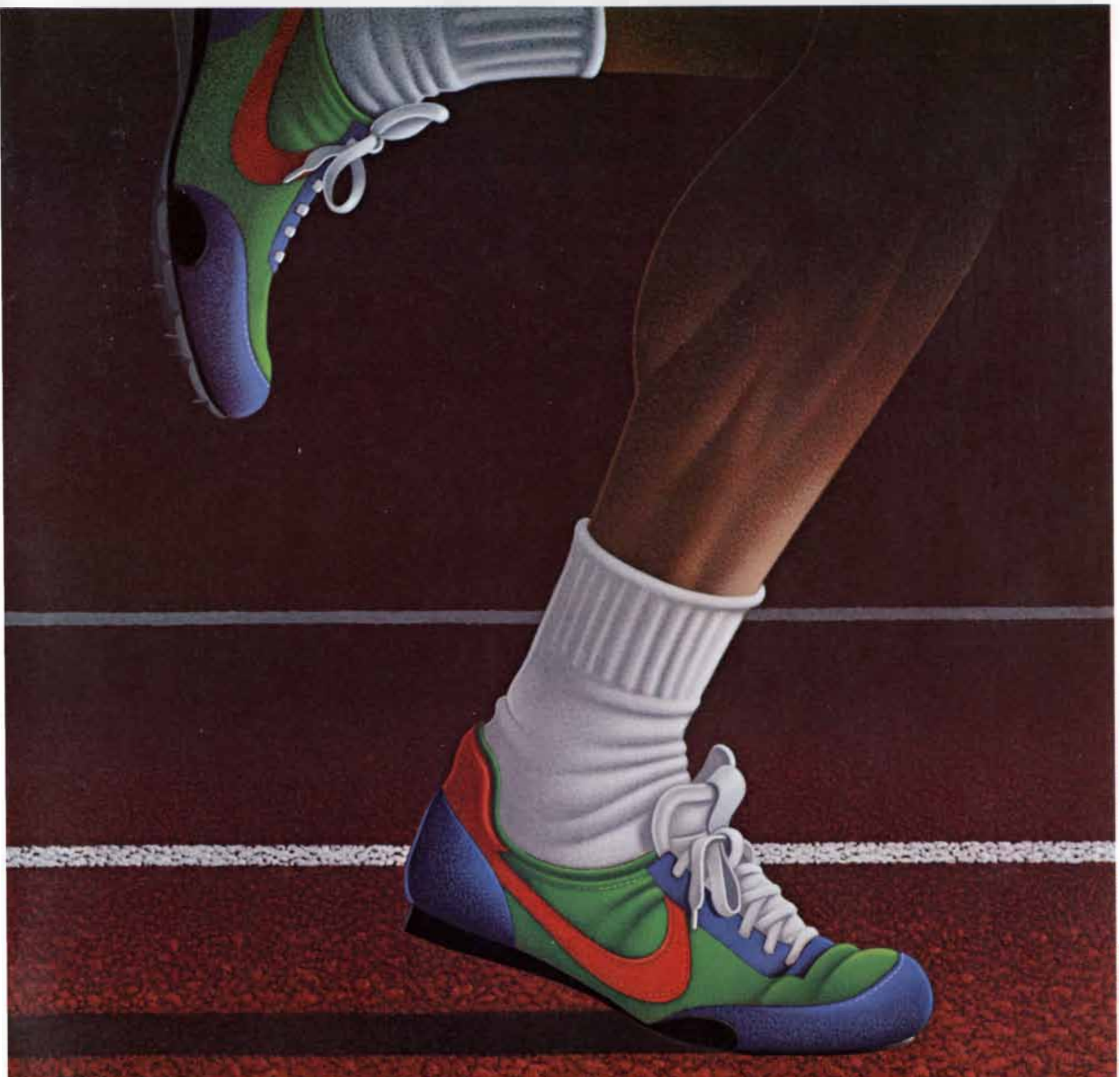
SCIENTIFIC AMERICAN



FAST RUNNING TRACKS

$1.50

December 1978




THE BMW IS BUILT FOR ROADS YOU'D BE WISE TO AVOID IN YOUR PRESENT LUXURY SEDAN.

Unaccountably, many of the world's luxury sedan makers seem to have arrived at the conclusion that the world is one long, flat highway where the driver need excel at nothing more serious than parallel parking.

