the relative elemental growth rate. Therefore both the direction of growth and the magnitude of the local growth rates must be evaluated in an analysis of a leaf's development, as was first done in 1945 by Oscar W. Richards and A. J. Kavanagh of the American Optical Company.

The detailed pattern of veins in a leaf provides an abundance of identifiable points that can be recognized in successive photographs of the same leaf. In a study of the growth of cocklebur (*Xanthium*) leaves we made up sets of three photographs. The x and y coordinates of about 250 points in each of the photographs were recorded with computer-assisted digitizing equipment and computations were made of the components of velocity at each point and also of the divergence of velocity, which can be termed the relative elemental rate of increase in area.

One finds great differences in divergence from one part of a leaf to another. After three days the tip of a typical partially grown leaf has essentially stopped growing but the lobes at the base are expanding in area at the rate of nearly 80 percent per day. These results have been subjectively correlated with the histological observation that the tip of

SCIENCE/SCOPE

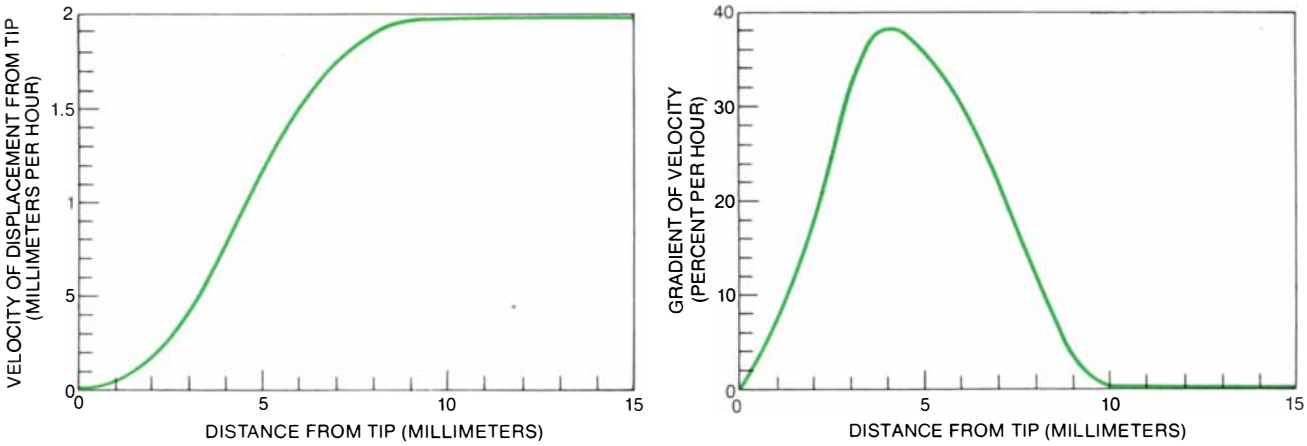
A one-of-a-kind test facility will prepare NASA's Project Galileo probe for the rigors of descent into Jupiter's atmosphere in the late 1980s. The six-foot diameter chamber, constructed by Southwest Research Institute for Hughes, simulates a helium atmosphere with the temperature and pressure extremes that the Hughes-built probe will encounter during its plunge through the Jovian sky. Test objects initially are exposed to a vacuum and temperatures of -200°F. Then, within 55 minutes, the pressure is increased to 235 pounds per square inch and the temperature is raised to 240°F. The Galileo project is managed by NASA's Ames Research Center.

A new video link for remotely piloted vehicles revives an old but surprisingly simple technique to resist jamming. The approach calls for video signals to be transmitted using phase modulation (PM) rather than frequency modulation (FM). Hughes engineers have found that with this method the TV picture gradually degrades as the jamming signal strength increases. By contrast, the performance of an FM system deteriorates rapidly after falling below a certain threshold. PM signals, when properly processed, require less bandwidth and can be coded using pseudo-noise and spread-spectrum techniques to avoid enemy detection.

Textiles are inspected extremely fast -- four meters per second -- with a laser scanner system, a South Carolina mill reports. The system uses laser output split into three beams, each of which scans the fabric independently in a pattern covering the entire surface. It detects flaws through changes in reflected light and flags these areas for elimination or repair. Spokesmen at Springs Mills, Inc. say one laser system working one shift performs the job of human inspectors at two plants working two shifts. The scanner was built by Ford Aerospace & Communications Corp. around a Hughes helium-neon laser.

Hughes Industrial Electronics Group -- with locations in Carlsbad, Irvine, Newport Beach, Torrance, and Sylmar, Calif. -- is seeking electrical, mechanical, and industrial engineers and physicists. Programs include digital/analog circuits, microprocessor communications, fiber optics, telecom switching, connectors, flexible circuits, semiconductor material and processes, MOS/bipolar/CCD, MOS test, hybrid microcircuits, lasers, mm-wave subsystems/devices, GaAs FET devices, GaAs IC devices, microwave communications, microwave amplifiers/tubes, cryogenics, and solar cells. Send resume to John G. Wilhite, Hughes Aircraft Company, IEG-SE, P.O. Box 2999, Torrance, CA 90509. Equal opportunity M/F/HC.

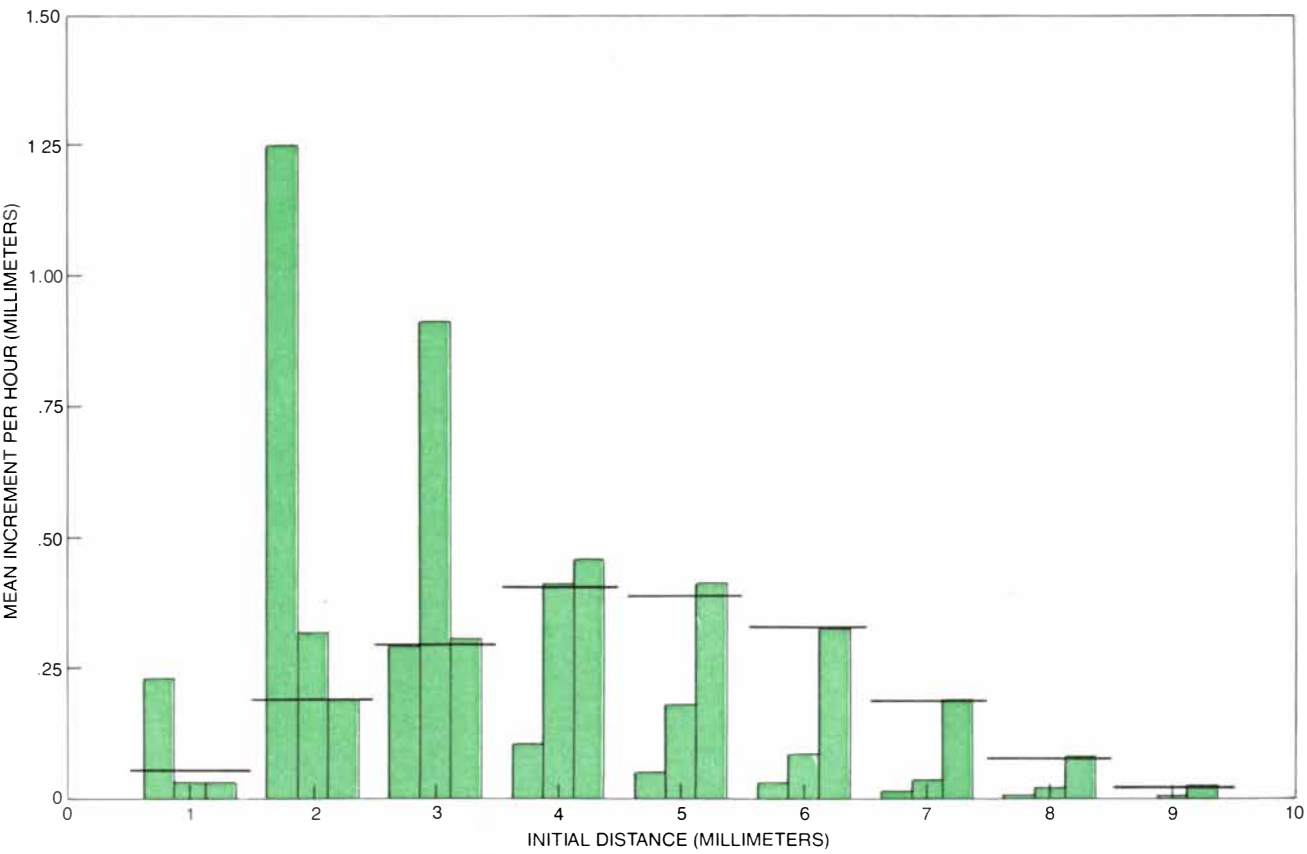
Indonesia's new Palapa B communications satellites will use flight-proven technology to ensure their eight years of planned service. The spacecraft are modeled after Canada's Anik C and Anik D series, as well as the Satellite Business Systems spacecraft that will serve U.S. businesses. Like the others, the Palapa B craft will have outer cylindrical sleeves of solar cells that will deploy in space. The arrangement nearly doubles the area of cells usable with the same size satellite, thereby increasing total power. Hughes, under contract to Perumtel, Indonesia's government-owned telecommunications company, is building two spacecraft and associated equipment to augment certain ground stations.



DISTRIBUTION OF GROWTH of a corn root is charted on the basis of streak photographs. On the growing part of a root the black marks are displaced as the root grows; the curve at the left reflects the velocity of the displacement of marks at various distances from the tip of the root at an instant of time. The curve at the right reflects the expansion of the cells in the growing region, that is, the rate of change of the velocity of growth with distance from the tip. This gradient of velocity is known as the relative elemental rate of elongation.

such a leaf has differentiated into its mature structure at a time when the tissues at the base are still undifferentiated.

Since the shape of the leaf changes during growth, it is evident that the growth cannot be regarded as steady. For a complete description of the process in spatial and material terms it would be necessary to evaluate growth velocities many times during the expansion of the leaf. We have not done this. We have, however, examined the directionality of growth at the half-expanded stage by separating the divergence at each point into its components in order to show their magnitude in the directions of maximum and minimum linear expansion. They are at right angles and for the most part do not differ much. In other words, although the growth of the leaf is heterogeneous, it is rather iso-



DISCREPANCY between the classical marking experiments and the streak-photograph analysis is indicated by sets of bars that show for 24 hours, six hours and one hour the mean hourly increase in length (stated in millimeters) of each one-millimeter segment of a corn root. The black line associated with each set of three bars represents the relative growth rate of the segment as calculated from a streak photograph. The discrepancy diminishes as the time interval of the marking experiment is made shorter. To be accurate an analysis of growth must be both elemental (pertaining to infinitesimally small segments) and instantaneous (pertaining to infinitesimally small units of time).

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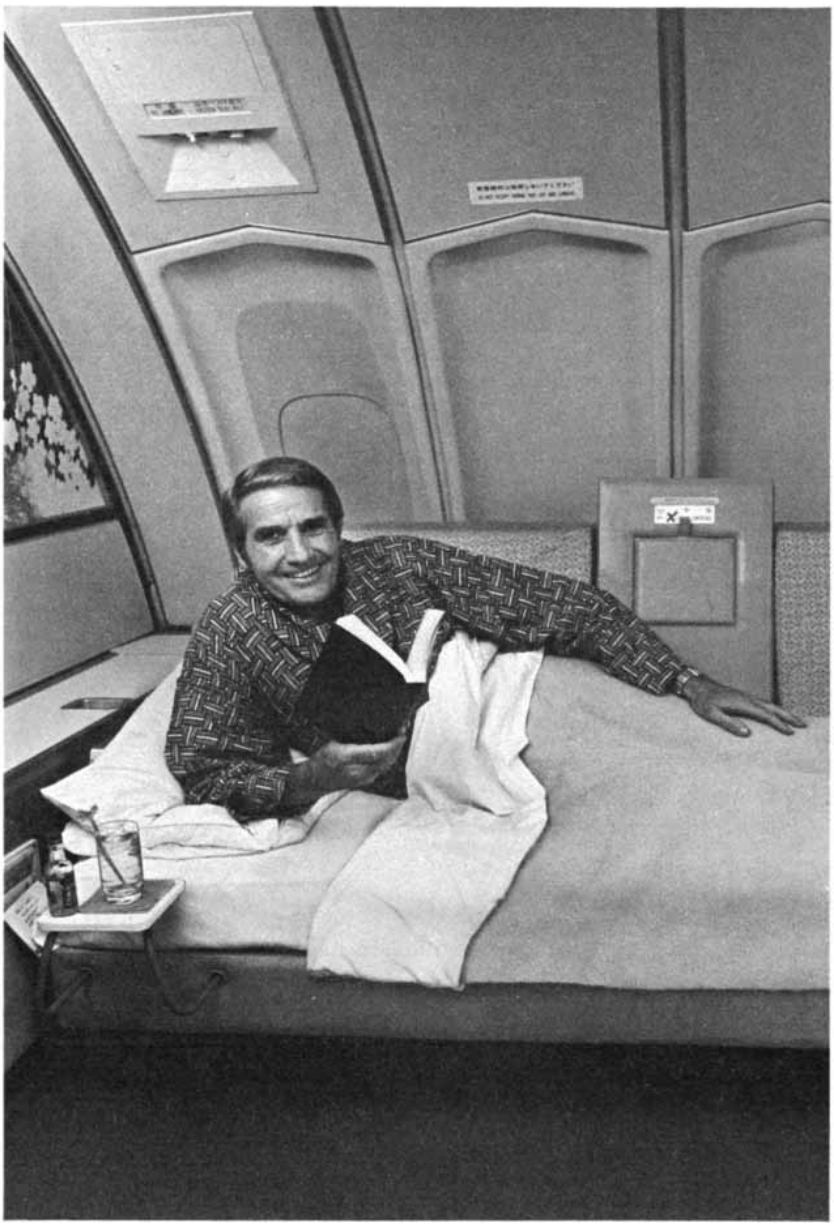

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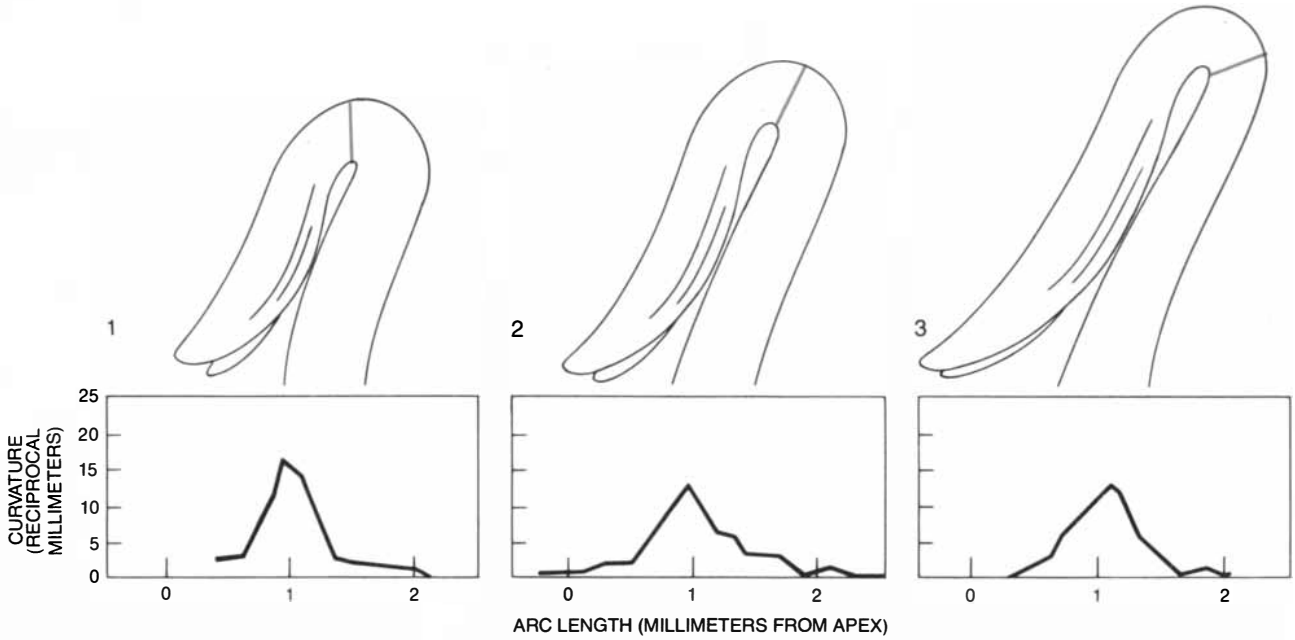
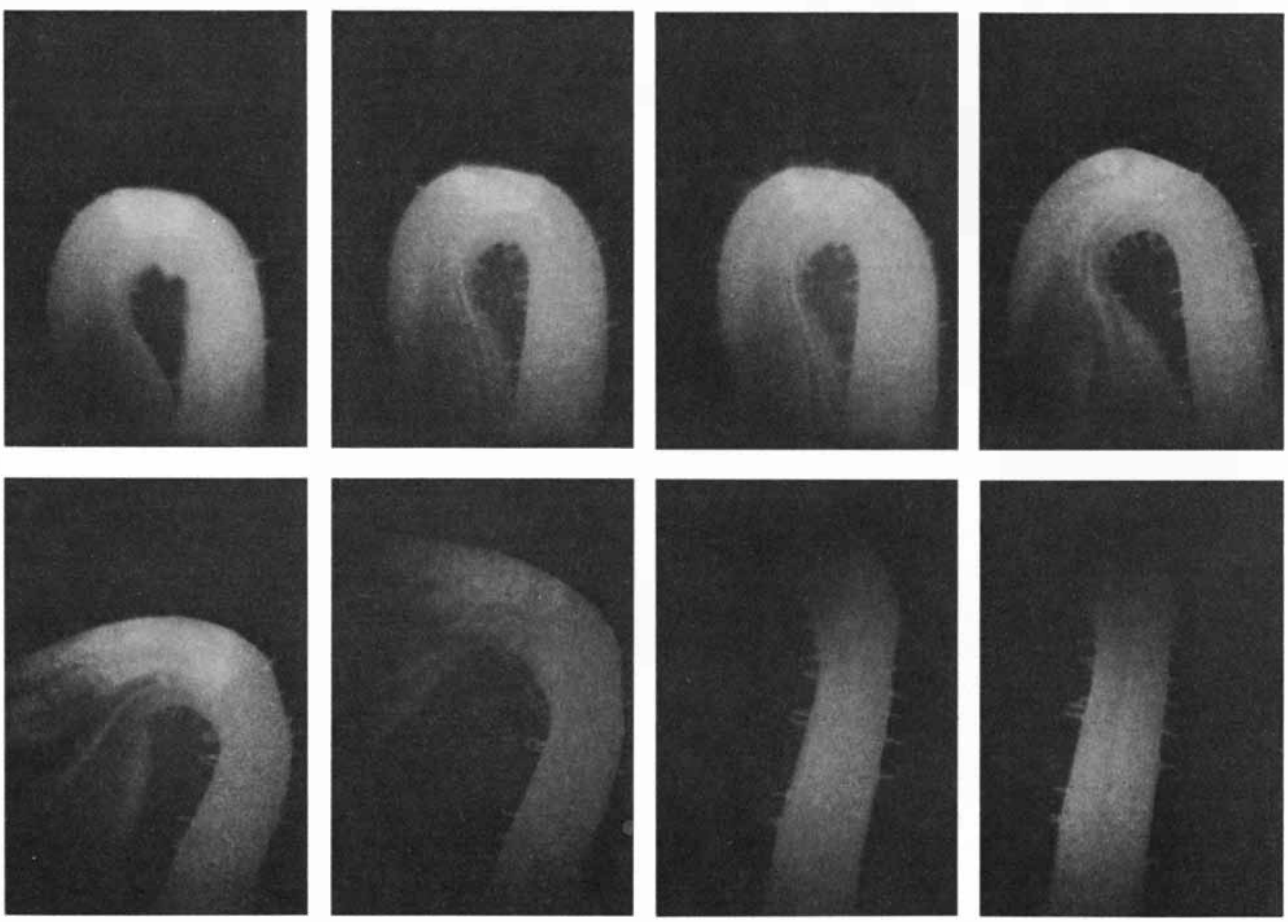


LETTUCE SEEDLING grown in dim light is depicted at two-hour intervals. The spatial pattern of the curvature does not change under these conditions, as is evident in the curves (*bottom*) plotting the curvature against distance from the apex, with the point of maximum curvature remaining about a millimeter behind the apex. A mark attached to a group of cells is seen to move through the bend in the stem. (The colored line represents the mark.) The unchanging geometry is made up of changing elements, that is, the cells of the plant.