Inevitably, this attitude has led to a proliferation of luxury sedans that provide the sort of driving experience one automotive expert has described as "...the ultimate act of motoring passivity."

At the Bavarian Motor Works, we have noted this trend and quite deliberately chosen to ignore it.

For the engineers at BMW—racing engineers by nature and profession—view driving as a thing that should be taken seriously and done well.

Which is why the BMW 528i—a luxury car by anyone's standards—is, nevertheless, a luxury car built to be driven on high-speed autobahns and over the tortuous roads of the Bavarian Alps. A sedan that is deliberately engineered to include the driver as a functioning part of the car itself—

Illustrated above, on turn number 5 at the Sears Point International race course, is the extraordinary BMW 528i four-wheel independent suspension system in operation. Note: as the car goes into the sharp high-speed turn, the unique angling of the MacPherson front struts reduces the lean of the inside front wheel, while the outside front wheel remains vertical, inside and outside rear wheels remain vertical due to the semi-trailing arm design in the rear.

the human part that completes the mechanical circuit.

WHY PEOPLE WHO OWN A BMW ENJOY DRIVING MORE THAN YOU DO.

It has long been our contention that—when all is said and done—extraordinary performance is the only thing that makes an expensive car worth the money.

Consequently, when you drive the BMW 528i for the first time, you will experience a unique sensation of control, an exhilarating sense of oneness with the car itself.

The suspension system in the BMW 528i—independent on all four wheels—allows each wheel to adapt itself quickly and cleanly to every driving and road condition.

Its steering system is sharp and accurate.

The four-speed manual transmission (automatic is available) slips precisely into each gear. And its acceleration comes up smoothly, with the turbine-like whine so characteristic of the renowned BMW 6-cylinder engine.

And, though it provides all the luxuries one could sanely demand of an expensive sedan, the interior of the BMW 528i has been meticulously engineered to facilitate driver control at all times, under all conditions.

So successful is this total integration of driver and machine that—perhaps for the first time—you will find yourself actually enjoying the act of driving.

If the thought of owning such a car intrigues you, call us anytime, toll-free, at 800-243-6000 (Conn. 1-800-882-6500) and we'll arrange a thorough test drive for you at your convenience.

THE ULTIMATE DRIVING MACHINE.

Bavarian Motor Works, Munich, Germany.

Of the 5 Great Liqueurs in the world only one is made in America. Wild Turkey Liqueur.

This Christmas give America's First Great Liqueur.

This Holiday season, give the first great liqueur made in America: Wild Turkey Liqueur, created in Kentucky by the originators of America's finest native whiskey, Wild Turkey.

Wild Turkey is the "sippin' sweet cream" of liqueurs, made to be savored slowly after dinner. You've tasted the great liqueurs of Europe. Now give America's great one—Wild Turkey Liqueur. Handsomely gift-boxed.

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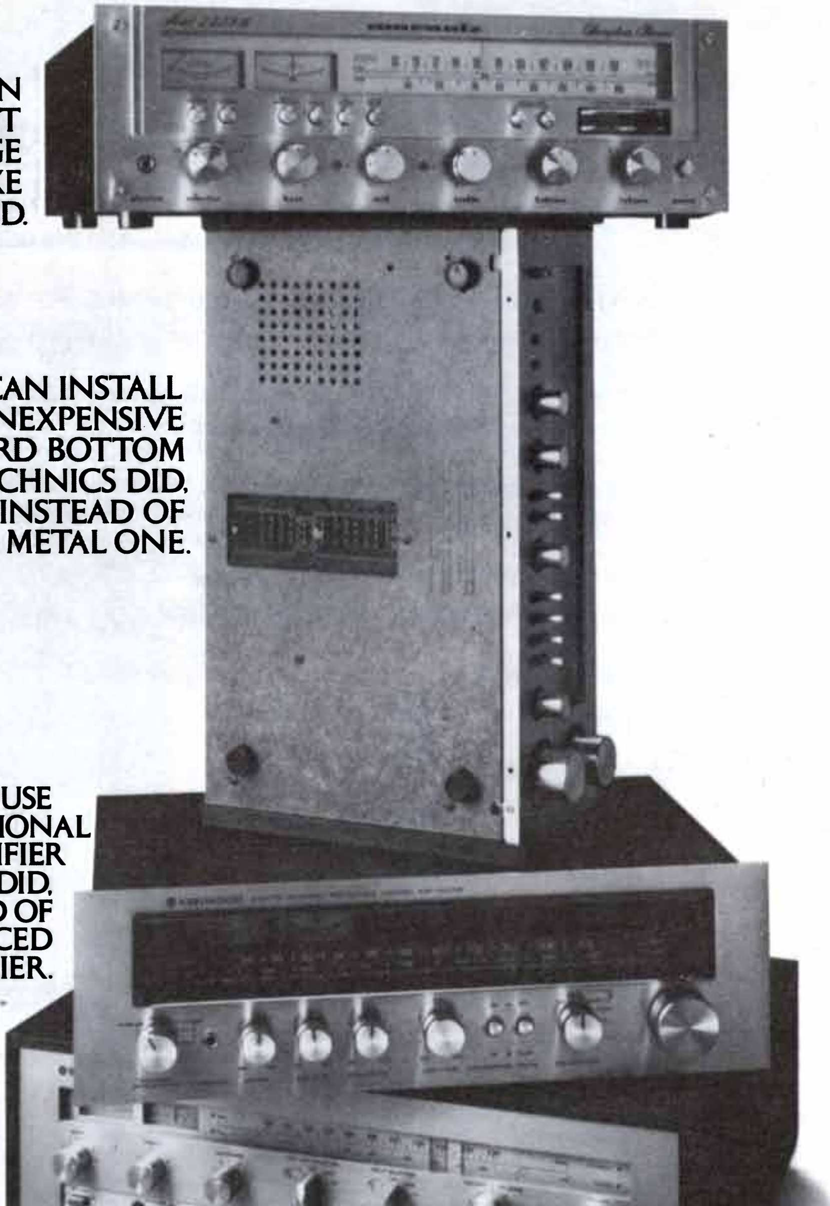
Established 1845 **SCIENTIFIC AMERICAN** December 1978 Volume 239 Number 6

ARTICLES

DEPARTMENTS

THERE ARE A LOT OF WAYS TO BUILD A RECEIVER THAT SELLS FOR UNDER $400.



YOU CAN LEAVE OUT DUAL WATTAGE METERS LIKE MARANTZ DID.

YOU CAN INSTALL AN INEXPENSIVE PRESS BOARD BOTTOM LIKE TECHNICS DID. INSTEAD OF A METAL ONE.

YOU CAN USE A CONVENTIONAL POWER AMPLIFIER LIKE KENWOOD DID. INSTEAD OF AN ADVANCED DC AMPLIFIER.

YOU CAN USE STANDARD HIGH BAND FILTERS LIKE YAMAHA DID. INSTEAD OF SPECIAL INTEGRATED CIRCUITS TO CANCEL THE UNWANTED FM PILOT SIGNAL.

PIONEER DID IT THE RIGHT WAY.

It seems that our competitors think they've mastered the art of building a moderately priced high fidelity receiver.

Unfortunately, most competitive receivers appear to be the work of cost reduction engineers, rather than high fidelity engineers.

At Pioneer, our philosophy is somewhat different. We build a receiver that sells for under $400 with the same care given to a receiver that sells for over $1000.

Metal shields our SX-780 from spurious noise.

A perfect example is the SX-780.

A STRONG CASE FOR THE METAL BOTTOM.

If you turn over our SX-780, you'll notice the bottom is made of heavy gauge metal. Not flimsy press board. It's designed that way to shield the tuning section from spurious noise and CB interference.

Then there's our special ventilating system that reduces FM drift due to overheated tuning elements and increases the life expectancy of the circuitry.

A DC AMPLIFIER WITH THE POWER TO ELIMINATE DISTORTION.

The SX-780 features the same DC power configuration found in today's most expensive receiver.

It provides cleaner sound and richer, more natural bass by eliminating feedback and transient intermodulation. (A form of distortion that keeps you from hearing the subtle overtones in your music). Which is why those receivers using a conventional power amplifier could possibly match the specs of the SX-780, but never the sound.

The DC power supply found on the most expensive receivers.

A PILOT SIGNAL CANCELING SYSTEM THAT'S ALL BUT UNHEARD OF IN THIS PRICE RANGE.

All stereo FM stations in America broadcast their music over a pilot signal of 19,000 hertz.

If not eliminated, this signal tends to create an extremely high pitched sound (hum) when combined with lower audible frequencies.