GROWTH PATTERN of a lettuce seedling grown in bright light is revealed in photographs made over a period of 28 hours. The growing stem comes out of the ground in a bent form that can be preserved in dim light as the seedling grows. The photographs show the seedling at (*left to right*) 0, 2, 10, 12, 14, 16, 20 and 28 hours. At 14 hours the stem is seen to straighten. In contrast to the growth of roots and seedlings in dim light, this pattern of growth is nonsteady (varying in time), and the local rates of change must be evaluated in growth analysis.

tropic; the change of shape is produced by the small degree of anisotropy and by large gradients in the magnitude of the strain rate. It should be emphasized that only a start has been made toward analyzing surface growth and therefore toward understanding the growth processes that lead to the beautifully regular shapes of leaves and many other determinate plant structures.

The growth of a shoot is far more complex than that of a root, a seedling or a leaf. One must recognize not only that the apical portion of the stem is increasing in length but also that new leaves are being formed periodically at the apical meristem of the shoot. The new leaves grow in a coordinated way with the stem. (Additional complexities arise with flowering and fruiting and with dormancy and seasonal growth, but we shall ignore them.)

Striking regularities in the vegetative growth of a shoot can be found that are as interesting and important as the patterns we have already discussed. It is difficult to observe the growth of the apex of a shoot because the young leaves are crowded together, overarching the apical dome. Usually they must be removed before the apex can be seen or photographed, and it is questionable whether the growth of the apex is normal after such an operation. Nevertheless, a good way to understand the morphology of the shoot apex is to dissect a bunch of celery.

The celery stalks are the petioles, or leaf stems, of the compound leaves. The oldest leaves on the outside of the bunch can be cut off at the base with a paring knife. Inside are progressively younger, smaller and paler leaves, which can be removed also. Now the partially dissected apex should be placed under a stereomicroscope or viewed with a hand lens.

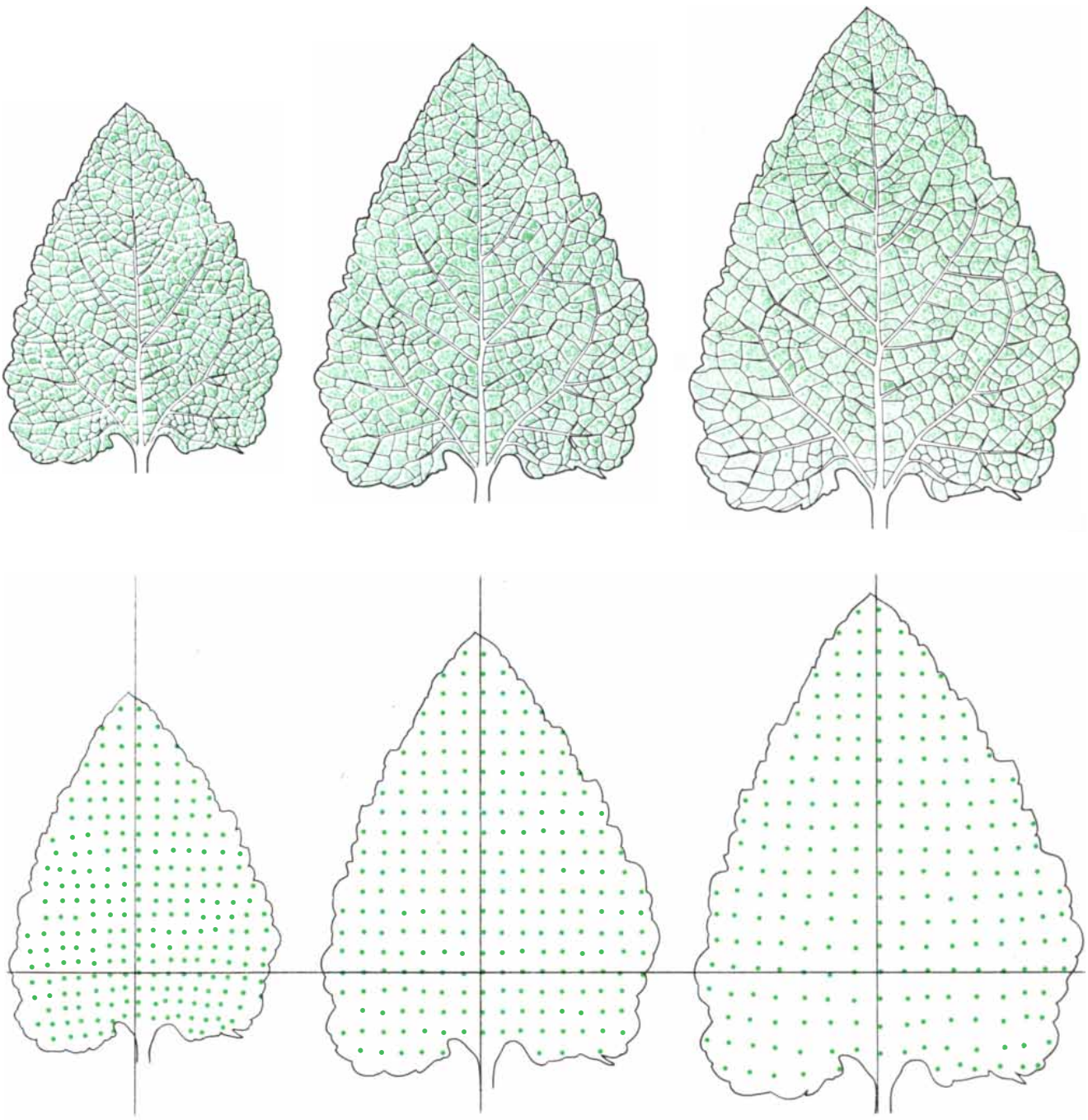
As young leaves (from 10 to 20 millimeters long) are removed with a small scalpel one can begin to see the broad, slightly domed apical meristem, which is where leaves originate. It is surrounded by primordial leaves that are progressively younger the nearer they are to the center of the apex. Some of them resemble hands with translucent green fingers. The youngest two or three primordia are simply bulges on the apical dome.

If the dissected apex is maintained on wet filter paper for a day or two and fungal infections are avoided, it is possible to observe the displacement of the young primordia away from the center as the shoot grows. One may even see the initiation of a new leaf primordium. Such a primordium appears first as a bright reflection at a predictable spot (about 137.5 degrees from the last visible primordium) and soon becomes a bulge on the surface. The area of the bare portion of the apex is now at its

minimum. The dome continues to enlarge, displacing the new primordium away from the center, and another leaf is initiated. In typical vegetative growth this process is repeated at equal time intervals if the temperature is constant. This time interval between the formation of successive leaves is termed a plastochron, a term proposed in 1880 by the German botanist Eugen Askenasy, who had studied with von Sachs.

A consequence of this growth pattern is that the growing part of a vegetative shoot bears a succession of leaves of different ages, each differing in age from the next-oldest and the next-youngest leaf by one plastochron. The successive leaves differ from one another in a highly regular way, not only in age but also in distance from the apex, in length, in weight and in degree of tissue differentiation. When the lengths of successive leaves are measured, for example, it is found that the ratio of the length of a leaf to the length of the next-youngest one is reasonably constant for leaves that are growing rapidly. This relation can be called the plastochron ratio and can be interpreted as the ratio by which a typical leaf increases in length per plastochron. Its constancy implies that the primordial leaves and the young leaves grow in length exponentially, that is, in a compound-interest manner.

In several plant species that have been investigated in this way the plastochron ratio has been found to be constant also for leaves that are large enough (from five to 50 millimeters long) to be seen



LEAF GROWTH is portrayed in drawings (*top*) based on photographs of a cocklebur leaf made on three successive days. In the bottom drawings a set of points identified by inspecting the photographs are plotted. The change in relationship of the points over the three days shows that growth is fastest near the bottom of the leaf. A leaf is a determinate structure: it reaches a certain size and stops growing.

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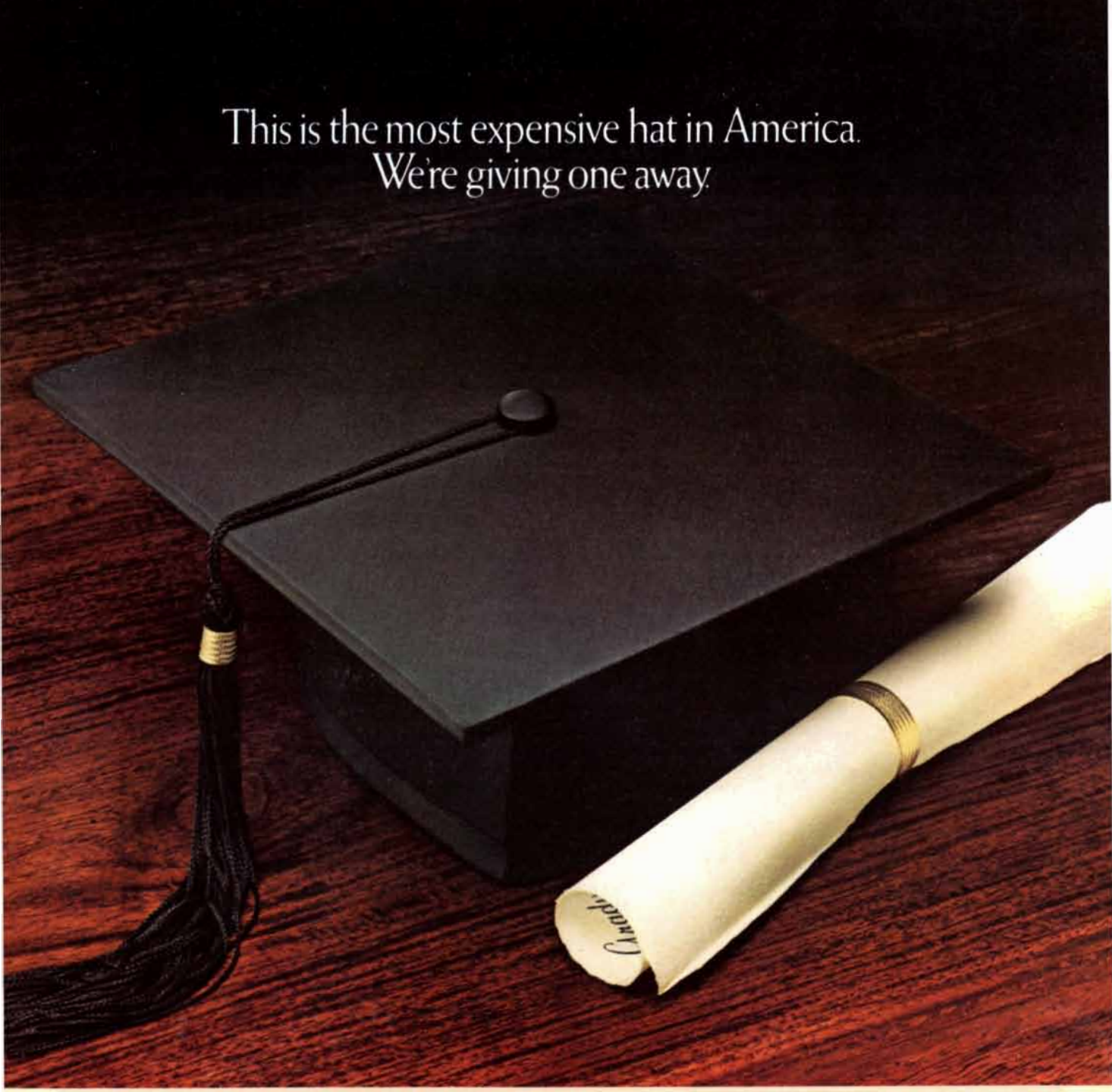

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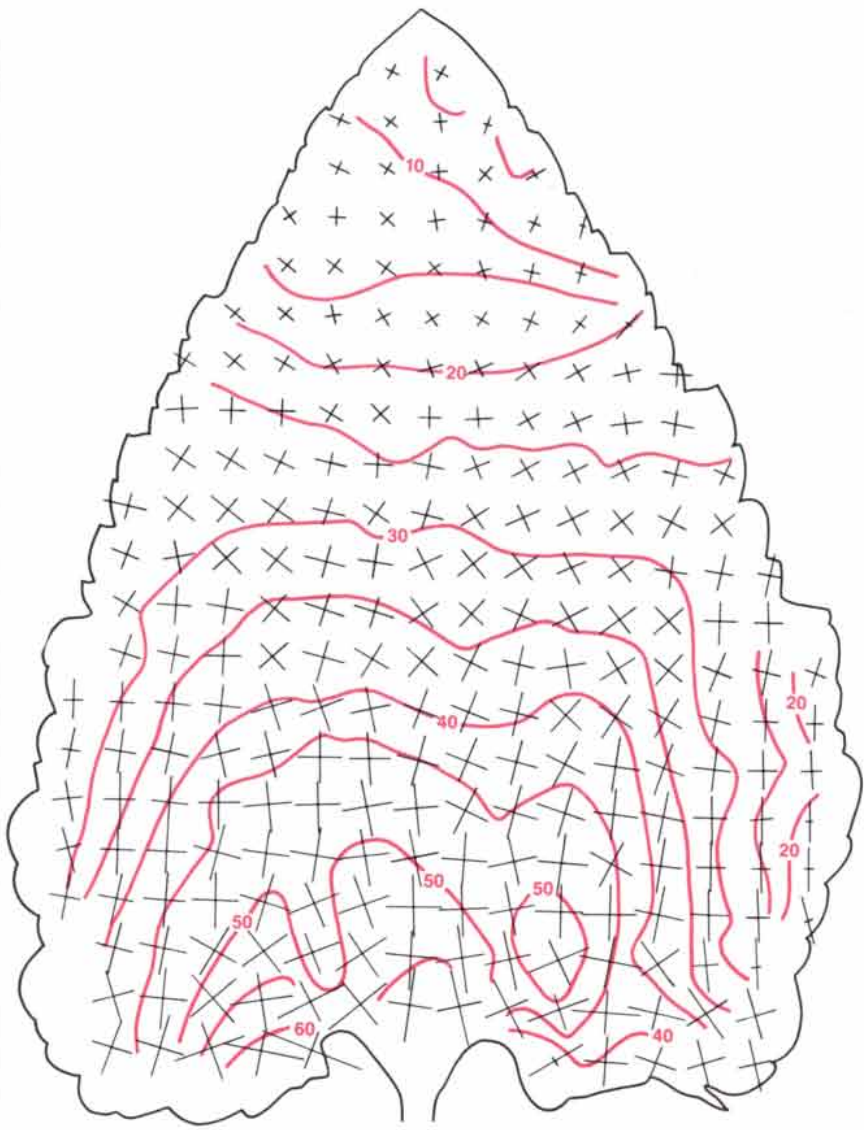
with the unaided eye and are accessible to measurement without damage to the plant. The plastochron ratio forms the basis for an index of the developmental age of a shoot: the plastochron index. Since new leaves are added to the shoot periodically, a rough index of the age of the shoot in plastochrons can be had by counting the leaves that are longer than a reference length, say 10 millimeters.

To be more exact one might specify that a plant in which, say, the fifth leaf is just 10 millimeters long has an age of exactly five plastochrons. If the fifth leaf were somewhat longer than 10 millimeters, the shoot would be somewhat older than five plastochrons but perhaps not yet six. From the measured length of the fifth leaf and the next-youngest one (the sixth) a fraction of a plastochron can be calculated that, added to five, is the plastochron age of the shoot.

The plastochron index, based on three simple nondestructive measurements, is a continuous developmental scale that can be employed to draw conclusions indirectly about the growth of the apical meristem of the shoot, the primordia of the leaves and the stem segments when direct observations are not feasible. The use of the index has begun in a variety of descriptive and experimental studies of shoot development.

If one now considers this pattern of vegetative shoot growth in terms of the spatial and material changes taking



PATTERN OF LEAF GROWTH is revealed in a drawing based on a computer calculation of the magnitude of growth in area of a cocklebur leaf, as is depicted by contour lines of equal rate (expressed as percent per day). The directions of maximum and minimum linear expansion are portrayed by crossed lines at each of the identified points on the leaf. The calculation shows the growth to be almost isotropic, that is, nearly equal in all directions. It also shows that the large spatial variation in the magnitude of the growth rate and the small amount of anisotropy are sufficient to account for the change in shape of the leaf as it grows to its mature form.

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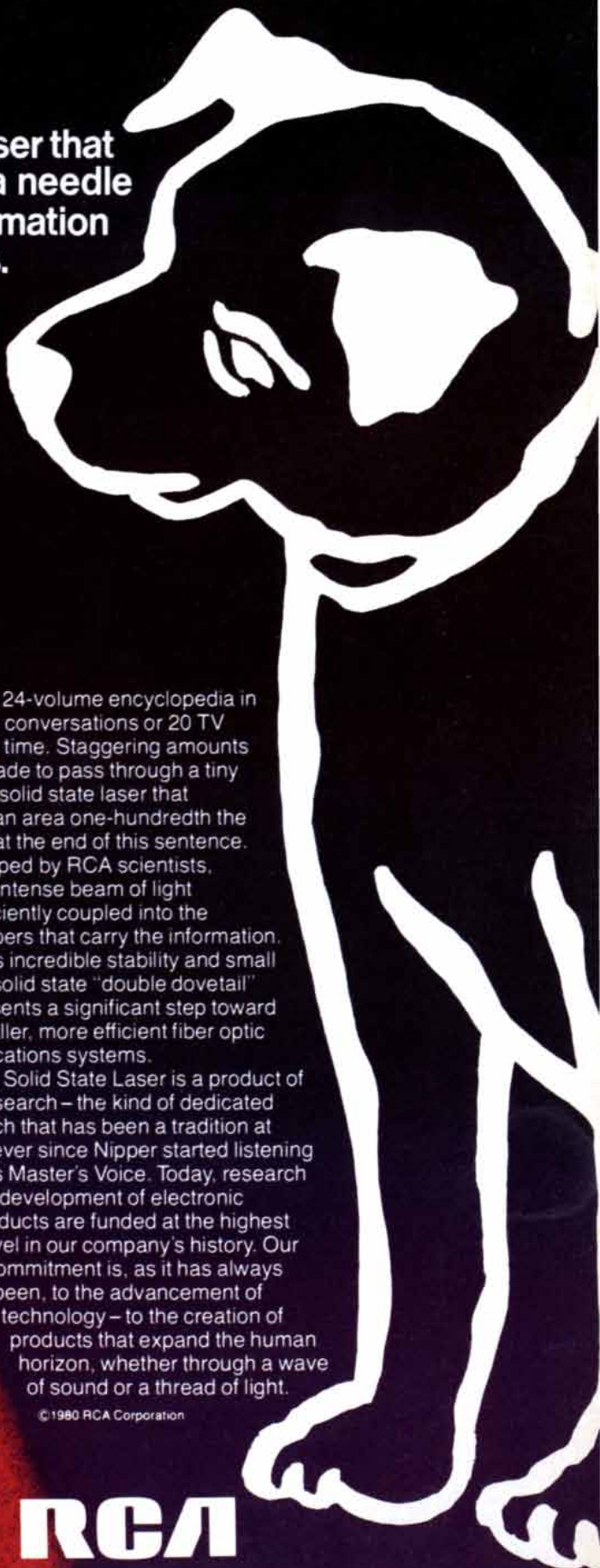

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place, it is immediately apparent that the growth pattern is not steady, as it is in root growth and the maintenance of the seedling hook. It may be that in the bare section of the apical meristem or in the stem region of the young shoot points are displaced with a pattern of velocities that is invariant with time, but the available data are not sufficient to decide the question. Certainly the emergence of a leaf primordium and its subsequent growth involve both material and spatial changes. It is a challenge for future research to develop adequate models for this complex process and efficient methods for analyzing data on the morphogenesis of the shoot.

One regularity of shoot growth does stand out. The events that happen during one plastochron (the initiation of a primordium, its displacement through the growth of the apex and its subsequent growth as a leaf) closely repeat the events of the preceding plastochron. This plastochronic rhythm of growth processes that are repeated in time and displaced in space is characteristic of the growth of a shoot. Other growth processes of the shoot, such as the transition of the apex to the production of a flower, seasonal growth and the phenomenon of unequal leaf growth, can probably best be studied as modifications of this pattern.