But instead of using standard high band filters like the others, Pioneer created a special integrated circuit that eliminates this pilot signal without affecting the music. So that you're assured of hearing everything the musicians had intended you to hear. Nothing more. And nothing less.

Obviously, the SX-780 is the only receiver in this price range that offers you this feature. The others offer you the noise.

A pilot signal canceling circuit that lets you hear only music and nothing more.

WATTAGE METERS THAT LET YOU SEE WHAT YOU'RE HEARING.

Wattage meters give you an accurate picture of exactly how much power is going through your speakers. So they not only help prevent unnecessary damage due to overloading, but help you make cleaner FM recordings.

You won't find them on any other moderately priced receiver.

Of course, the SX-780 has another virtue that's conspicuously absent from our competitors' models.

A built-in wood grain cabinet, which others give you the "option" of paying extra for.

But what really separates Pioneer's SX-780 from other receivers isn't a matter of wood cabinets, wattage meters, metal bottoms, DC power, or even price.

It's our commitment to giving you a quality high fidelity receiver, no matter how much, or how little you plan to spend.

So if you're planning to spend less than $400, you couldn't ask for more than the SX-780.

PIONEER
We bring it back alive.

POWER: 45 watts per channel min. at 8 ohms from 20-20,000 hertz with no more than .05% total harmonic distortion.
FM SENSITIVITY: Stereo; 37.0 dBf
S/N RATIO: Stereo; 72 dBf
CAPTURE RATIO 1.0 dBf
POWER METERS: 2
SPEAKERS: A, B, AB
TONE CONTROLS: Dual
TAPE MONITORS: 2

PIONEER'S SX-780.

THE COVER

The painting on the cover depicts a runner's foot rebounding from the surface of a new indoor running track at Harvard University. The track, which has a primarily wood substructure and a polyurethane top surface, is much springier than ordinary tracks. As a result the track is more comfortable to run on and a runner can move substantially faster on it (see "Fast Running Tracks," by Thomas A. McMahon and Peter R. Greene, page 148). Soft, or very springy, tracks are the slowest and so it is commonly held that hard, or very stiff, tracks are the fastest. Through the analysis of a model of the mechanics of running, however, it has been determined that there is a range of intermediate track stiffnesses at which running speed is actually increased over its hard-surface value. The rough texture of the polyurethane on the track surface visible in the painting is designed to protect the surface from the spikes on running shoes.

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Cover painting by Robert Giusti

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SAAB

Introducing the SAAB 900 series.

THE NEW LOOK OF PERFORMANCE.

The new Saab 900 series. Advanced technology fused to stirring design creates new and superior performance automobiles.

The totally new Saab 900 series. The longest, sleekest Saab cars ever. But increasing length wasn't for looks alone. Their longer wheelbase is integrated with a new steering system and new suspension geometry for outstanding roadability.

The totally new Saab 900 series. Introduces a new and innovative asymmetrical instrument panel. Controls are practically equidistant from the driver's hands. Gone forever is searching and fumbling.

The totally new Saab 900 series. Even the air inside the car hasn't been overlooked. Saab engineers have designed a unique fresh air filter that eliminates all airborne pollen. You won't find it on any other car in the world.

To these striking new automotive advances the new 900 series adds fuel injection, front wheel drive, and rack and pinion steering. The result? Truly astonishing performance. Even for the world acclaimed Saab.

The 900 Turbos

The high point of the thrilling, new 900 series. Probably the most exciting cars you can buy. The remarkable Saab turbo engine delivers the kind of energy formerly reserved for racing, but puts it at your command in everyday driving situations. With the Turbo you can have your exhilarating performance in either 3-door or for the very first time, 5-door configuration.

The 900 EMS

This is the Saab for the sports-minded. An extraordinary sports sedan. It's fast, responsive and well-equipped. Automatic transmission with power-assisted steering is now available for the first time. Bilstein gas shock absorbers and sports steering wheel are standard. Sliding steel sun roof (as shown) is optional.

The 900 GLE

One of the few cars in the world that can truly be called a high-performance luxury sports sedan. The interior is sheer elegance. Plush, soft velour, color coordinated door panels, seamless deep-pile carpeting, electrically heated front seats, and stereo speakers are standard. Automatic transmission, power steering and sun roof are available as options.

These are just a few of the examples of how the 900 series has become the new look of performance. To appreciate the complete excitement test drive one of the new 900's at your Saab dealer. The new look of performance will be a driving revelation.

THE SAAB 900 SERIES
THE COMMAND PERFORMANCE CARS

LETTERS

Sirs:

A principal reason for this letter is to point out that new evidence exists for relating the microfossils in Dr. Schopf's article ["The Evolution of the Earliest Cells," by J. William Schopf; SCIENTIFIC AMERICAN, September] and the proteinoid microspheres introduced in Dr. Dickerson's article in the same issue ["Chemical Evolution and the Origin of Life," by Richard E. Dickerson; SCIENTIFIC AMERICAN, September]. The new evidence is in a recent paper by Susan Francis, Lynn Margulis and Elso S. Barghoorn in *Precambrian Research,* Vol. 6, pages 65–100, 1978. These authors applied Barghoorn's novel method of artificial fossilization to proteinoid microspheres and to algae and fungal spores. The morphologies are essentially indistinguishable. On the basis of such comparisons, as already published for unfossilized microspheres in both the 1972 and 1977 editions of *Molecular Evolution and the Origin of Life,* by Sidney W. Fox and K. Dose (Marcel Dekker Inc., 1977), Professor John Keosian, for example, stated in *The Origin of Life and Evolutionary Biochemistry,* by Dose et al. (Plenum Press, 1974): "Structurally, the oldest microfossils have closer resemblance to clusters of some of Fox's microspheres than to primitive algae."

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The photographs that are printed in Dr. Dickerson's article for A. I. Oparin's coacervate droplets and our proteinoid microspheres are unfortunately interchanged. Definitively judging the possibility that the microfossils are of proteinoid microspheres, or anything else, requires a number of photographs, together with data on chemical composition, biochemical activities and consistency within an overview. As a passage in Dr. Dickerson's fluent article suggests, the coacervate droplets cannot explain how biopolymers arose when there were no biological organisms to produce them. (Protamine comes from evolved organisms.) The geochemical simulation, which yields proteinoid microspheres, is not disqualified in this way.

To clarify a few other points, a *requirement* of formation of amino acids *in* the ocean and heating amino acids on a cinder cone is a scenario of others, not mine; I have tried since 1965 to correct that as an erroneous requirement. For the next step, in which the formation of protocells from thermal proteins and water is simulated, I wonder where Dr. Dickerson got the specification of 130–180 degrees Celsius? We have repeatedly reported the formation of microspheres at room temperature. In fact, 130 degrees C. could not be used: the water would boil off from the open glassware we insist on in order to simulate lunar or planetary surfaces adequately. In this regard the need to study biological and other natural processes in nonequilibrium *open* systems was emphasized by Ilya Prigogine in 1955.

An omission from the text that I find to be crucial to an evolutionary overview is the extensively supported *principle of the self-ordering of amino acids.* That principle, we maintain, is the first of two erstwhile "missing links" in the chain of evolutionary events between the elements and the first reproducing protocell. It is described in my chapter "The Origin and Nature of Protolife" in *The Nature of Life,* edited by W. Heidcamp (University Park Press, 1978), a record of papers presented at the Nobel Conference on the Nature of Life held at Gustavus Adolphus College in October, 1977.

SIDNEY W. FOX

University of Miami
Coral Gables, Fla.

Sirs:

Dr. Dickerson does not appear to appreciate fully the dire implications of Francis Crick and Leslie Orgel's suggestion of "directed panspermia," according to which terrestrial life might have been deliberately seeded by extraterrestrial intelligent beings. Contrary to Dickerson's belief, that suggestion is relevant to the inquiry of his article, since it

This may become the most popular camera idea in America.

The one and only Minolta 110 Zoom SLR.

It's a wonder no one ever did it before: combine the convenience and simplicity of a cartridge-film pocket camera with the versatility and quality of a reflex camera.

Not only does the Minolta 110 Zoom SLR give you this unique combination, but it does so in a camera weighing only 15.1 ounces. And measuring only 5.3 inches by 4.3 inches by 2.1 inches.

It has a zoom lens.

Instead of changing lenses to get different effects, you just turn the lens to zoom in for a picture-filling portrait or zoom back to get more into the scene.

Close-ups, too.

A built-in close-up lens gives you shots as close to the camera as 11.3 inches.

You look through the lens.