We have shown that a knowledge of the spatial and temporal variation in growth rates within tissues is essential for an understanding of the morphological aspects of plant development. The application of this growth analysis can also be a powerful tool in physiological studies. For example, if one were interested in the biosynthesis of protein, the spatial distribution of both the displacement rate and the protein content must be known in order to compute local rates of protein biosynthesis in growing tissue. One would then find that even if the local tissue content of a biosynthate is steady, the plant is producing the substance at a rate necessary to maintain the content during the local expansion plus or minus an amount necessary to maintain the existing spatial gradient during the displacement of cells.

Little of the existing literature on the physiology of growing tissue contains this kind of information. Indeed, studies of the spatial variation of growth rates within growing plant organs are rarely found in the botanical literature. The recent advent of inexpensive interactive computer graphics implies that the analysis of growth rates is at least no longer difficult. The next decade should see much progress in the analysis of morphogenesis and in determinations of rates of cellular change, local rates of biosynthesis and local rates of transport in growing plants.

The Origins of Copper Mining in Europe

The age of metals began with the use of "native" copper in the Old World. As rising demand required the mining of copper ores one of the first mines in Europe was opened at Rudna Glava in Yugoslavia

by Borislav Jovanović

Man's earliest mastery of metallurgy, the evidence for which is a variety of copper artifacts found in Europe and in western Asia, marked the end of one great cycle of prehistory and the beginning of another. In terms of technology the cycle that ended might be called the cycle of primary discoveries and basic innovations. That cycle began with man's control of fire and concluded with the Neolithic revolution: man's mastery of plant and animal husbandry.

Until recently studies of the origin and development of copper metallurgy in southeastern Europe, the area where I work, have focused on early copper tools, weapons and ornaments and have neglected how the metal was obtained. These studies are nonetheless of prime importance. After all, copper was man's first abundant metal, and tools made of it gave rise to almost as many basic transformations in human existence as the adoption of agriculture or even man's more ancient mastery of fire. One important difference between the most recent of these crucial events and the earlier two should be kept in mind: the exploitation of fire and the domestication of plants and animals were based on clearly apparent natural resources. Essentially all that was needed to inspire the mastery of these practices was the recognition of how advantageous to human activities their adoption could be. The processing of metal calls for a more radical change in the natural state of affairs: the profound and permanent alteration of materials. Once the new technology had been developed it enabled human communities to make desirable artifacts out of a substance that had entirely novel properties.

Here I shall tell what has been learned about early copper mining, the earliest known anywhere in Europe, at one accidentally discovered site in Yugoslavia: Rudna Glava, near the border with Romania 140 kilometers east of Belgrade. At the same time I shall attempt to relate the mine at Rudna Glava to early copper mining elsewhere in the Balkans, in other parts of Europe and in western Asia.

The copper first exploited by prehistoric man was doubtless "native" copper, that is, the metal in a pure form rather than in the form of various ores. In many areas where rich copper-ore deposits exist it is quite easy to collect nuggets of native copper lying on the surface. Such supplies of the metal, however, are limited, and so the first metallurgists must soon have exhausted them. Thereafter they had to dig for ore and to smelt it.

One might think in view of the fact that copper mining played such a crucial role in human history early copper mines would have been an important component of the studies of interested prehistorians. They have not been, and for good reason: most of the early mines were obliterated by later mining operations. Such was nearly the fate of Rudna Glava.

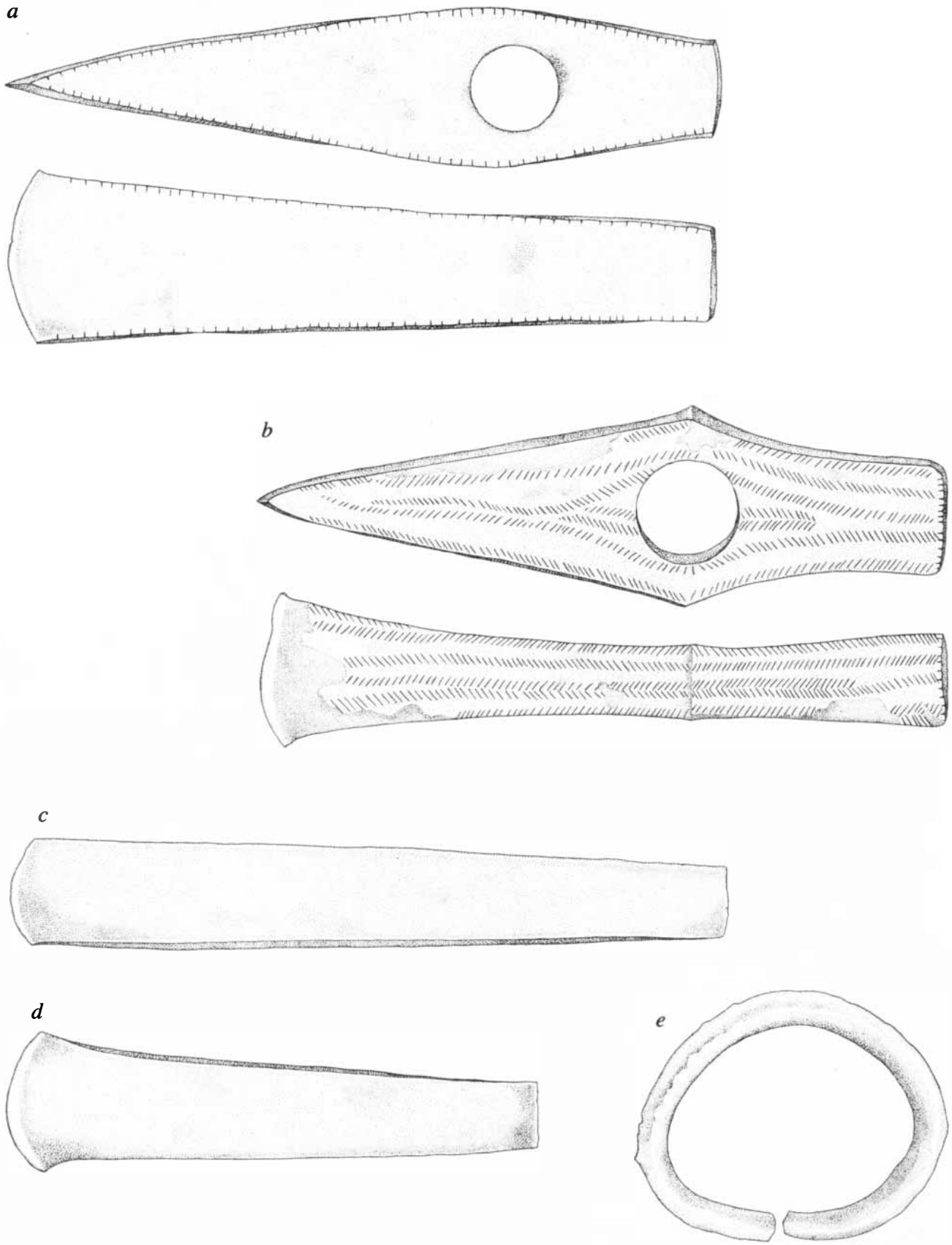
The veins of copper ore at Rudna Glava run through a massif of limestone. They were formed by the slow decomposition of chalcopyrite, a copper-iron sulfide associated with the iron ore magnetite that is present in the limestone. Magnetite was mined in open-pit operations at Rudna Glava until as recently as 1968. These operations destroyed a number of the ancient copper-ore mine shafts before anyone recognized them as the works of prehistoric man. Since then the site has been intensively investigated under the combined auspices of the Museum of Mining and Metallurgy in Bor and of the Archaeological Institute in Belgrade.

Mining was practiced long before the age of metals. Moreover, contrary to the opinion of those who regard most technological advances in the area north of the shores of the Mediterranean as borrowings from the more progressive cultures to the south, mining in Europe was a well-developed art in Neolithic times. It had even been done regularly, although on a comparatively small scale, in late Paleolithic times, at least as far back as 10,000 years ago.

The Paleolithic miners and those who followed them were mainly in search of flint for stone tools, but they also dug out other desirable minerals. For example, close to the site of Vinča outside Belgrade the red mercury ore cinnabar was extracted to serve as a pigment. Elsewhere the iron oxide ocher was mined for the same purpose. On the Greek islands and in the mountains of Hungary deposits of the volcanic glass obsidian were exploited. A wide variety of igneous rocks were collected as the raw material for heavy-duty axes and chisels. White marble and other semiprecious minerals were made into amulets. Fossilized seashells, mined along the Mediterranean, were transported to southeastern and central Europe. Early miners everywhere exploited local deposits of clay for the manufacture of pots and similar fire-hardened artifacts. Hence long before the rise of copper metallurgy prehistoric Europe had an advanced mining technology all its own.

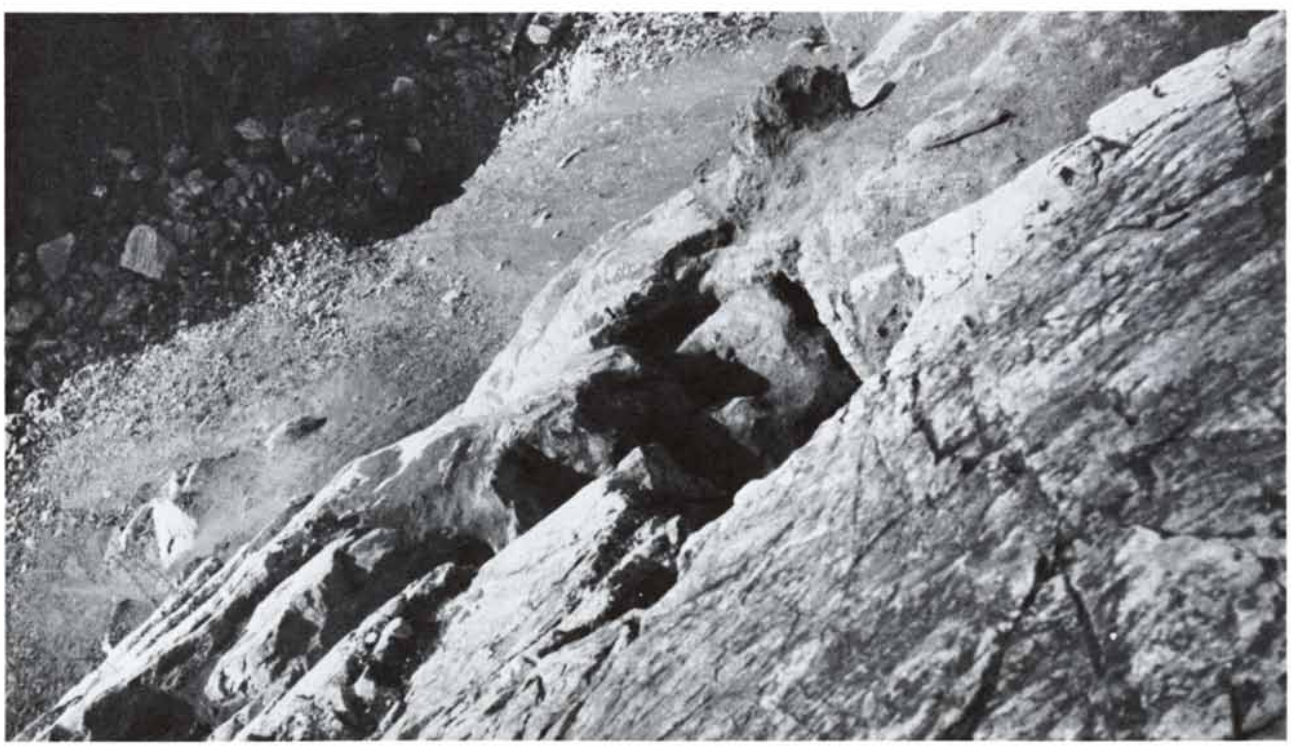
Mining, then, like hunting and gathering, is a human activity much older than agriculture. One might even propose an adage: The husbandry of minerals long preceded that of animals and plants.

In Paleolithic times flint was mined by the digging of shallow pits or trenches. In Neolithic times vertical shafts and horizontal galleries were dug into flint deposits. The technology of mining copper at Rudna Glava was much the same. Flint-bearing strata are generally horizontal and the copper-ore veins at Rudna Glava are vertical, but the miners got the ore out by digging a horizontal access platform into a slope where a vein reached the surface and then excavating narrow vertical shafts into the vein. The basic tool of excavation was a stone maul. In the flint mines,



COPPER ARTIFACTS typical of the Vinča culture that flourished in the central Balkans during the fifth and fourth millenniums B.C. come from Pločnik, a site in Serbia 165 kilometers south-southeast of Belgrade. At the top (*a*) is a socketed axe shown in front and side view; it is 17 centimeters long. Below it (*b*) is a second axe that is decorated with an elaborate herringbone pattern; it is 16.5 centimeters long. At the bottom are two chisels; the longer one (*c*) is 17 centimeters and the shorter (*d*) is 12.6 centimeters. To their right is a bracelet (*e*), one of the variety of copper ornaments made by Vinča craftsmen. The demand for copper tools, weapons and ornaments at the end of the Neolithic period and the start of the Chalcolithic promoted the local mining of copper ores such as that discovered at Rudna Glava.

EARLY COPPER MINES that have survived obliteration by later mining operations are known from Ireland and Spain eastward to Turkey and Iran. Of the five mines (*triangles*) on this map, however, only two in the Balkans (Rudna Glava in Yugoslavia and Ai Bunar in Bulgaria) and one in Spain were active during the Chalcolithic period, the interval separating the Neolithic period from the start of the Bronze Age. Of these three Rudna Glava is the earliest, as is demonstrated by the discovery there of pottery typical of the Vinča culture.



MODERN OPEN-PIT IRON MINE at Rudna Glava exposed this sheer rock face seen from above. The limestone of the mine is rich in the iron ore magnetite, with which is associated the copper-iron sulfide chalcopyrite; the decomposition of the chalcopyrite gave rise to the veins of copper ore in the rock. The miners of Vinča times excavated the ore by digging down along the veins; the modern iron miners, by cutting horizontally into the rock, exposed the copper miners' vertical shafts. The bottom of one such shaft is seen at the center.

as a matter of simple economy, the mauls were usually made out of flint, the material nearest to hand. At Rudna Glava the mauls were usually made out of large pebbles of gabbro (a granular igneous rock) with a groove pecked or ground into them so that the stone could be swung by a strap or a loop of rope tied around it. This kind of fastening was preferred evidently because a maul with a wood handle would have been difficult to wield in the cramped confines of the mine shaft.

The stone mauls, on the average some 25 centimeters long and 10 centimeters wide, weighed between two and four kilograms. All that have been found, either on the access platforms or in the vertical shafts, show signs of heavy wear on their work surfaces. Many of them were broken. Antlers were also found; presumably they served as picks, as did the antler tools found in abundance in the Neolithic flint mines of Europe.

After preparing an access platform the Rudna Glava miners followed the vein of ore downward, in some places to a depth of between 15 and 20 meters. Where the lateral extent of the vein made it worthwhile they also excavated short horizontal galleries, but they devoted their main effort to the ore-rich vertical shaft. Most of the ores they quarried in this way were malachite and azurite, respectively green and blue carbonates of copper that can be of gemstone quality.

The archaeological campaign at Rudna Glava has found more than 20 such ore-following shafts. There is no regularity to the dimensions of the shafts; they vary with the size of the ore veins. Some veins ran together, and some split apart where there were rifts in the limestone matrix. At places where an excavated shaft appeared to be in danger of collapse the miners built drystone supporting walls, utilizing the rubble left by their own digging. The maximum depth of excavation seems to have been set by the availability of fresh air.

The air supply was important not only for the miners' own well-being but also because they used a technique of alternate heating and cooling to break up the ore and facilitate quarrying. They carried down jugs of water and built small fires against the face of the ore, and a good air supply was necessary if the fires were to burn well. When the rock was well heated, the miners splashed it with water; the sudden contraction of the cooled rock cracked it. It was now that the antler tools (and doubtless wood wedges that have long since crumbled to dust) came into play as the miners widened the cracks and pried out loose lumps of ore. The ore was probably lifted in sacks to the surface, where it may have been sorted according to color.

The copper ore was apparently not

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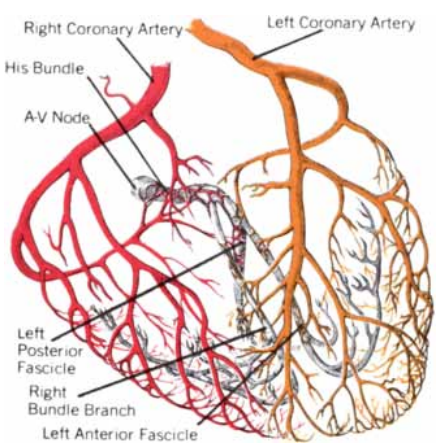

Branches of the right and left coronary arteries supply blood to the AV node and intraventricular conduction system.

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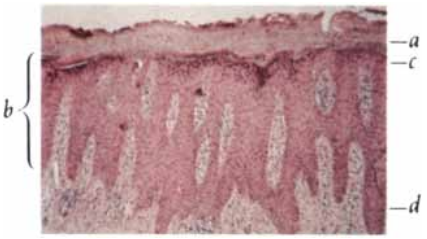

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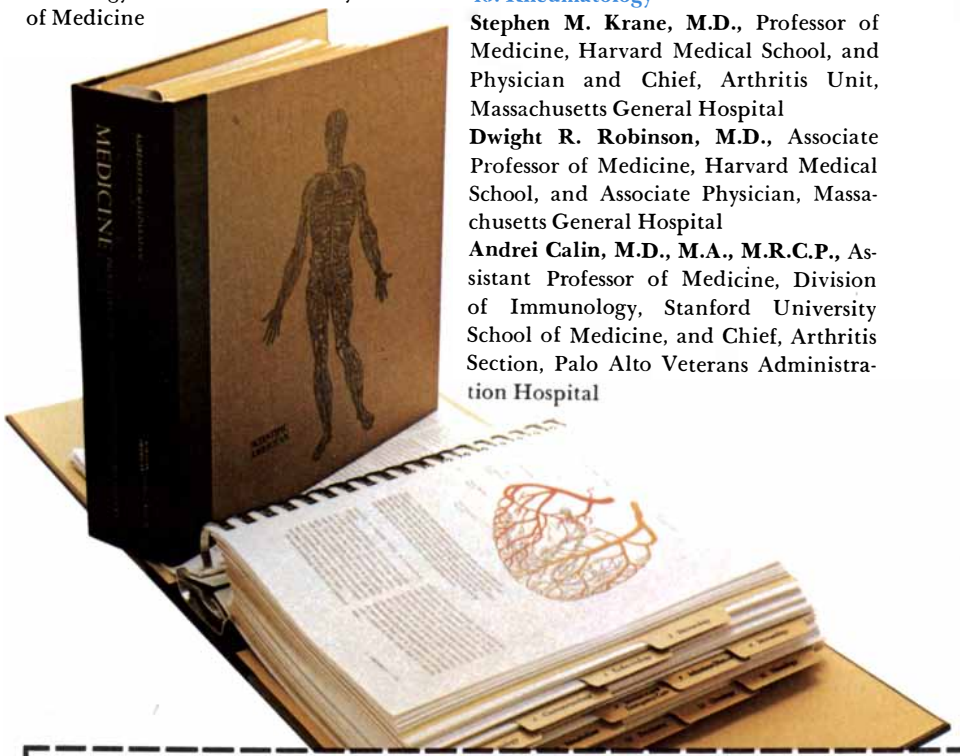

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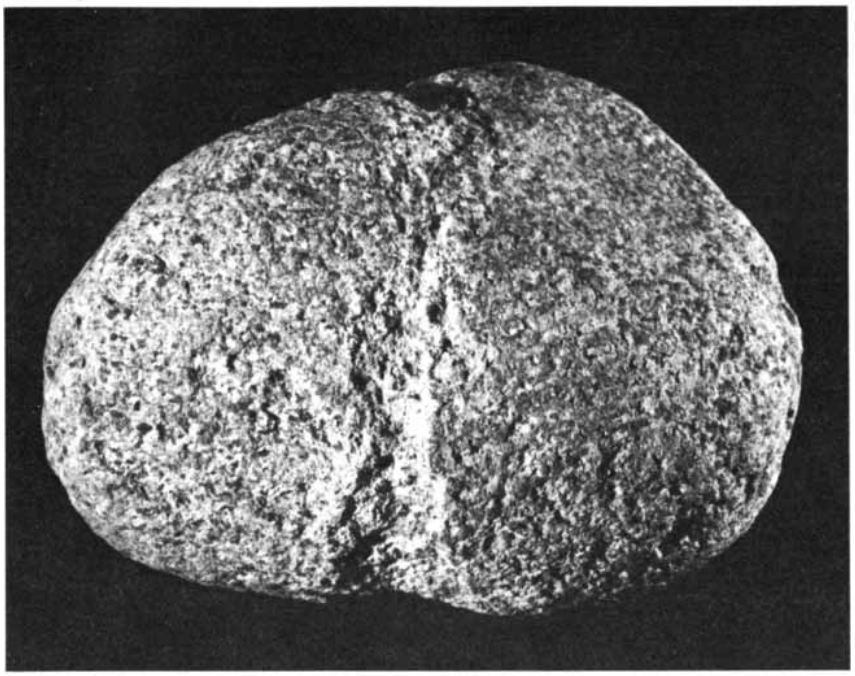

MINER'S MAUL is one of many found in the mine shafts at Rudna Glava. It is a pebble some 20 centimeters long. The groove held a strap or rope with which the maul could be swung.

smelted anywhere near Rudna Glava. In spite of a careful search of the site and its surroundings no evidence of such activity has been found. It seems that the ore was carried from the mine at Rudna Glava to the nearest population center, about 80 kilometers to the west in the valley of the Morava River. At the copper-mining site of Ai Bunar in southern Bulgaria the practice appears to have been the same. Ores from that mine, ready for processing, are found in a number of contemporaneous settlement sites in the same vicinity.