When you look into the viewfinder of the 110 Zoom SLR, you're seeing what will appear on the film, so you don't have to worry about cutting people's heads off in close-up pictures. It's the same as with the finest professional reflex cameras.

Easy focusing.

In the center of the viewfinder, you'll see a circle where the image appears to be broken up. Just turn the lens until everything appears clear and your picture will be in focus!

There's information in the viewfinder, too.

Glowing lights tell you if your batteries are O.K. If there's too much or not enough light to shoot. And whether or not the camera is set for automatic operation.

Exposure: the camera does the work.

The 110 Zoom SLR will automatically choose the precise shutter speed for a perfectly exposed picture. Anywhere from 1/1000th of a second to a full ten seconds. And there's a control so you can adjust the exposure manually for unusual light situations.

Automatic flash.
There's a Minolta Auto Electroflash for the 110 Zoom SLR that lets you take flash pictures automatically without flashbulbs.

Finally...

So you won't take a picture accidentally, you can lock the camera. And the 110 Zoom SLR comes with a removable rubber lens shade to keep stray light from interfering with your pictures. If you would like to see what photography is coming to, try the Minolta 110 Zoom SLR at your photo dealer. For more information, write Minolta Corporation, 101 Williams Drive, Ramsey, N.J. 07446. In Canada: Minolta Camera (Canada), Inc., Ontario.

MINOLTA

110 Zoom SLR. There's never been a camera like it.

invalidates his assertion that "if [terrestrial] life did not evolve on the earth, it must surely have evolved on a planet not drastically different from the earth in its temperature and composition." On the directed-panspermia scenario the intelligent extraterrestrials could have represented a form of life that is utterly different from ours (for example no DNA, no RNA, no protein) and arose under conditions that never existed on the earth. These intelligent extraterrestrials, having gained knowledge of the temperature and composition of our planet, would have designed and synthesized in their highly competent exobiology research laboratories an artificial prokaryote (with DNA, RNA, protein and all) likely to prosper in the terrestrial environment. They shipped this laboratory artifact off to the solar system, and the rest is history.

In other words, what Crick and Orgel have shown is that without invoking divine creation it is at least logically possible that what Dickerson is trying to explain in his article, namely the chemical evolution of the only form of life *we* know, never actually happened.

GUNTHER S. STENT

University of California
Berkeley

Sirs:

The first part of Professor Fox's letter is a statement rather than a question and does not require an answer. I do stand corrected on the reported feasibility of the formation of protocells at room temperature from thermal proteinoid material. There seems to be a dispute among origin-of-life scientists over whether thermal proteinoids do have a significant degree of self-ordering and nonrandomness: see *Molecular Evolution and the Origin of Life,* cited by Professor Fox, and *The Origins of Life on the Earth,* by S. L. Miller and L. E. Orgel (Prentice-Hall, 1974).

Incidentally, I should like to mention that the bibliography for my article, which was shortened by the editors of *Scientific American* as the article was going to press, included the above two books and also *The Origin of Life,* by J. D. Bernal (World Publishing Company, 1967) and *Genesis and Evolutionary Development of Life,* by A. I. Oparin (Academic Press, 1969).

Dr. Stent is absolutely correct in his assertion that we cannot disprove the theory that the earth was "seeded" by extraterrestrial beings, perhaps using structural, metabolic and genetic principles quite different from their own. Neither, to quote an even older logical paradox, can we ever disprove the theory that our universe was created five milliseconds ago with everything in place, including quite spurious "pseudomemories" in our minds, as if the universe had had a long prior existence. But both of these theories, although not logically disprovable, do not at present seem to be demanded by the information at hand. It is possible to develop a scenario for the independent evolution of life on this planet that is plausible in general outline, and to believe (here faith enters?) the current gaps of knowledge in this scenario are of a kind that probably can be filled by systematic research. We may be wrong, of course, and clear evidence of either extraterrestrial involvement or divine intervention would raise the problem to an even higher level of intellectual interest. When speaking of events three billion years ago, one can never say "This happened . . . " but only "This probably happened, for the following reasons. . . ." To the extent that we understand the problem of the origin of life today, extraterrestrial footsteps on the sands of history do not seem to be mandatory.

Lastly, Thomas Jukes has written to remind me that although molybdenum may be scarce in the crust of the earth as a whole, it is far from scarce in seawater, being as common as zinc or iron. Hence, assuming that life evolved in the oceans, the shortage of molybdenum that worried Crick and Orgel in their paper on directed panspermia does not exist.

RICHARD E. DICKERSON

California Institute of Technology
Pasadena

Sirs:

The view of the proton synchrotron at the Fermi National Accelerator Laboratory on page 73 of the October issue of *Scientific American* was strikingly similar to the aerial photographs in another article in the same issue, "The Prehistoric Ground Drawings of Peru," particularly the photograph on page 141 of the Pampa Colorada. Both patterns have broadly spaced spirals and wide lines running in different directions; they appear to be variants on a single theme. Perhaps an archaeologist in a distant millennium would conclude on the basis of design alone that the two patterns came from the same civilization or closely related civilizations.

Functionally both efforts do have some commonalities: they both represent socially important endeavors with a significant economic impact. They both appear to reflect their respective societies' understanding of the basic regularities in the universe—ours on a subnuclear scale and the Nazcans' possibly on the scale of the solar system.

ROBERT N. SOLLOD

New York University
New York

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

DECEMBER, 1928: "In the belief that an agreement limiting all the principal types of war craft would diminish naval competition and tend to remove the causes of war, the United States sought at the Geneva Conference last year to secure such an agreement to cover types other than capital ships. It was only natural that we should seek to extend the principle of the 5–5–3 ratio (for the relative strengths of Great Britain, the United States and Japan) that already applied to capital ships and plane carriers. The British have been more inclined than we to talk in terms of numbers. Their Admiralty experts have stated, for example, that their actual needs for cruisers would be 63. Our naval opinion has fixed our cruiser needs at 43. If we now compare the tonnage of the 63 British cruisers with the 43 desired for us, we find that they actually amount to the same in each case, about 400,000 tons. It therefore seems that a basis of an agreement between the United States and Great Britain may be in sight. Such an agreement would be an example of how much better it is to base a treaty on actual needs rather than arbitrary figures. A solid basis for peace is a force adequate to needs but still limited. Unless it is limited, sooner or later competition will arise, with the inevitable dissension, suspicion and distrust that are contributing causes to war."

"There are three general types of X-ray examination. One deals with the gross structure of objects as shown by radiographs, a second with the characteristic X-ray diffraction patterns produced by the fine structure of the substance under examination and the third with the spectrographic study of materials used as targets in X-ray tubes. The examination of the fine structure of materials has been most fruitful in producing fundamental information. Improved equipment has made it possible to examine crystalline organic compounds as well as heavy elements. More recently colloidal and amorphous substances have been investigated. Rubber, when stretched, has shown a crystalline-fiber diffraction pattern. Cellulose has proved to be crystalline (rhombic) and to have the composition $(C_6H_{10}O_5)_4$. Some amorphous substances exhibit patterns made up of two or three diffuse diffraction rings, which appear to indicate the distance of nearest approach of the molecules in the materials."

"Although the *Graf Zeppelin,* the world's largest airship, dwarfs her sister, the U.S.S. *Los Angeles,* American dirigible designers and enthusiasts are looking forward to 1931, when the all-American *ZRS-4,* a dirigible with nearly twice the capacity of the German one, will take the air. A little less than a year later the *ZRS-5,* a sister ship from the same patterns, will be produced by the Goodyear Zeppelin Corporation on a contract with the United States Navy. The new Navy airships, when completed, will be only 14 feet longer than the *Graf Zeppelin,* but they will hold 6,500,000 cubic feet of gas compared with the *Graf Zeppelin's* 3,708,000. The American ships will incorporate some new design factors that promise to make them unique. They will contain inert helium instead of explosive hydrogen, and so it will be possible to place the eight engines inside the hull. The internal engines will allow the ship to slip through the air with less resistance, and there will be less danger of the engines' being torn off in a severe storm."