It is always risky to build a hypothesis on negative evidence, but the absence of any evidence of copper smelting at Rudna Glava suggests that mining was not a year-round activity but a seasonal one. Moreover, some positive evidence does point to the same conclusion. Discarded mauls have been found at different levels in the same shafts, many of them tucked away in lateral cracks. This suggests that the mauls abandoned nearer the surface mark the end of one mining campaign and those found farther down the shaft mark the end of subsequent campaigns. The same kind of pattern is apparent in the many pottery vessels the miners abandoned underground after using them to carry water for the heating-and-cooling technique of breaking up the ore. Some of the richest archaeological finds at Rudna Glava have come from mined-out shafts that were filled with debris from later mining; this too suggests, although it does not absolutely demonstrate, a periodic pattern of mining. If the demand for copper ore was continuous, which seems probable, the most likely periodic pattern would have been a seasonal one.

So far I have not identified the miners of Rudna Glava either in terms of their culture or of the prehistoric period when they were active. In this regard it was fortunate for us that the miners had left behind some of their pottery. The Balkan culture characterized by these vessels is well known through the excavation of numerous early habitation sites throughout southeastern Europe, and its age has been determined in both relative and absolute terms.

The culture is named Vinča; it is a late Neolithic culture named after the site near Belgrade mentioned above. Carbon-14 analyses place the early phase of the Vinča culture in the second half of the fifth millennium B.C. In this phase the Vinča people came to occupy the central Balkans and the southern part of the Pannonian plain, south and west of the Danube. The pottery found in the mine shafts at Rudna Glava belongs to a transitional stage of the Vinča culture that divides the earlier Vinča period from the later.

Three different accumulations of pottery recovered from the mine shafts provide the basis for this finding. The older of the three accumulations was found on the edge of one access platform, specifically the platform associated with shafts No. 2-*r* and No. 2-*g*. There, together with a damaged antler tool and a large maul, the excavators found a squarish vessel made in the general shape of a deer and three vessels of the kind called amphoras by classical archaeologists. The deer effigy is an arti-

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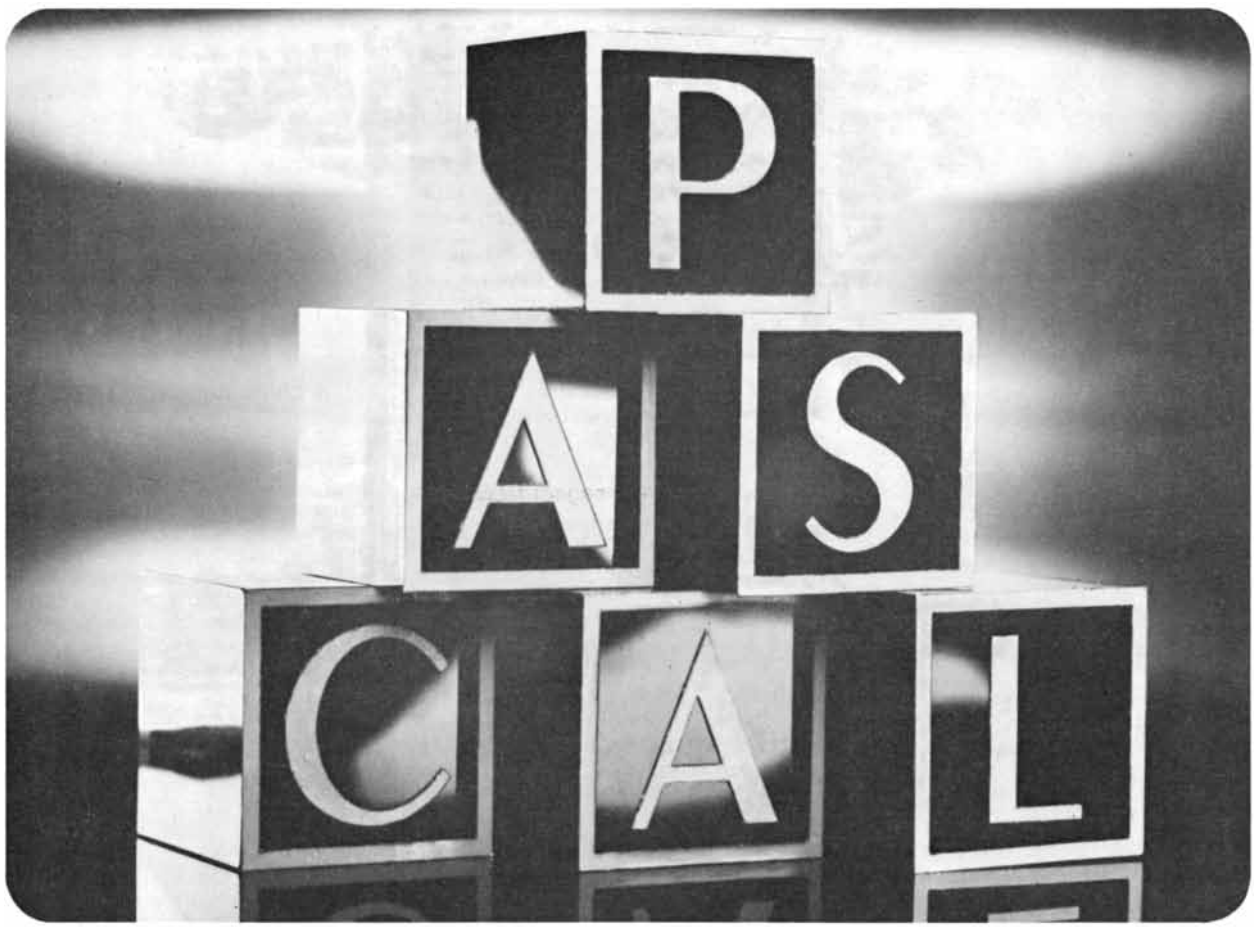

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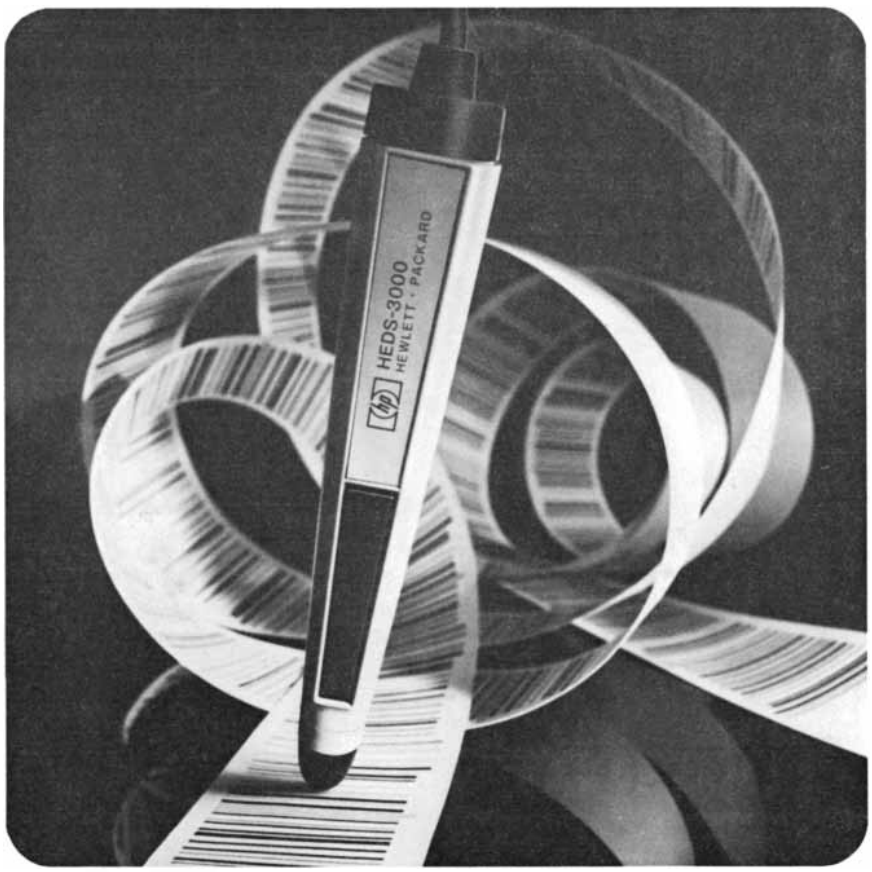

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CACHE OF POTS was one of three caches found at Rudna Glava. The miners broke up the ore by heating the veins with a small fire and then cooling them by throwing water on them. The water was brought to the ore in the pots. The vessel is typical of Late Vinča ware.

BOTTOM OF MINE SHAFT contained a miner's maul (*left foreground*), perhaps abandoned when the ore was worked out. Mauls abandoned at different depths in the mine shafts suggest that mining at Rudna Glava was not a year-round activity but a seasonal one.

fact of the kind called an "altar" because offerings could be burned in its basin-shaped back. It seems more probable that in the mine such effigies served as lamps. Of the amphoras, one was black, had a burnished surface and was ornamented with a motif of spirals. Pottery of this kind is characteristic of the final phase of the earlier Vinča culture, a phase that is contemporaneous with the end of the Neolithic period in southeastern Europe some 6,000 years ago.

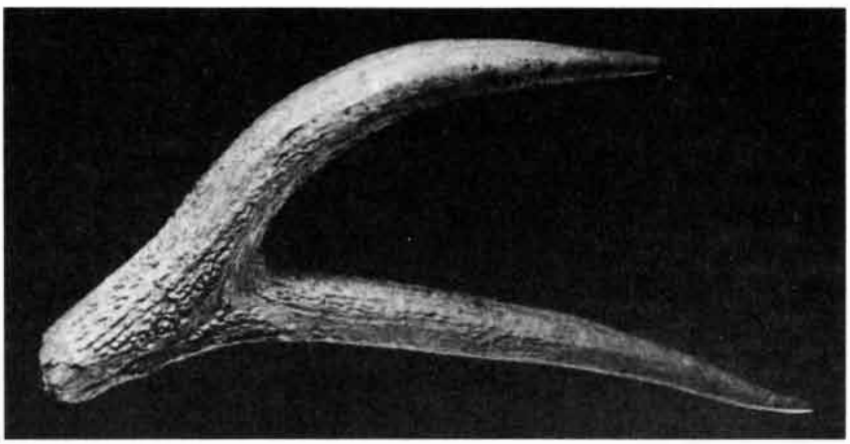
The other two pottery accumulations were found on the access platform for shaft No. 7. The first accumulation consisted of one pot of coarse ware and one amphora. The amphora was black, burnished and ornamented with a shallow spiral motif. The second accumulation consisted of two amphoras with a conical neck, both of them gray and burnished. Both accumulations are characteristic of the initial phase of the later Vinča culture, a phase that is generally contemporaneous with what European archaeologists call the Eneolithic or Chalcolithic, a transition period between the Neolithic and the subsequent Bronze Age. The Chalcolithic (literally "copper and stone") varied in duration in different parts of the Old World and was sooner or later supplanted everywhere by the Bronze Age and the dawn of history.

Thus the Rudna Glava copper-ore mine shafts, at least those that escaped accidental destruction and are available for our scrutiny, can be dated to the interval in prehistory when cultures previously without metal, the cultures of the Neolithic, were being exposed to the first products of metallurgy: copper artifacts. What was the situation elsewhere in the Old World? Not far from Rudna Glava, at Ai Bunar in Bulgaria, deposits of copper ore were exploited at an early date by open-pit mining. The miners evidently did their work with much the same kind of stone maul found at Rudna Glava, although only one of the mauls has been found. Archaeological evidence at Ai Bunar associates its mining operations with a culture known as Karanovo VI, which is placed in the late Chalcolithic. This culture is therefore considerably younger than the earliest-known Rudna Glava one, which dates to the end of the Neolithic.

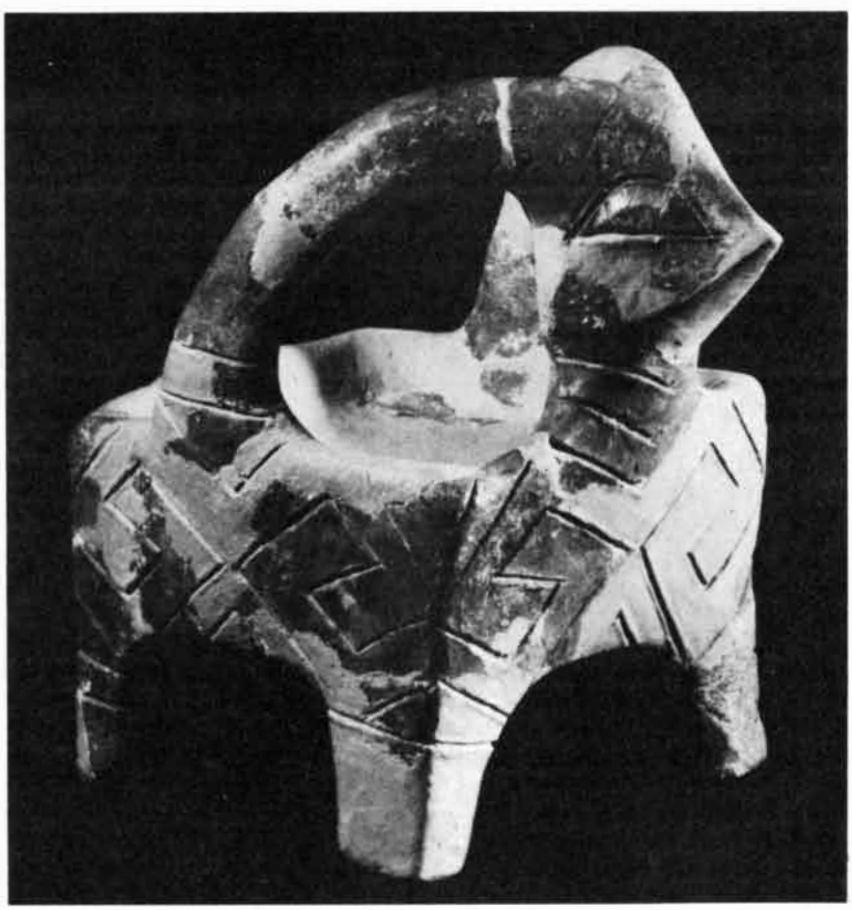
Early copper mines are known in other parts of Europe. One such mine has been discovered quite recently at Chinflon in Spain. It was exploited chiefly during the Bronze Age, but it also contains evidence of mining in Chalcolithic times. All the other mines are younger. At Mount Gabriel, in the west of County Cork in Ireland, the miners worked with stone mauls like those at Rudna Glava, but they did so in the Bronze Age. At Mitterberg in Austria mining

was done in the Late Bronze Age. Outside Europe a copper-mining site in the Veshnoveh area of Iran, featuring underground galleries 40 meters long, was worked by miners with the same kind of stone mauls that were found at Rudna Glava. The Veshnoveh miners also did not begin their work until the Early Bronze Age. The site of Kozlu in central Turkey is another early copper mine in western Asia; its shafts are said to be more than 50 meters deep. Again the mining was done in the Early Bronze Age, specifically in about 2800 B.C.

Is Rudna Glava perhaps the world's oldest copper mine? It is most unlikely. The copper artifacts of western Asia are much older than those of the Bal-



WORN TOOL MADE OF ANTLER was another of the miners' artifacts found in the shafts at Rudna Glava. The Neolithic flint miners of Europe also used antlers as picks and pinch bars.



POTTERY FIGURE IN THE SHAPE OF A DEER was found in the earliest cache of pottery discovered at Rudna Glava. Seen reconstructed in this photograph, it is 21 centimeters high. Its rectangular body forms a shallow basin. It may therefore have served as a miner's lamp.

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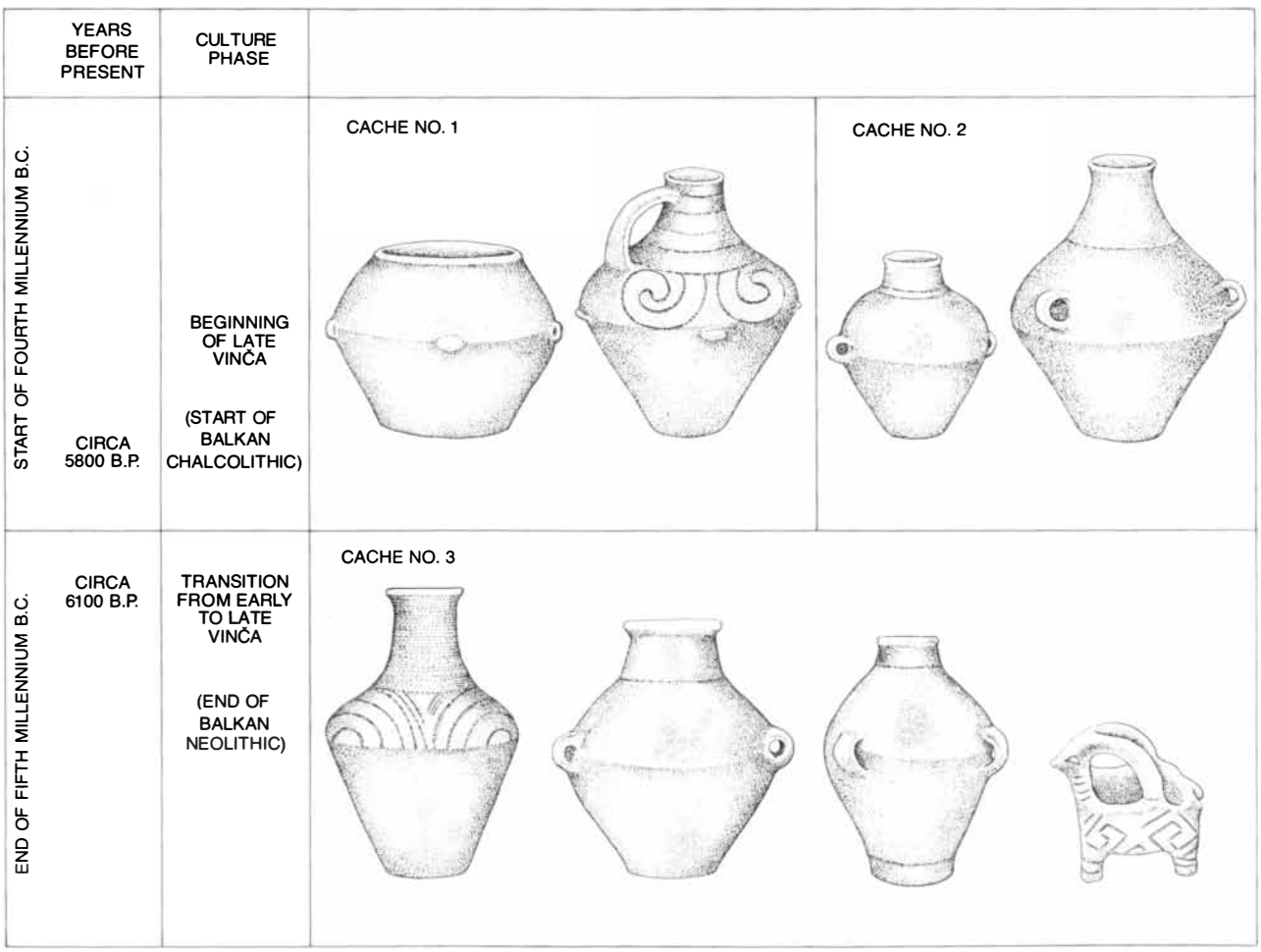
kans, and they cannot all have been fashioned out of native copper. What can be asserted, however, is that the Vinča people, and perhaps even earlier inhabitants of the Balkans, developed the technology of copper production entirely on their own. This ability to extract a new kind of raw material with methods developed millenniums earlier to win flint was not, as some have supposed, a technology merely borrowed by Balkan barbarians from the more technically advanced inhabitants of the Mediterranean shore.

How might the Vinča people have developed a talent for finding copper ore? At Rudna Glava even an untrained eye would have sufficed. On that bare limestone massif the places where veins of ore reach the surface show up as bright patches of color. It was exactly at such sites that the miners began their excavations. They were not, however, undiscriminating about the sites they chose. They left some ore veins untouched, and modern analysis has shown that the neglected ores are poor in the particular minerals (azurite, malachite and cuprite) the Vinča miners prized.

One may also ask what need provided the strong motivation for undertaking this kind of heavy and hazardous work. A few decades ago the question would have been difficult to answer. Today, however, archaeological findings throughout the central Balkans bearing on the Vinča culture indicate that these people were notably active in the manufacture of copper tools, weapons and ornaments. One example is four hoards of Vinča copper axes and chisels recently unearthed at Pločnik in southern Serbia. There can be little doubt that the Rudna Glava mines came into existence in response to a heavy demand for copper among the Vinča people. How many other Balkan copper mines were being worked in the same period may never be known. As is the case elsewhere in Europe and in western Asia, later mining has probably obliterated them.

Any analysis of the introduction of copper to the peoples of prehistoric Europe must deal with two separate phenomena: on the one hand the earliest knowledge of copper and on the other the earliest ability to obtain and use it. The existence of copper metallurgy in western Asia at an early date suggests that knowledge of the metal would have diffused to Europe, perhaps at the same time the early farmers of the Mediterranean basin first moved northward. It follows that copper would have been known in Europe long before the metal was actually mined, smelted and made into tools, weapons and ornaments.

In this sequence of events the earliest mining of copper ore in Europe would be conclusive evidence for the smelting and utilizing of copper—for copper metallurgy—in Europe at the same time. The Rudna Glava mine provides just such evidence dating back some 6,000 years, to the end of the fifth millennium B.C. One must therefore conclude that advanced copper metallurgy, supported by its own mining industry, had evolved in the Balkans by that date.



DATING OF POTTERY found in the Rudna Glava mines is possible because many residential sites of the Vinča culture, containing pottery of the same types, have been dated precisely by means of carbon-14 analysis. Thus the wares of caches No. 1 and No. 2 at Rudna Glava are typical of the first phases of the Late Vinča culture, which flourished in the first half of the fourth millennium B.C., during the Chalcolithic period in the Balkans. The wares of cache No. 3 are typical of the transition from the Early Vinča to the Late Vinča culture.

The N-Ray Affair

Early in this century an eminent physicist discovered a new kind of radiation, and others confirmed his work. The radiation turned out to be totally imaginary, proving that believing can be seeing

by Irving M. Klotz

Science, like any other area of human endeavor, has had its grand illusions: compelling concepts that have excited a substantial segment of the scientific community and yet have turned out to be totally wrong. Since history tends to record the successes in science rather than the failures, even the most striking of these concepts are likely to disappear. An exception to the rule is a completely imaginary form of electromagnetic radiation known as N rays. For a brief time the extraordinary reported properties of this radiation captured the imagination of scientists all over the world. Today N rays are remembered only for the insights they provide into the psychosociology of science.

To understand the significance of N rays one must consider the climate in which they were "discovered." The beginning of the 20th century was one of the most exciting periods in modern science. In 1895 W. K. Röntgen had generated X rays. Then radioactive emissions had been identified: alpha rays, beta rays and gamma rays. By 1900 it seemed inevitable that other types of rays would be found. Then in 1903 René Blondlot, a distinguished French physicist at the University of Nancy, announced that he had discovered the new type of radiation he called N rays.

Blondlot, a member of the French Academy of Sciences, was not a crackpot. His discovery of N rays was a mistake, not a hoax. Indeed, if the rays had been discovered in the 1880's, a decade before X rays and radioactivity, they would have been without precedent, and Blondlot would almost certainly have subjected his findings to a much more rigorous analysis. In the 1900's, however, a good physicist was psychologically prepared to encounter a new type of ray, just as other scientists were psychologically prepared to receive word of one. As a result Blondlot's findings touched off a hysterical reaction in parts of the scientific community, a wave of self-deception that took years to subside. The story, then, is a complex one that begins with Blondlot.

Blondlot was an accomplished experimenter in the physics of electromagnetic radiation. He had studied electric discharges through gases, the same type of phenomenon that had led Röntgen to the discovery of X rays. Therefore it was not surprising that after 1895 Blondlot became deeply involved in research on X rays. In particular he addressed himself to a question that was troubling many physicists around the turn of the century: Were X rays particles or were they electromagnetic waves?

It is now known that any form of matter or energy can exhibit the characteristics of both a particle and a wave, but in Blondlot's time physics had standard criteria for determining the nature of rays from a particular source. On the one hand it was known that particles coming from an electrified source normally carried an electric charge, so that if they were made to pass in a straight line between two metal plates, one charged negatively and the other positively, they would be bent out of their original trajectory. On the other hand it was known that although electromagnetic waves could not be deflected by charged plates, they could be polarized: they could be made to oscillate in a single two-dimensional plane. Blondlot planned to apply this last property of electromagnetic waves to determine the true nature of X rays.

If X rays were waves, Blondlot reasoned, they might be polarized as they emerged from the electric-discharge tube in which they were generated. To detect such polarization he proposed placing in various orientations in the path of the X rays a detector consisting of a pair of sharply pointed wires with a short electric spark jumping in a straight line between them. If the line along which the spark was jumping could be oriented so that it lay in the plane of the polarized X rays, the electric component of the electromagnetic wave should reinforce the energy of the spark and increase its brightness. When Blondlot carried out the experiment, he found to his delight that if the spark-gap detector was placed at a certain angle with respect to the electric-discharge tube, the brightness of the spark did indeed visibly increase.

Blondlot's excitement was quickly dampened, however, by his next discovery. Further testing with the detector revealed that the radiation acting on the spark was bent when it was passed through a quartz prism. Previous experiments had shown unequivocally that X rays are not bent when they traverse such a prism. It was at this point that Blondlot made what turned out to be a disastrous conceptual leap. He reasoned that the visible increase in the brightness of the spark showed that some wave was impinging on the spark-gap detector, and so if the waves were not X rays, they had to be some new form of electromagnetic radiation. He named the new radiation n rays, and later N rays, for the University of Nancy.

As an experienced physicist Blondlot knew that he also had to rule out the possibility that traces of ordinary light waves from the electric-discharge tube were responsible for the increase in spark brightness that signaled the presence of the N rays. Therefore he developed a photographic apparatus for recording spark intensities in which the spark-gap detector was covered by a cardboard box. Visible light rays could not penetrate the cardboard box but the N rays could. Comparing photographs made when an N-ray source was aimed directly at the box with those made when a special screen that blocked N rays was placed between the source and the box clearly demonstrated that the effect of N rays on the spark was not diminished by the exclusion of light. Encouraged by this success, Blondlot went on to develop more sensitive devices for detecting N rays, the most successful of which relied on phosphors: substances that emit light when more energetic radiation impinges on them.

With these improved detection methods Blondlot was able to carry out a wide-ranging study of the properties and

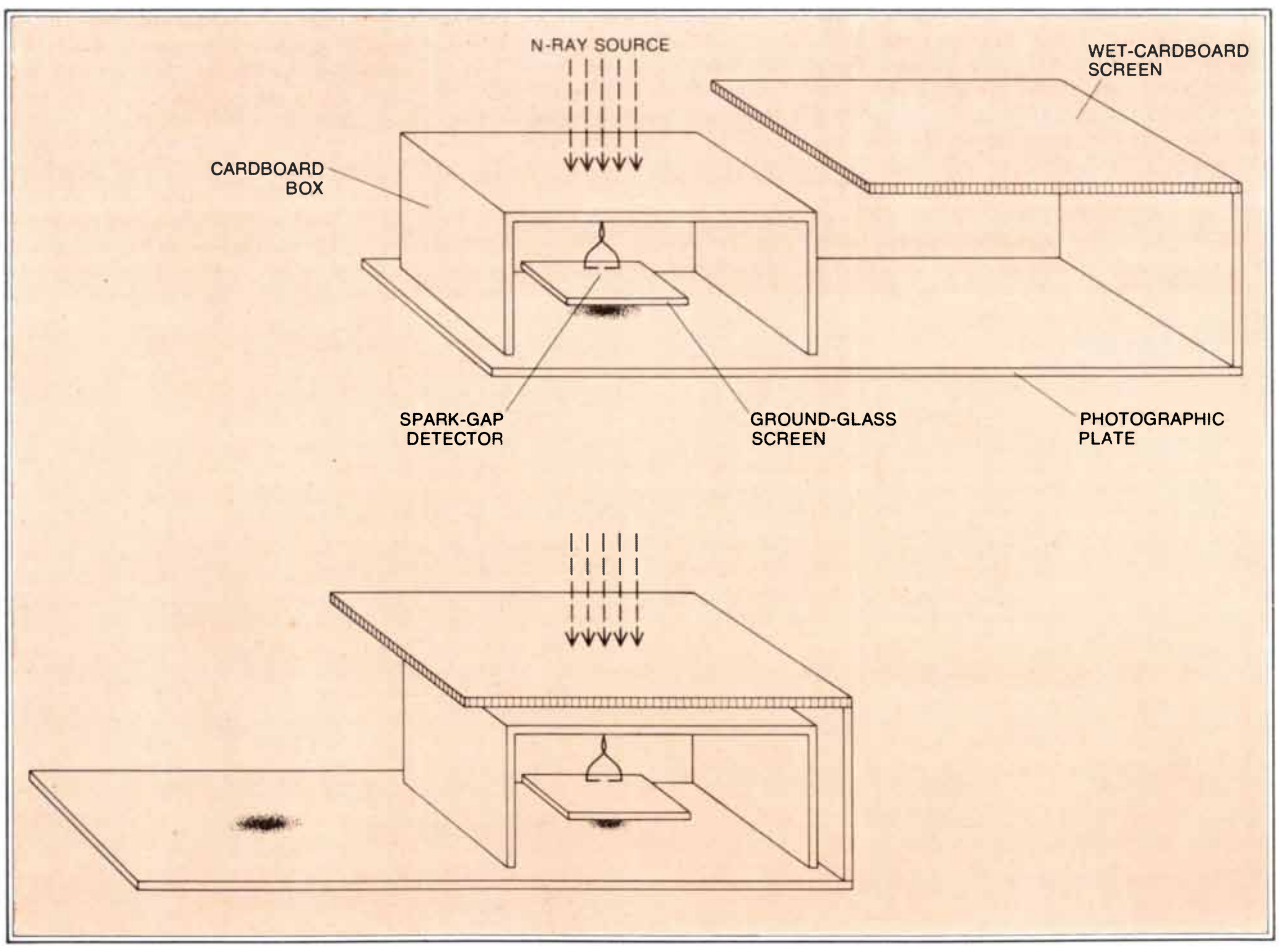
sources of N rays, and early in 1903 he began publishing his findings in *Comptes rendus,* the annals of the Academy of Sciences. Soon Blondlot was joined in his efforts by scientists of every description. Physicists, physiologists and psychologists all leaped to meet the challenge of investigating and exploiting the new form of radiation.

This massive research effort soon uncovered properties of N rays that were quite remarkable. Almost all the materials that proved to be transparent to the rays were opaque to visible light. Wood, paper and thin sheets of iron, tin, silver and gold were found to efficiently transmit N rays. In fact, Blondlot made aluminum lenses and prisms for focusing and bending the rays. Mica, quartz and paraffin were also shown to be transparent to the rays; water and rock salt blocked them and therefore could be employed to screen them out.

It was quickly discovered that there were many sources of N rays in addition to the electric-discharge tube. The Welsbach mantle, a type of gas burner widely used for home lighting around the turn of the century, proved to be a rich source of N rays. So did the Nernst glower, a lamp in which a thin rod of rare-earth oxides was heated to incandescence by an electric current. Heated pieces of silver and sheet iron emitted the rays, but surprisingly the Bunsen burner did not. More interesting, however, was the discovery of N-ray sources in nature.

Blondlot himself found that the sun emitted N rays. Late in 1903 another member of the Nancy faculty, a respected professor of medical physics named Augustin Charpentier, submitted to the Academy of Sciences a report on N-ray emissions from the human body. In the report, which was sponsored by the distinguished French physicist and academy member Arsène d'Arsonval, Charpentier described the discovery of particularly strong N-ray emissions from nerves and muscles. He later announced that he was able to detect N-ray emissions from bodies after death, and a Monsieur Lambert reported that even enzymes isolated from body tissues gave off the rays. (Charpentier put these discoveries to practical use. Early in 1904 he announced that the increase in N-ray emissions accompanying motor activity could serve as the basis for improved methods of exploring the body for clinical purposes, for example to detect the outline of the heart.)

As often happens with major advances in science, the pioneers of N-ray research—Blondlot, Charpentier and their colleagues—were challenged by other workers who maintained they had been the first to discover and investigate the new form of radiation. In the spring of 1903 Gustave le Bon, a dabbler in many



TANGIBLE PHOTOGRAPHIC EVIDENCE for the existence of N rays was obtained in the experiment schematically re-created in this cutaway diagram. The presumed detector of the rays was the spark gap; the spark was said to get brighter when N rays fell on it. The detector was enclosed in a cardboard box. At the bottom of the box was the photographic plate. Between the spark-gap detector and the photographic plate was a ground-glass screen, which diffused the light from the spark so that it made a fuzzy spot on the plate. It was believed cardboard was transparent to N rays, so that when the rays (*arrows*) fell on it (*top*), they would pass through it, make the spark brighter and make the spot on the photographic plate darker. Water, however, was believed to be opaque to N rays, so that when a screen of wet cardboard was pushed into place over the box (*bottom*), the water in the screen would block the rays, making the spark dimmer and the spot on the photographic plate lighter. Many other factors affected the degree of darkness and lightness of the spot, however, and in the end it appeared that the experimenters' willingness to believe in the validity of the experiment led them to overinterpret their results.

different areas of physics, sent Blondlot a letter (which Blondlot subsequently published) asserting that seven years earlier he had discovered a form of radiation that could penetrate metals. In December of the same year one P. Audollet submitted a petition to the Academy of Sciences, stating that he and not Charpentier had been the first to discover the emission of N rays from living organisms. A month later a spiritualist named Carl Huter entered a similar claim, but in the spring of 1904 the academy declared in a solemn report by d'Arsonval that Charpentier's findings had preceded all the others.

In 1904 the academy also bestowed on Blondlot the prestigious Prix Leconte, which included a cash award of 50,000 francs. According to the citation accompanying the prize, it was given to Blondlot for (to translate from the French) "the whole of his works"; his "new ray" is mentioned only at the end of a three-page listing of his achievements. The citation does conclude, however, by expressing support for Blondlot and offering him encouragement in his investigations of N rays. Rumors circulated through the French scientific community at the time to the effect that the first draft of the citation had dealt exclusively with the discovery of N rays but that caution had finally prevailed. (When Albert Einstein was awarded the Nobel prize in physics in 1922, it was for his "discovery of the law of the photoelectric effect." Relativity was mentioned only obliquely, by a reference to "services to theoretical physics.")

With this kind of encouragement research in N rays flourished. In the year and a half following Blondlot's announcement of his discovery the number of publications on the subject grew almost explosively. In the first half of 1903 four papers on the subject appeared in *Comptes rendus;* in the first half of 1904 the number had risen to 54. (It is interesting to note that in the latter period *Comptes rendus* carried only three papers on X rays.) Thereafter the explosion came to an abrupt halt; in 1905 *Comptes rendus* published no papers on the subject at all. A catastrophe had befallen N rays. It was a visit to the University of Nancy by the American physicist R. W. Wood.

Wood, professor of physics at Johns Hopkins University, was an internationally known expert in optics and in spectroscopy, the branch of physics that specializes in the analysis of electromagnetic radiation. He was naturally excited by the report that Blondlot had identified a new type of radiation and, as is customary when a new phenomenon is discovered, had promptly set about trying to reproduce Blondlot's striking results. As he told his biographer William Seabrook, he failed completely "after wasting an entire morning."

Wood's experience was not unique. Other physicists, including Lord Kelvin and Sir William Crookes in Britain and Otto Lummer and Heinrich Rubens in Germany, had been equally unsuccessful. In fact, other workers began urging Wood to go to Nancy and observe Blondlot's experimental procedures for himself. Wood decided to visit Blondlot's laboratory, where as he put it "the apparently peculiar conditions necessary for the manifestation of this most elusive form of radiation [appeared] to exist."

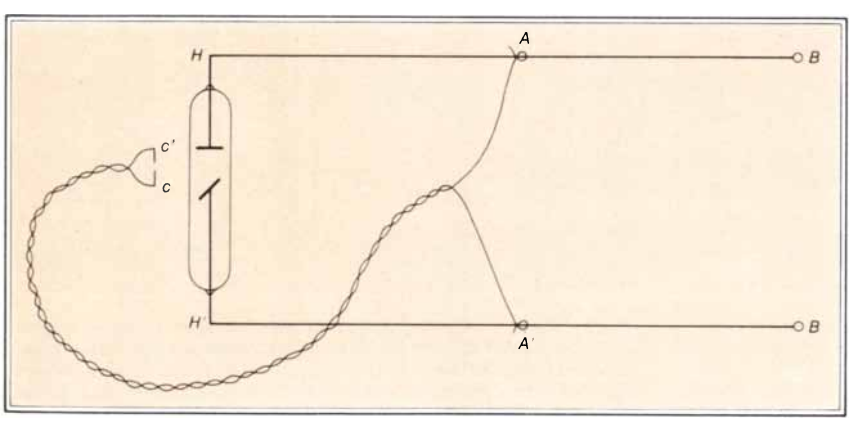
Wood's qualifications for the assignment were not only scientific. Ebullient and perceptive, he was a man of many interests outside physics. Among his numerous publications is *How to Tell the Birds from the Flowers,* a small parody of a nature manual in which Wood's humorous verses are accompanied by his own drawings of birds and plants. Wood was in all things a showman, and long after adolescence he was an inveterate perpetrator of pranks and hoaxes. As an example, he once used his redoubtable talents in optics to fabricate what must have been one of the first photographs of an unidentified flying object. He was also a relentless pursuer of frauds such as spiritualistic mediums. One medium maintained he was in touch with the deceased British theoretical physicist Lord Rayleigh. Wood framed some abstruse questions about electromagnetism for the medium to ask the ghost, and there was no response.

The extent to which these predilections came into play in Wood's confrontation with Blondlot can be judged from Wood's report of his visit to Blondlot's laboratory, published in the September 29, 1904, issue of *Nature.* (Wood does not identify Blondlot in the article, but in his biography of Wood, Seabrook reports that all the events Wood describes in the article took place in Nancy.) According to Wood, Blondlot and his colleagues received him cordially and for his benefit did a series of experiments intended to demonstrate the diverse properties of N rays.

The first experiment Wood witnessed was an improved version of the one that originally revealed the existence of the N rays to Blondlot. N rays emitted by a Nernst lamp were directed through an aluminum lens, which served to concentrate them on the spark of a spark-gap detector. Blondlot and his colleagues said that if an observer held his hand in the path of the rays at any point between the source and the spark, the blockage of the rays would be visible as a decrease in the brightness of the spark. A small plate of ground glass on the side of the detector opposite the source served to diffuse the light of the spark so that changes in its brightness could be more easily observed.

Wood described the outcome of the experiment as follows. "It was claimed that [the fluctuation in the brightness of the spark] was most distinctly noticeable, yet I was unable to detect the slightest change. This was explained as due to a lack of sensitiveness of my eyes, and to test the matter I suggested that the attempt be made to announce the exact moments at which I introduced my hand into the path of the rays, by observing the screen. In no case was a correct answer given, the screen being announced as bright and dark in alternation when my hand was held motionless in the path of the rays, while the fluctuations observed when I moved my hand bore no relation whatever to its movements."

Visual judgments of light intensity are notoriously unreliable, but the next demonstration Wood observed was one of those Blondlot had devised to give photographic evidence for the existence of N rays. The apparatus for this experiment included a horizontal photographic plate with a screen of ground glass above it. Above the ground glass was a spark-gap detector, and above that was a screen of cardboard (actually the top of a lighttight box covering the appara-



ONE SOURCE OF N RAYS was a gas-discharge tube (*H–H'*). In this diagram based on one published in France in 1903 the spark-gap detector (*c–c'*) is wired into the discharge-tube circuit. Most observations of the effects of the rays on the spark in the gap were made visually.

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"Nature's logic—that's how I see aerodynamics. The dolphin, the swallow, the cheetah, each moves with speed, attuned to its environment, yet each minimizes the expenditure of energy. What better lesson for a designer?"

Robert Opron
Director of Styling/Régie Renault

Robert Opron's name has been associated with the successful use of aerodynamic principles in automotive styling for 20 years. (His credits include a U.S. "Car of the Year" award, an Italian styling award and the prestigious Prix Européen.) Today, his aerodynamic enthusiasm is a designer's contribution to solving the energy enigma. "The CX (a scientific measurement of aerodynamics) is a scientifically credible and demonstrable principle. The energy crisis has restored a goal that never should have been forgotten. Styling that significantly reduces the amount of drag, promotes more efficient use of energy."

"Practicality for the user" is another guiding principle for Opron. Trained to be an architect, his first job was designing kitchen appliances. This early training and work apprenticeship helped instill user-practicality in his design philosophy. "After all, when you design a building. . . or are involved with *la cuisine*, you deal with real life, real people, real problems."

For five years now, Opron has been responsible for the design and styling of all Renault cars; and all products bearing the Renault name, a range that includes trucks, industrial and agricultural machines, marine equipment and such everyday tools as lawnmowers. Whatever the project, however, he stresses the human imperatives: "How can this product be better designed to answer human needs. . . to make life a little pleasanter or easier?"

A typical week's work schedule has Opron in Milan for two days (Renault

Portrait by Marie Cosindas

maintains a design atelier there as well as in Paris); and then he might be off to the U.S. or, possibly, South America for another two days. Back in Paris to review current design projects, he seems to thrive on the accelerated pace.

Trucks, one of Opron's current design enthusiasms, are also subject to his aerodynamic basics. "Trucks must become more economical, *ergo*, you must have more sophisticated aerodynamics in the styling." Opron sees the growth of electronics in the auto industry as adding to his *nouvel humanisme*. Vital data for the driver—upcoming road conditions or weather—could be standard dashboard information thanks to electronics

Opron's home, which he and an architect friend designed and built, is brimful with his practical humanism. The house, an unassuming *petite villa de la campagne* is sited in an abandoned orchard a short ride from Paris. As Opron's wife Geneviève and the two Opron children (Philippe, a 26-year-old medical student and Valérie, a *lycée* teenager) all testify, it seems a perfect machine for living in. Its quintessential modernity can be seen in the details The ingenious open floor plan is studded with pockets of privacy; there's easy garden access from all rooms; a socially-magnetic central hearth; and throughout, an underlying practicality of materials. "The design," says Opron, "is 'internal', not a facade."

In addition to the "energy imperative"—there's also the "internationalization imperative": Renault products must meet human needs in "the mosaic of different cultures" in which they will be used. Then, too, the aesthetics of a given design are another imperative—"after all, these are Renault products." In facing these not necessarily confluent requirements, Opron reiterates the importance of the human factor. "Even as I respond to the urgent needs of the present, I dream of automobiles whose very being—in the pertinent words of the Roman architect Vitruvius—'would make living easier for all mankind.' That perhaps, is my true designing logic."

We welcome your comments, questions or thoughts about any of the above. Write to: Renault, U.S.A., Inc., Corporate Group, Englewood Cliffs, N.J. 07632.

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tus and the photographic plate). Above the entire array was the N-ray source.

The photographic plate extended to one side of the cardboard box and could be slid from side to side under it. Mounted with the plate was a wet-cardboard screen that could be slid over the box. Thus when the photographic plate was in one position, it could record the brightness of the spark without the wet cardboard between the spark and the N-ray source, and when it was in the other position, it could record the brightness of the spark with the wet cardboard between the spark and the source. Since N rays were blocked by water, the spark would presumably be dimmer when the wet cardboard was between it and the source.

Wood was shown a number of plates that had been made in this way, and one plate was exposed in his presence. All of them had a distinctly more exposed image on the side that was not screened by the wet cardboard. In other words, the plates appeared to show the existence of the new radiation. Wood pointed out, however, that the photographs had all been made "under conditions which admit of many sources of error." The fact that the brightness of the spark fluctuated naturally (by an amount Wood estimated to be as much as 25 percent) was alone enough to make "accurate work impossible."

Furthermore, in this experiment every pair of photographic images was made by exposing both sides of the photographic plate not once but several times, so that whatever disparity there was between the two experimental states—with and without N rays—would be intensified. Each exposure was supposed to last for five seconds, and so the experimenter had to slide the plate from one side to the other at five-second intervals. Wood pointed out that this procedure introduced the possibility of experimental bias: "It appears to me that it is quite possible that the difference in the brilliancy of the images is due to a cumulative favouring of the exposure of one of the images, which may be quite unconscious, but may be governed by the previous knowledge of the disposition of the apparatus."

So far neither the Nancy experimenters nor the skeptical Wood had proved their point. The photographic plates did support Blondlot's interpretation, but Wood was "unwilling... to believe that a change of intensity which the average eye cannot detect when the n-rays are flashed 'on' and 'off' will be brought out as distinctly in photographs as is the case on the plates exhibited." Wood pointed out that "experiments could be easily devised which would settle the matter beyond all doubt." His own suggestion was to employ two screens in conjunction with Blondlot's photographic apparatus, one "composed of two sheets of thin aluminium with a few sheets of wet paper between, the whole hermetically sealed with wax along the edges," and the other "exactly similar [but containing] dry paper." On Blondlot's hypothesis the screen incorporating wet paper would block the N rays and the screen containing dry paper would transmit them. Wood thought that if "the person exposing the plates [was] ignorant of which screen was used in each case... the resulting photographs would tell the story." Indeed, he felt "very sure that a day spent on some such experiment as this would show that the variations in the density on the photographic plate had no connection with the screen used."

The next experiment Wood observed, however, was quite different from the one he had in mind: he was shown how N rays were bent when they traversed an aluminum prism. In the apparatus used to demonstrate this behavior N rays from a Nernst lamp were first passed through screens of aluminum foil, black paper and wood (so that all types of electromagnetic radiation other than N rays would be blocked out) and then through a screen of wet cardboard in which had been cut a vertical slit about three millimeters wide. The stream of N rays that came through the slit fell on the prism, which, according to Blondlot, served not only to bend the rays but also to spread them out in a spectrum. In other words, there appeared to be N rays of different wavelengths!

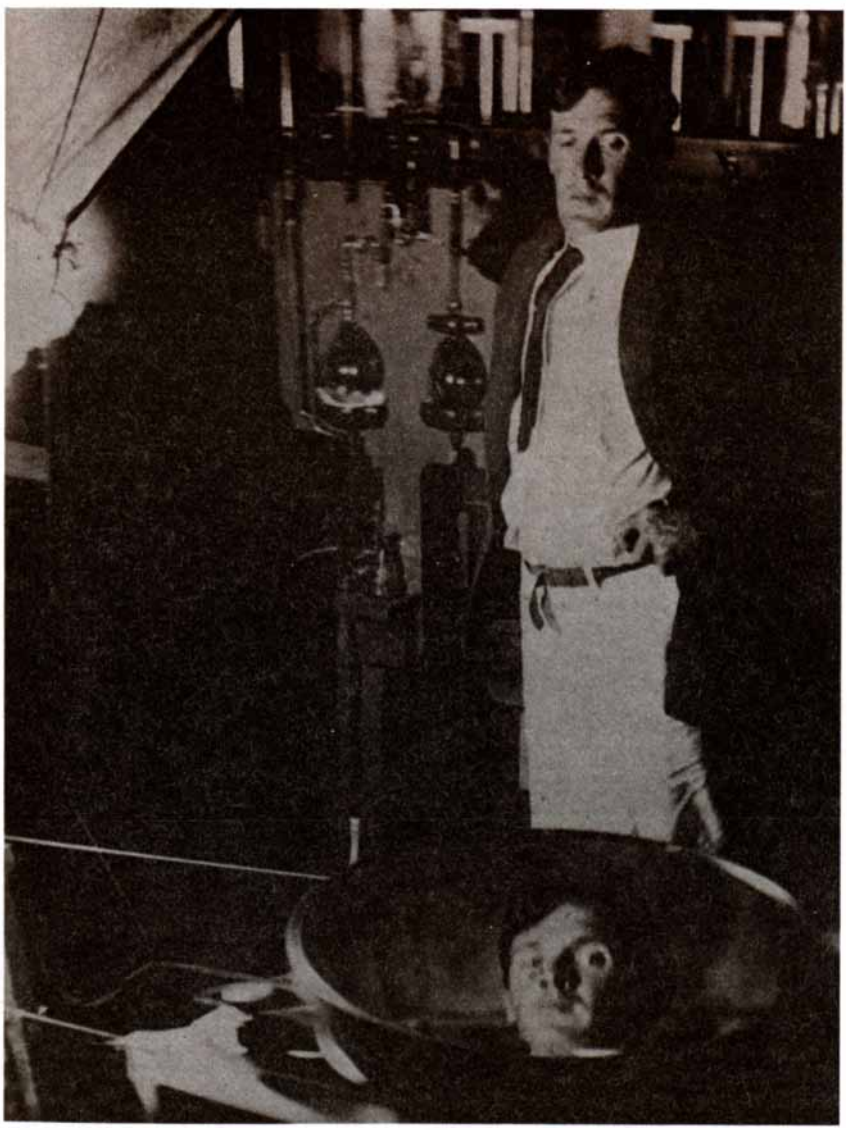
To locate the position of the deviated rays Blondlot employed a small piece of dry cardboard mounted on a curved steel support. A narrow strip of phosphorescent paint was applied down the middle of this detector, which could be moved along the support with the screw of a ruling engine: a machine originally designed for making precisely spaced grooves. The calibrations of the ruling engine made it possible to measure exactly where the strip painted on the detector underwent changes in brightness, that is, where the deviated rays fell on the support. Blondlot and his colleagues

RENÉ BLONDLOT (1849–1930) was the physicist who thought he had discovered N rays. A respected professor at the University of Nancy, Blondlot was much honored for his work on this subject and others. He appears wearing the robes of the French Academy of Sciences.

maintained that at least four such locations, or at least four different N-ray wavelengths, could be identified by this procedure, and that at each location a movement of the detector of no more than .1 millimeter was sufficient to cause the phosphorescent strip to go from dim to bright and back again. Wood expressed surprise that a beam coming from such a broad opening (three millimeters wide) could be resolved into such thin components (.1 millimeter wide); his hosts assured him that this was one of the inexplicable and astounding properties of N rays.

When Wood moved the detecting device up and down the N-ray spectrum, he was unable to perceive any change in the brightness of the phosphorescent strip. At this point he was moved to play a prank of a serious kind. In order for changes in phosphorescence to be visible the experiment had to be done in a darkened room, and so Wood was able to surreptitiously remove the most important element of the experimental apparatus: the aluminum prism. In his *Nature* article he wrote: "The removal of the prism... did not seem to interfere in any way with the location of the maxima and minima in the deviated (!) ray bundle."

Wood went on to discuss some of the even more fantastic properties attributed to N rays. For example, in investigating the effects of N rays on various physiological activities Charpentier had determined that the rays acted to sharpen the senses. By the end of 1904 Blondlot and his colleagues had, possibly independently, reached the same conclusion. They presented to Wood a series of experiments designed to show that exposure to N rays increased visual acuity.



R. W. WOOD (1868–1955) was the physicist who discredited N rays. An expert in optics and spectroscopy, Wood spent his career at Johns Hopkins University. Here he is seen reflected in a mirror made by rotating mercury in a bowl, an apparatus that had nothing to do with N rays.

In a dimly lighted room a large steel file—an N-ray source—was held near an observer's eyes. On the wall of the room was a clock. The subject of the experiment assured Wood that the hands of the clock, which were normally not clearly visible to him, became brighter and much more distinct when the file was nearby, a phenomenon credited to the peculiar effect of N rays on the retina. Again Wood was "unable to see the slightest change." Since the room was not completely dark, Wood could not perform quite the same kind of control experiment he had performed by removing the aluminum prism. He was nonetheless equal to the challenge. As he wrote, "the substitution of a piece of wood of the same size and shape as the file in no way interfered with the experiment." The substitution was of course made without the knowledge of the observer.

Wood spent some three hours observing various N-ray experiments at Blondlot's laboratory. At the end he found himself "unable to report a single observation which appeared to indicate the existence of the rays." Indeed, he "left with a very firm conviction that the few experimenters who have obtained positive results have been in some way deluded." Many leading scientists had already failed to reproduce Blondlot's results, and the publication of Wood's account of his experience at a center of N-ray research effectively put an end to support for N rays outside France.

The French proponents of N rays continued, however, to defend them vigorously. After all, the existence of the rays had been confirmed by 20 French scientists, including such well-known figures as Charpentier and Jean Becquerel, son of the discoverer of radioactivity, Henri Becquerel. Furthermore, many others had personally witnessed the various manifestations of N rays at demonstrations given by Blondlot and his followers at the University of Nancy or in Paris. After Wood's visit Blondlot wrote defiantly: "Several eminent physicists, who have been good enough to visit my laboratory, have witnessed [the photographic detection experiments]. Of... forty experiments, one was unsuccessful.... I believe this failure, unique, be it noted, to be due to insufficient regulation of the spark, which undoubtedly was not sensitive."

Blondlot nonetheless went to great lengths to respond to Wood's criticism of his experimental procedures. Wood had suggested that the photographic evidence supporting the existence of N rays could be discounted as natural fluctuations in the brightness of the detector spark and irregularities in the exposure times. In 1905 Blondlot described new procedures for regulating exposure times automatically and for monitoring

the stability of the spark by means of a telephone receiver inserted in the power source. Moreover, for the images made in the absence of N rays he began allotting time bonuses: increases in the exposure times of between .5 second and 1.5 seconds. Soon after introducing numerous checks and precautions such as these Blondlot presented a large number of new photographs demonstrating once again that N rays brought about a striking increase in the intensity of the spark.

In 1905 Blondlot also published an elaborate set of instructions on how to best observe the manifestations of N rays: It was essential in these experiments to avoid all straining of vision, whether deliberate or the result of accommodation to low levels of illumination, and to avoid any conscious fixing on the luminous source whose variations in brightness it was sought to ascertain. One had to, so to speak, see the source without looking at it, and even to glance in a slightly different direction. The observer was required to play an absolutely passive part, on pain of perceiving nothing useful. Silence had to be kept as much as possible. Any smoke, particularly tobacco smoke, had to be avoided, as it was likely to perturb or even entirely mask the effect of the N rays. The observer had to accustom himself to looking at a luminous detector in the way a painter, particularly an impressionist painter, would look at a landscape. To gain such abilities would require practice and would surely not be easy. Some people, in fact, might never be able to gain them.

According to Blondlot and his disciples, then, it was the sensitivity of the observer rather than the validity of the phenomena that was called into question by criticisms such as Wood's, a point of view that will not be unfamiliar to those who have followed more recent controversies concerning extrasensory perception. By 1905, when only French scientists remained in the N-ray camp, the argument began to acquire a somewhat chauvinistic aspect. Some proponents of N rays maintained that only the Latin races possessed the sensitivities (intellectual as well as sensory) necessary to detect manifestations of the rays. It was alleged that Anglo-Saxon powers of perception were dulled by continual exposure to fog and Teutonic ones blunted by constant ingestion of beer.

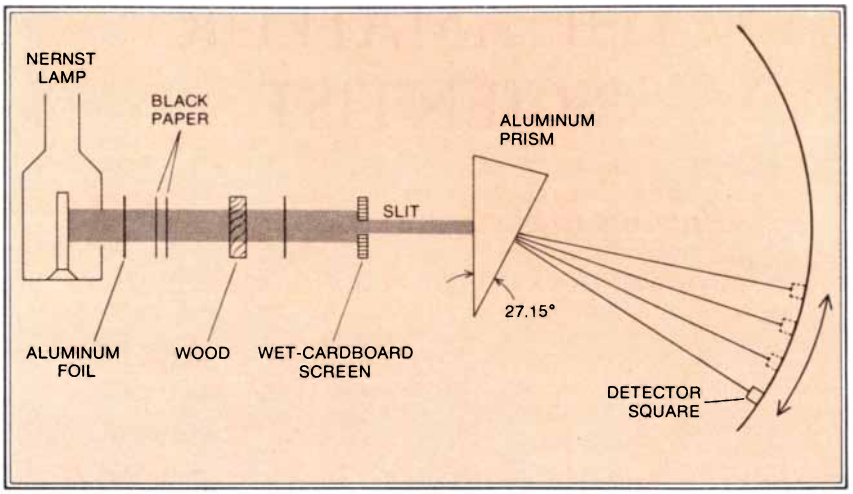
Actually French scientists deserve a great deal of the credit for the debunking of the N rays. No country, of course, greeted Blondlot's discovery with more enthusiasm than France, but as soon as experiments done with precautions similar to those suggested by Wood failed to produce any sign of the rays, French scientists began to take a more critical look at the published accounts of successful experiments. One funny thing soon became evident: there was a curious localization of positive results in the vicinity of Nancy. (The findings coming from Jean Becquerel's laboratory in Paris were an exception to this effect, but they too became suspect when Becquerel reported that he could stop pieces of metal from emitting N rays by "anesthetizing" them with chloroform.)

Eventually the French journal *Revue scientifique,* whose staff was particularly sensitive to the possible embarrassment to French science represented by N rays, launched an effort to resolve the question once and for all. In addition to providing a forum for a discussion of N-ray research the journal made a valiant effort to push Blondlot into making a definitive test of the existence of the rays. Following the suggestion of several physicists the journal proposed that two small wood boxes be submitted to Blondlot, one containing a piece of tempered steel (an alleged source of N rays) and the other a piece of lead. The weights of the boxes would be identical, so that once the boxes were sealed they would be indistinguishable except for an identification number. In other words, it would be impossible for anyone except the person who made and numbered the boxes to tell which held the N-ray source. Blondlot, using either a spark-gap detector or a phosphorescent detecting device, would be required to determine which box was emitting N rays, that is, which one contained the tempered steel.

Blondlot did not respond to the proposal for a long time, but finally in 1906 he wrote: "Permit me to decline totally your proposition to cooperate in this simplistic experiment; the phenomena are much too delicate for that. Let each one form his personal opinion about N-rays, either from his own experiments or from those of others in whom he has confidence."

In effect that is exactly what happened. Science has no vicar on the earth to reveal doctrine and no central committee to proclaim dogma. In general, however, the evolution of scientific theories does appear to follow a pattern that is perhaps best described in an aphorism attributed to James Clerk Maxwell, the founder of the mathematical theory of electromagnetism. Maxwell is said to have observed in an introductory lecture on light: "There are two theories of the nature of light, the corpuscle theory and the wave theory; we used to believe in the corpuscle theory; now we believe in the wave theory because all those who believed in the corpuscle theory have died."

Blondlot died in Nancy in 1930.



REFRACTION OF N RAYS was demonstrated by Blondlot with this apparatus. Radiation from a Nernst lamp (an incandescent lamp believed to emit N rays) was first filtered through screens of aluminum foil, black paper and wood so that all forms of radiation other than N rays would be blocked. A screen of wet cardboard with a vertical slit about three millimeters wide was employed to direct a beam of the rays onto an aluminum prism with an angle of 27.15 degrees. According to Blondlot, the prism served not only to bend the N rays but also to spread them out into a spectrum, demonstrating that there were N rays of different wavelengths. To detect the deviated rays Blondlot used a square of cardboard with a phosphorescent strip painted down the middle. The square could be moved along the curved steel support on which it was mounted by means of the calibrated screw of a ruling engine. Changes in the luminosity of the painted strip signaled the location of a refracted ray. Blondlot and his colleagues detected such changes at several points on the steel support, and their results were confirmed with remarkable precision by other workers. When Wood observed the experiment, he was unable to perceive any change in the luminosity of the painted strip. Since the experiment had to be done in a darkened room, he was able to surreptitiously remove the prism from the apparatus, an adjustment he found did not change the experimenters' perception of refracted rays.

THE AMATEUR SCIENTIST

Illusions in the snow: more fun with random dots on the television screen

by Jearl Walker

Last month I described visual illusions that can be seen in an array of random dots or in the "snow" on a television screen when the set is tuned to a channel on which no broadcast is being made. The visual system somehow organizes these random displays into coherent flows and patterns. How it does so is poorly understood.

Another kind of organization of the random noise on a television screen that has been investigated in recent years is better understood. If you watch the visual noise while one eye is covered with a very dark but not opaque filter, the snow may break up into two layers that move in opposite directions and appear to lie at different depths. One layer seems to be recessed in the screen. The snow of this layer flows from the covered eye toward the uncovered one. The other layer protrudes from the screen and has snow that drifts in the opposite direction. The drift speed across your field of view is from five to 10 degrees per second. Some observers have difficulty perceiving the illusion; many others detect more than two layers.

Some workers have classified the effect in the general category of the Pulfrich illusion, which I discussed in this department for March, 1978. In the most familiar presentation of the illusion a pendulum is made to swing across the observer's field of view. One of the observer's eyes is covered with a dark filter and the other eye is left uncovered. Under these conditions the pendulum appears to swing not in a straight line but in an ellipse. According to most hypotheses about the Pulfrich illusion, the dark filter delays the perception of the visual signal at the retina of the covered eye. As a result the uncovered eye sees the moving object in its true position and the other eye sees the object in the position it occupied a moment earlier. In order to make sense of the scene the observer considers the object to be either closer to or farther from him than it is. If it is moving from the covered eye toward the uncovered one, the mental convergence of the apparent rays places it farther from the observer than it is; if the motion is in the opposite direction, the object seems to be closer than it is.

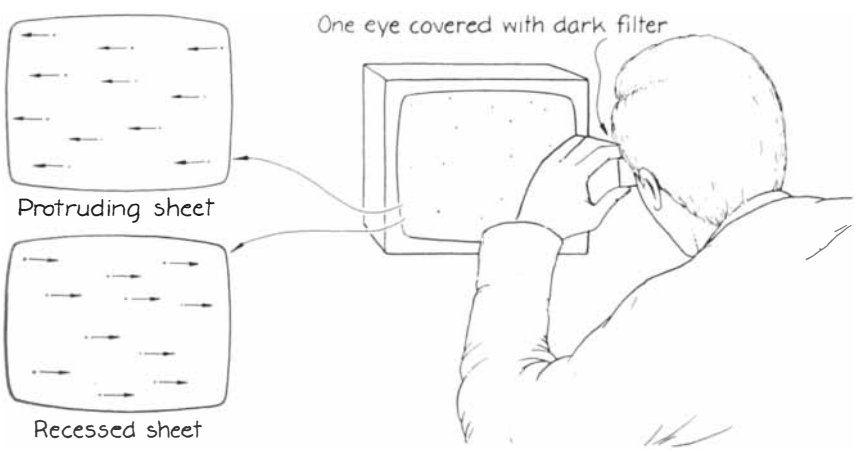
The snow on the television screen is not a real moving object, but apparently the same type of illusion can result if the screen is viewed with one eye covered by a dark filter. The effect was originally discussed by Christopher W. Tyler of the Smith-Kittlewell Institute of Visual Sciences and John Ross of the University of Western Australia. Recent work by Joseph J. Mezrich and Albert Rose of the Exxon Corporate Research Laboratories in Linden, N.J., has further clarified the effect. Still, like most other visual illusions, the effect is not understood in all its details.

Suppose a noise element appears on the screen. According to a current hypothesis, if it is the left eye that is covered with the filter, the right eye perceives the spot immediately and the left eye perceives it a short time later. Now suppose that just then a second spot appears slightly to the right of the place originally occupied by the first one, which has now faded from the screen. The right eye immediately sees the second spot, whereas the left eye is just then seeing the first one. To make sense of the situation the observer's visual system in effect causes the apparent light rays from the two spots to converge, so that the screen seems to have a single recessed spot. The same thing would happen if a third spot appeared as the second spot faded from the screen. If the sequence of spots is appropriate, they will appear to move to the right as a single recessed spot. The illusion turns up repeatedly and frequently across the screen. Even though the pattern of spots is in fact random, an appropriate sequence gives the illusion of a sheet of moving spots recessed in the screen.

Similarly one sees spots as protruding from the screen and moving to the left if the sequence of spots is such that each one appears slightly to the left of the preceding one. The delay of one eye's response creates confusion unless the observer believes the light rays from the two spots come from a single spot a little off the screen. Hence the random noise of white spots on the screen is organized into sheets that seem to be at different depths and to move in opposite directions. If the observer moves the filter to the other eye, the directions of flow of the two sheets are reversed.

Mezrich and Rose discovered several curious features of the apparent motion of random noise. When they varied the density of the noise spots on the screen, the apparent speed of the spots across the screen was affected weakly, but below a certain threshold of spot density the effect disappeared. With densities somewhat above the threshold only a recessed sheet of moving spots was seen. Both sheets could be seen when the spots were at the density found on a television set tuned to an unused channel. (Sometimes the set will need a normal adjustment of its controls.) The fact that the apparent speed of the spots was independent of their density, provided the density was above the threshold, gave Mezrich and Rose one of the clues by which they explained the illusion.

The illusion also depended on the angle the screen subtended in the observer's field of view. As that angle was decreased from a large starting value the threshold for the spot density increased.



Apparent depth and motion in television "snow"

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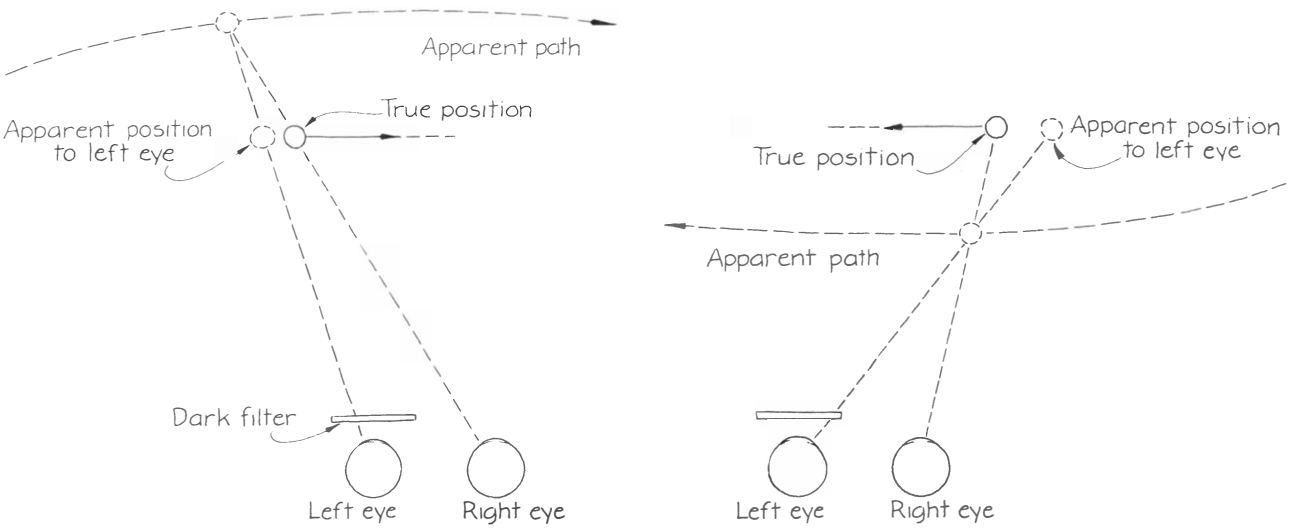
Apparently as the display of noise was increasingly limited to the center of the fovea (the depression on the retina where the photoreceptors are packed most densely) greater densities of the noise elements were needed to provide the illusion of depth. When the angle was reduced from 30 minutes to 15, the spot-density threshold required for the illusion jumped to a much higher value. When the angle was reduced further, the illusion disappeared. These unexpected results provided another major clue to the nature of the illusion.

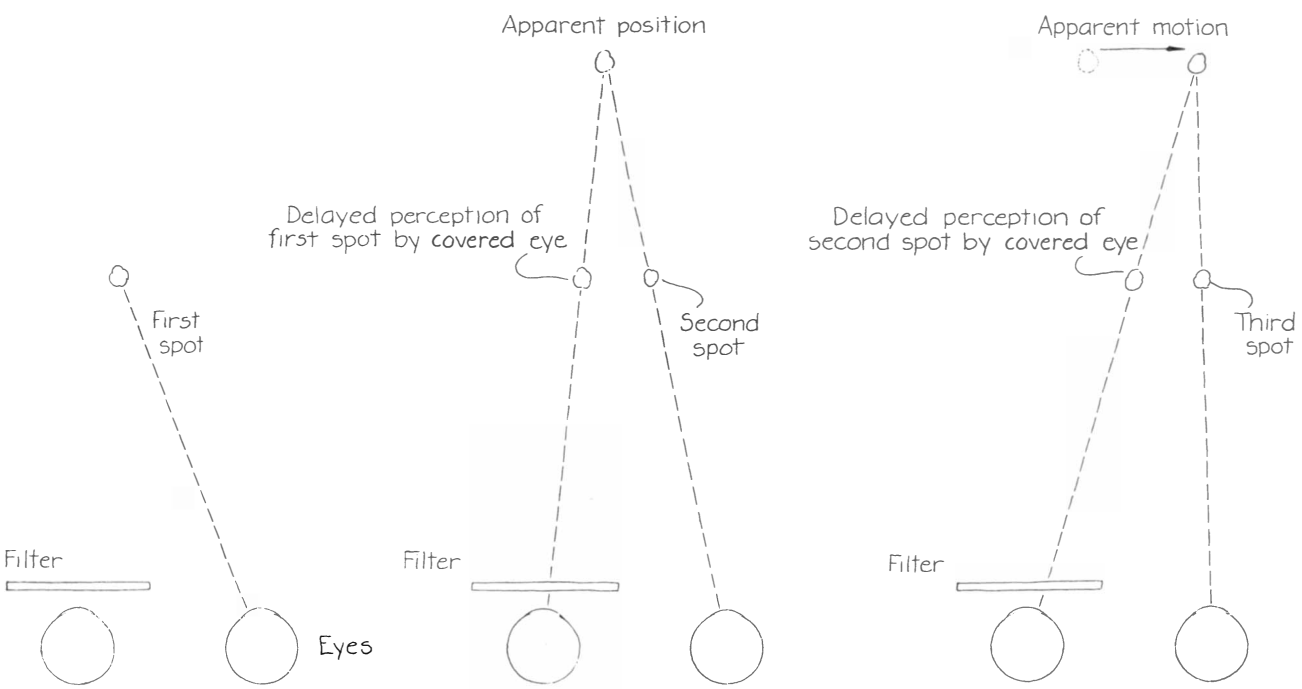
How do the two clues fit together? The apparent speed of the spots is fixed by a characteristic angle (somehow determined by the observer) divided by a characteristic time that is important in the observation. The characteristic time is probably the time, 1/60 second, in which a fluctuation in intensity on the screen can occur. The characteristic angle is not as easy to guess. Two factors must be considered.

One factor stems from work that has been done with stereopsis in random-dot displays. In these experiments an observer usually views two displays simultaneously, one with each eye. Either display seen alone appears to have a purely random distribution of dots, but when the two displays are viewed simultaneously and fused, the observer can perceive depth and structure. Experimenters have found that if depth is to be perceived, the centers of the protruded area and the recessed area must be separated by at least eight minutes of angle. Therefore the mentally fused displays must occupy at least 15 minutes of angle in the observer's field of view to give enough separation.

Here, then, is a number related to the lower limit of the angle a television screen should occupy in an observer's field of view if the random-noise elements are to be organized into sheets at different depths. The screen must occupy at least 15 minutes of angle. If it occupies more than 30 minutes, the observer can organize the noise elements fairly easily. If it occupies between 15 and 30 minutes, the organization is more difficult. Then the threshold of spot density has to be higher to ensure that enough spots are present to give ar-



The analogous Pulfrich illusion with a swinging pendulum



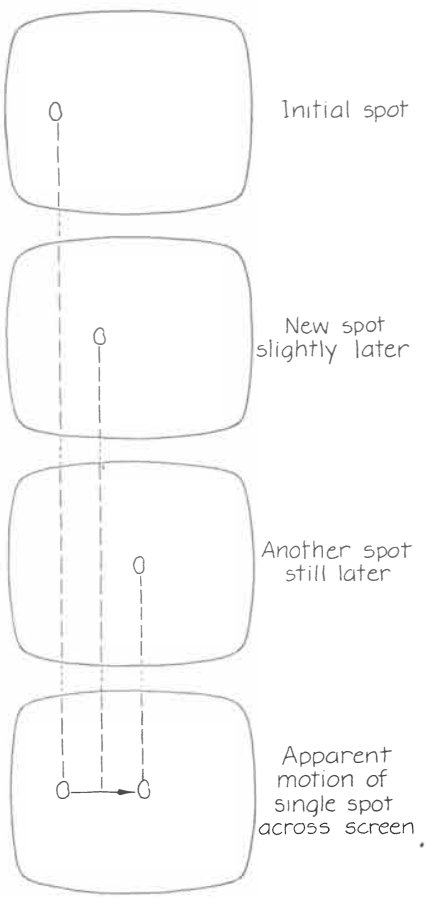
The Pulfrich illusion with spots on a television screen

eas of recession and protrusion separated by at least eight minutes of angle.

Another matter to consider is that the spots appear to move smoothly across the screen when actually they do not move at all. Why does the observer perceive movement when the only thing happening on the screen is that the light is fluctuating in intensity? Previous research has been done on the illusion of motion perceived when stimuli are sequential and slightly separated. You have seen the illusion when lights in a row are blinked one after another to give the impression that the entire row is moving. It is commonly seen in displays outside theaters and motels.

If two sequential spots on a television screen are to be perceived as a smooth flow of one bright spot, the spots must be separated by no more than about 15 minutes of angle. The smooth flow, which is termed both a cascade and "phi motion," will be seen only if the flow in one direction is distinguishable from the flow in the other. Lacking the distinction, the observer will not be able to sort out the random fluctuations to perceive the cascade effect. The dark filter over one eye gives rise to the distinction between directions of cascade flow because it forces the two apparent flows onto sheets at different depths.

The speed of the flows is therefore determined by the angle limitations set by the cascade illusion and the depth illusion; the speed is also governed by the minimum time in which fluctuations arise. The angle limitations require that the sequential spots be separated by no more than 15 minutes of angle. The depth illusion requires that the adjacent areas of protrusion and recession be separated by at least eight minutes. Thus when a recessed spot and a protruding one cross each other, their initial separation must be at least eight minutes of angle, and their separation 1/60 second later must be at least eight minutes but no more than 15. Dividing an angle of between eight and 15 minutes by a time of 1/60 second gives an apparent speed for the spots of between eight and 15 degrees per second, which is consistent with the measurements made by Mezrich and Rose.



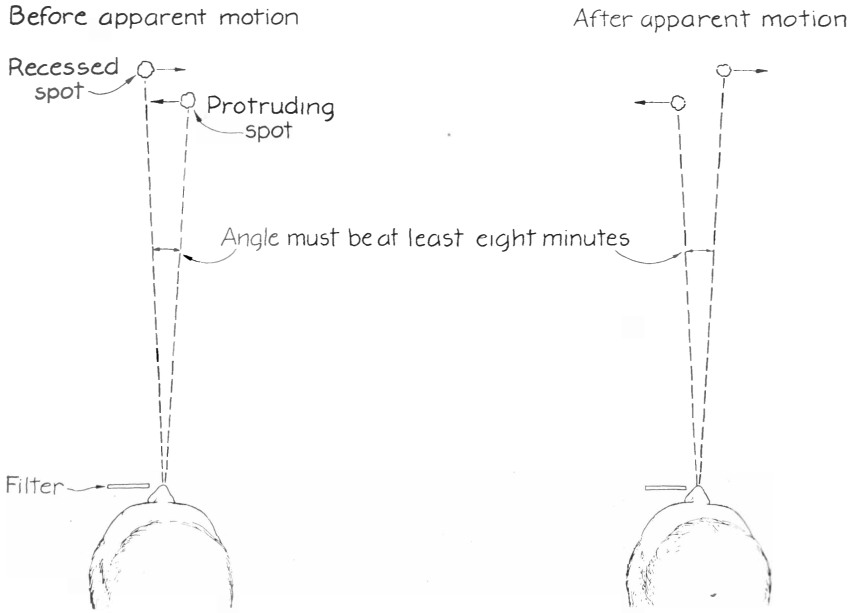
The cascade effect

Recent work by David S. Falk of the University of Maryland and Robert Williams of the University of Bristol suggests that the spots are further organized after they have been assigned to a particular sheet. The observer first sees the spots appearing randomly on the television screen. Monocular vision assigns speeds to the apparent cascading of the spots to the left or the right. Binocular vision, with the response of one eye delayed by a filter, assigns depth to the spots according to the Pulfrich illusion. At this point the speed and depth should show a range.

Falk and Williams suggested that the observer further organizes the spots by comparing the speeds of different groups. Patches that have smaller apparent speeds and are relatively far apart give the impression the noise on the screen is moving faster than the patches are. Patches that have larger apparent speeds and are relatively close to each other will instead give the impression the noise is moving slower than the patches seem to be. Falk and Williams therefore argue that visual processing after the stereoscopic assignment of depth is responsible for the molding of the spectrum of speeds and depths into the illusion of spots on a single sheet moving at an approximately constant and uniform speed. There is one such sheet in each direction, left and right.

An alternative to the Pulfrich model is "random spatial disparity." According to this hypothesis, pairs of random spots are chosen and every pair of spots are fused into a single spot that is assigned depth. The greatest depth is assigned to pairs of spots that are separated by about 15 minutes. Only then is motion assigned. If the pattern fluctuates in 1/60 second, the apparent speed of the spots is 15 degrees per second. Further experimentation will determine whether this hypothesis accounts for the illusion better than the Pulfrich model or some other one.

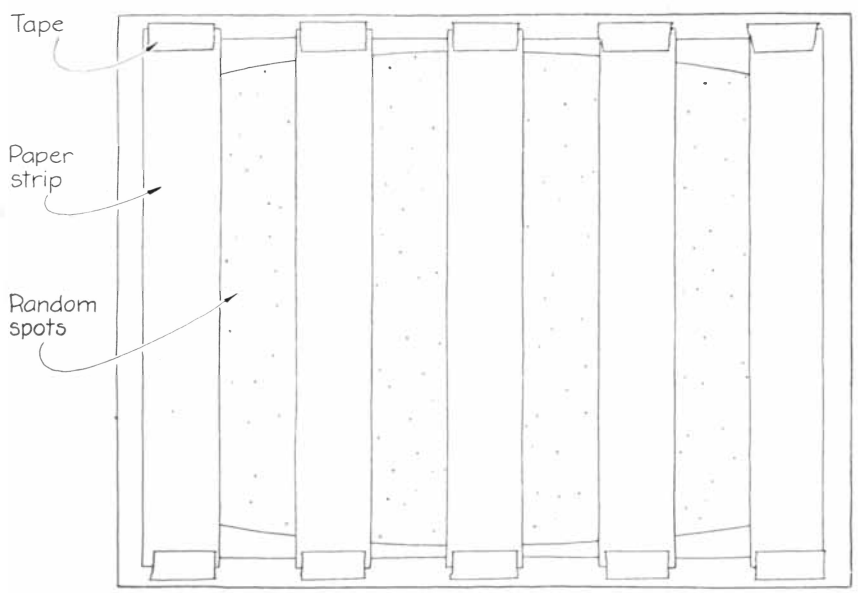
I repeated some of the experiments



The angular separation required for the depth illusion

of several investigators by holding two crossed polarizing filters in front of one eye while watching the snow on my black-and-white television set. I had several variables to control. The brightness and contrast on the screen could be modified and the transmission through the filters could be adjusted. With partial transmission and with the controls for brightness and contrast set close to their normal position the illusion of two sheets of coherent spots was readily apparent. It was fainter or absent if I turned the brightness all the way down. The screen then appeared to have a flat display of glowing water bugs skimming around on the glass, sometimes briefly forming geometric patterns. The illusion also disappeared when the transmission through the filters was very low, that is, when the polarizing axes of the filters were almost perpendicular. With no filters in place, of course, the illusion was absent.

I noted one important difference between what I saw and the illusion described in the research papers. Usually the spots I saw swirled coherently. When the crossed filters were in front of my left eye, the swirling was clockwise, and when the filters were in front of my right eye, the swirling was in the opposite direction. I do not fully understand why I saw swirling at all. Its appearance was not critically dependent on the television controls. It still appeared when I



How to make strips of random spots on the screen

replaced the polarizing filters with colored cellophane; hence it did not depend on the polarization of the light.

My guess is that the swirling resulted when I organized the coherent flow after making a stereoscopic fusion of the screens seen by my eyes. This level of further organization is along the lines suggested by Falk and Williams. The cascade effect seen monocularly leads to the illusion of moving spots. The mechanism of the Pulfrich illusion made me assign distance to the moving spots. I then further interpreted the spots by narrowing the range of their apparent speeds, but in addition I organized the moving patches into a swirl. For example, when the filters were in front of my left eye, the top of the screen was dominated by the patches moving to the right and the bottom by the patches moving to the left. The result was an apparent clockwise swirling. The illusion was so convincing that when I concentrated on only one sheet of spots, they also seemed to swirl.

I noted two additional effects. With the filters in place I closed my eyes alternately so that I could view the screen monocularly and without stereoscopic fusion. The uncovered eye saw a random array of spots, as would be expected and as is normally seen in television snow when the observer views it binocularly. The covered eye saw a dimmer screen and therefore saw not random spots but waves moving randomly as the random spots were organized into cascades. The same type of cascade can be seen if the screen is viewed without filters when the intensity is lowered.

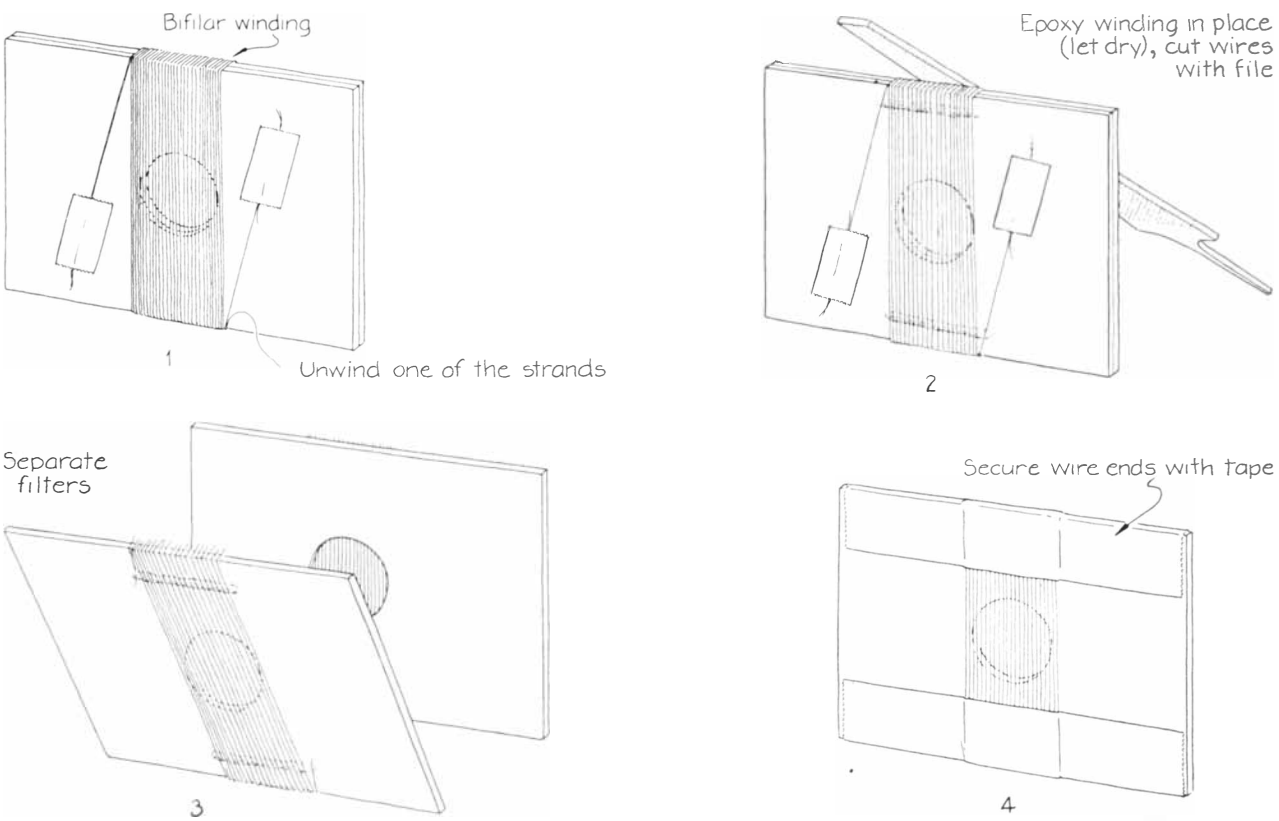
The second effect I noted is similar to one I described last month. When one views a screen of snow monocularly, the center of the field of view appears to boil in a frenzy of activity while the surrounding area is relatively calm. Observing with filters, I noted the same hyperactive area on the screen when I looked at the screen monocularly with either the covered eye or the uncovered one. When I looked with both eyes and saw sheets of spots moving to the left or the right, the hyperactive area disappeared. When the spots broke into swirls, however, they seemed to circle in the hyperactive area. I checked this impression by rapidly switching from monocular viewing (closing either eye and locating the hyperactive area) to binocular viewing (with the swirling present).

Mezrich and Rose did another experiment that I repeated in a slightly different version. They were able to break up the random spots into spotted vertical strips and blank vertical strips. These strips were always uniform in width, but the experimenters were able to adjust their number. When the strips were relatively wide, so that the screen contained few of them, the illusion of coherently moving spots lying on sheets developed independently within each strip. With narrow strips and therefore more of them the coherent motion was seen across all of them.

The transition between the two effects was made when the frequency of strips was between one cycle and two cycles per degree in the field of view. (One cycle consists of a spotted strip and a blank one.) When the screen had one cycle per degree, the patches of recessed and protruding spots were separated enough so that the Pulfrich illusion of depth could be seen. (Remember that the separation must be at least eight minutes of angle.) At a frequency of one cycle per degree a strip of spots is 30 minutes wide and so can have enough separation of the patches. The observer then sees the illusion of depth and coherent motion within the strip.

When the frequency is two cycles per degree, a strip of spots is only 15 minutes wide. The patches are less likely to have the required separation, so that the illusion of depth and coherent motion is also less likely. On the other hand, the strips of spots are then close enough for the required separation to develop between adjacent strips. The illusion of depth and coherent motion then appears but is evident across all the strips rather than in individual ones.

I was able to achieve the same results by taping strips of paper vertically to my television screen. Although I worked with various widths, all the strips were the same width in any one experiment. Each time I made the uncovered parts of



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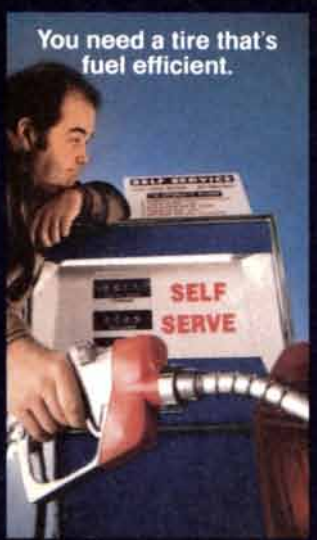

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the screen the same width as the strips. In all the experiments I tried to position my head exactly as before so that the screen always occupied the same angle of view. The transition from coherent motion in individual strips to coherent motion across all the strips was at approximately the same frequency of strips found by Mezrich and Rose.

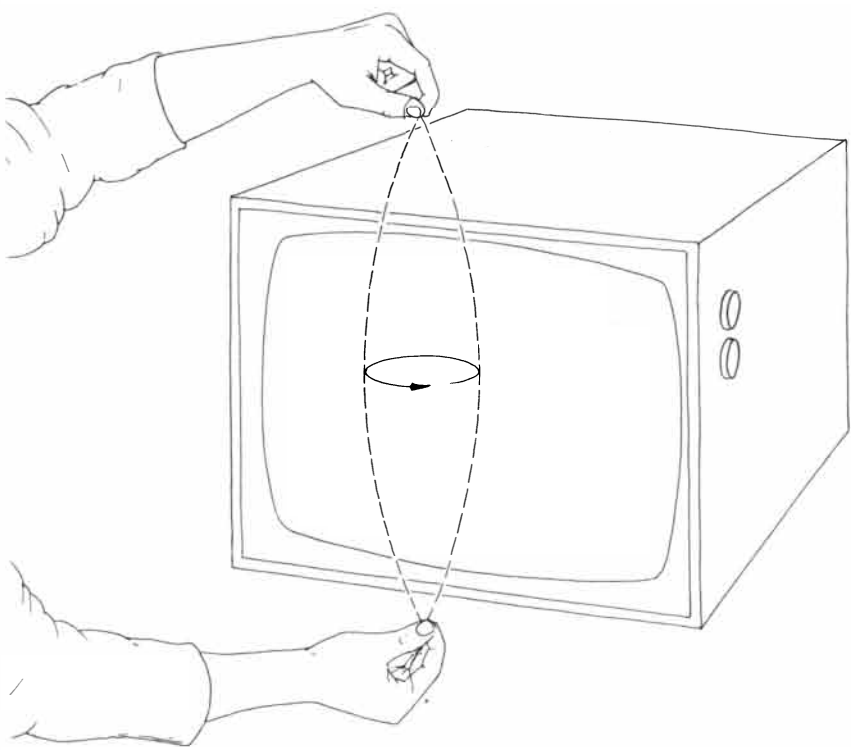
Recently a completely different set of observations with a television set was sent to me by Dwight M. Brown, Jr., of Shreveport, La. Brown noted that when he held a comb or a grid in front of his set, moving the object sometimes made things appearing on the screen seem to move. The illusion probably results from a moiré effect between a periodic spacing in the picture and the periodic spacing of the comb or grid.

Brown's grid was a Ronchi filter that he made from two pieces of thin aluminum plate and some bifilar (two-thread) No. 32 wire. He punched a $1\frac{1}{8}$-inch hole in each plate and wrapped the wire around the plate. Both sides of the hole then had wire wrapped across them. Brown fastened the wire on the side of the metal with epoxy and cut the wire with a file to separate the two metal pieces. Next he removed every second wire and put tape over the cut ends of the remaining wire.

Brown also experimented with stroboscopic effects associated with the television screen. You may have already noted that a spinning object in front of an active screen can create such an effect. Years ago I noted that a flat top spun in front of a television screen would appear to be stationary or even to move counter to its true direction of spin. The television picture is created by the electron beam inside the picture tube's sweeping from left to right, line by line until the bottom of the screen is reached. As a result the intensity of the screen fluctuates periodically.

Suppose a top with a pattern of lines on its upper surface is set spinning in front of the screen. If it is spinning at the same rate as the intensity fluctuations on the screen are changing, the upper surface of the top will be illuminated each time the pattern is in the same orientation. Unless the illumination is swamped by the room light, an observer will constantly see the pattern in the same orientation and the top will appear to be stationary. If the top's rate of rotation is slightly higher than the rate at which it is illuminated by the screen, the pattern will appear to turn slowly in the same direction as the top. If the top's rate of rotation is slightly lower than the illumination rate, the pattern will be illuminated each time in an orientation it achieves slightly before its orientation in the previous illumination. Consequently the pattern will seem to be turning in the direction opposite to the spin of the top.

Brown was able to achieve a stroboscopic effect with the line sweep of the screen in a rather simple way. He swung a string in a circle in front of the screen. When he looked through the rotating string and at the screen, dark lines flicked across the screen and the string seemed to jump from one position to another.



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Subject:
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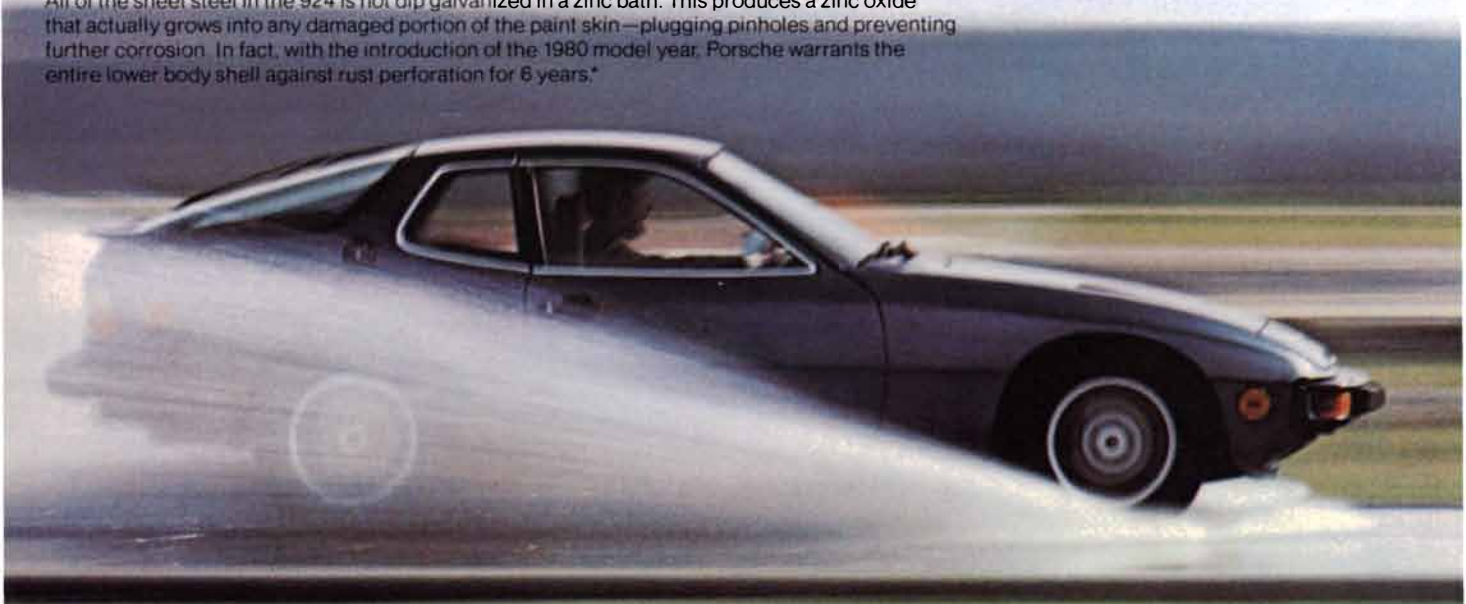
Paint alone is no protection against rust. Moisture—and other corrosive elements—can attack metal through pinholes on a painted surface. Unchecked, rust can expand, mar the finish, and weaken an ordinary steel body. And so, in addition to a 4-step paint process, the Porsche 924, like all Porsches, is protected by a hot dip galvanizing process.

All of the sheet steel in the 924 is hot dip galvanized in a zinc bath. This produces a zinc oxide that actually grows into any damaged portion of the paint skin—plugging pinholes and preventing further corrosion. In fact, with the introduction of the 1980 model year, Porsche warrants the entire lower body shell against rust perforation for 6 years.*



1. The Porsche 924's sheet steel is drawn through a 500°C liquid zinc bath.

2. The high temperature causes the zinc to diffuse into the steel, creating an iron-zinc fusion layer.

3. When the galvanized sheet is taken out of the bath, a pure zinc protective coating forms on the fusion layer.
If the zinc coating is damaged so that the steel is exposed, and if moisture contacts the damaged spot, the moisture acts as an electrolyte, producing a local galvanic element.

4. Between iron and zinc, there is a voltage potential of approximately 0.3 volts. Because zinc has a negative potential, it becomes the anode.

5. The result is an ion migration from zinc to iron, neutralizing the exposed steel surface. The zinc sacrifices itself to the steel and protects the damaged spot against iron rust. The process is called the cathodic rust protection of zinc.

*Porsche + Audi warrants that Porsche vehicles are free from rust perforation for the duration of 6 years. If rust perforation develops under normal use and service and the vehicle has been maintained in accordance with manufacturer's requirements, any Porsche + Audi authorized dealer will replace or repair the defective parts free of charge.

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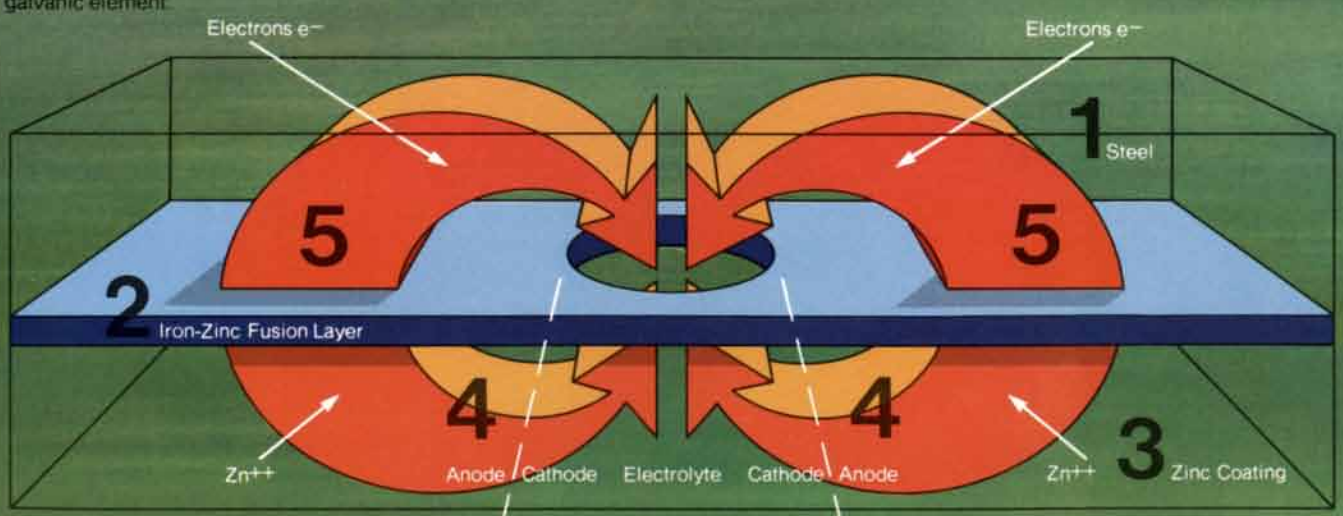

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The flyby of Voyager 1 and 2 has given us the best look we've ever had of this fantastic world. And the only two-way communication link between the Voyager spacecraft and Earth is Motorola equipment: not only for transmitting the incredible pictures, but for receiving all commands sent to the spacecraft, relaying all scientific and engineering data, and serving as the spacecraft terminal for all tracking and navigation functions. And it's all designed to operate for over a decade on a comparative trickle of power from radioactive isotopes.

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Motorola has over twenty years' experience in this esoteric technology, extending back to the earliest unmanned space probes. For example:

America's first venture into space, Explorer 1, in 1958, sent its information to ground-based Motorola equipment.

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Motorola's command receivers were on board Alan Shepard's Freedom 7 Mercury spacecraft for the first U.S. suborbital mission in 1961.

In 1965, Mariner 4 made a close flyby of Mars, snapping pictures all the way, and sent them to Earth by a Motorola transmitter.

For the Gemini series, in 1965-66, Motorola developed and produced the spacecraft's digital command system.

Neil Armstrong's historic "one small step for man" was

PICTURES OF THE GIANT.

relayed from Moon to Earth in 1969 by a Motorola S-band transceiver.

In 1971 the Lunar Rover, first car on the Moon, had a Motorola FM receiver.

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