SCIENTIFIC AMERICAN

DECEMBER, 1878: "The electric arc seems from its very nature to present insuperable obstacles to the economical production of a large number of small lights in a circuit, in other words, such lights as we require in our dwellings, offices, factories and shops. The production of light through the incandescence of a pencil of carbon or metal, forming part of an electric circuit and heated by its internal resistance to the passage of the electric current, offers an entirely different field for exploration. The achieved success of Messrs. Sawyer and Man, not to speak of the reported success of Mr. Edison, clearly indicates that this is the line along which the practical solution of the problem of household illumination is to come. In the Sawyer-Man electric lamp the light is produced by the incandescence of a slender pencil of carbon. A fatal defect in all previous lamps depending on incandescent carbon has arisen from what has been alleged to be the vaporizing of the carbon. Many gases indifferent to carbon at ordinary temperatures attack it destructively at the temperatures obtained in the electric lamp. Mr. Sawyer claims to have overcome this difficulty by his method of charging the lamps with pure nitrogen, and by providing for the fixing of any residual oxygen left in the lamp. Another stumbling block on which other workers in this field have come to grief has been the crumbling or disintegration of the carbon burner, due to sudden heating when the lamp is lighted. This is avoided in the Sawyer-Man lamp by an ingeniously devised switch. By this means it is impossible to turn the current on or off suddenly, to the disruption of the carbon."

"The discovery of the new metal gallium differs in its history from that of any other element. All other elements have been accidentally discovered, and it has been only after their discovery that we became acquainted with their properties. The 'blende' found at Pierrefitte, in which gallium was discovered by Boisbaudran, was examined by him with a view to finding a new element the existence of which he was firmly convinced. The existence of an element corresponding in its properties with gallium had been predicted in 1871 by Mendelejeff and Newlands. It had been found that the elements form a series of numbers, the amounts and successions of which are governed by certain laws. At the same time it was observed that the properties of the elements showed peculiar relations with the arrangement of these numbers. The series formed by the numbers show irregularities, as if certain numbers were missing. The position to be filled by one of the missing elements indicated the properties of its occupant. These properties had been to the smallest particular described by Mendelejeff. He ascertained the specific gravity of the metal yet to be found as 5.9. In operating on small quantities Boisbaudran found at first 4.7. In 1876, when larger quantities of the metal were obtainable, he found 5.955, exactly as Mendelejeff had predicted."

"The Chinese of California have developed a large and profitable industry along the shores of San Francisco Bay in the capture and curing of shrimp, with which those waters swarm. Over 500 Chinese are engaged in this work, distributed mainly along the southern portion of the bay, in camps of from 12 to 40 men each."

"The recent reports concerning the discovery of oil near the shores of the Caspian Sea in Russia seem to be fully confirmed. From one of the wells a stream, free from gas and froth, is forced to a height of 75 feet, yielding at the rate of 10,000 barrels a day. It is reported that companies are forming at Odessa, Novo-Tcherkask, Astrakhan and other cities for the purpose of obtaining oil. Two large manufacturing concerns that have their headquarters in New York recently received orders for considerable quantities of oil-line pipes, steam pumps, engines, boilers and other apparatus, to be shipped immediately to St. Petersburg."

THE NEW ERA.
SENSOR TOUCH CALCULATORS.

Close inspection will reveal there's something important missing from these calculators. Buttons. Buttons are important because they're usually the first thing to go on calculators. Now they're gone.

Sharp, which made the first solid-state electronic desktop calculator, as well as the first hand-held calculator, has become the first to eliminate push buttons with its exclusive Sensor Touch line of calculators. Now, numbers are entered at the touch of a finger. The procedure is so fast and effortless there's culture shock; an electronic tone assures you that each entry has actually taken place.

To do away with buttons, Sharp had to invent a new way to bond onto Polymid film. This also enabled us to do away with thickness in calculators. Our 5808 Scientific Calculator is all of 5mm thick, yet it handles complex algebra, trigonometry, statistical analysis, and other advanced mathematics.

For general calculating, credit Sharp with developing the 8145, which is literally the size of a credit card and only slightly thicker: 3.8mm front to back. And yet it's a serious calculator. Sensor Touch Entry; power-saving 8-digit liquid crystal display (Sharp was the first to develop liquid crystal display for calculators); a Storage Computer that holds any number, even an English-to-metric conversion, for later use; Safe Guard circuitry that protects the number even after the power goes off; Sharp's A.P.O.–Automatic Power Off–which does just that after 7 minutes of nonuse; and many other features.

Our 8130 model, called the "Super Thin Man" (5mm thin) is the calculator that does everything you'd want and makes it all easier with an independently addressable 4-key memory for convenient storage and retrieval of totals.

Then there's our CT-600, a 24-function calculator with two memories, a world clock with an alarm, a 200-year calendar, and a stopwatch that counts up or down.

But Sharp's innovations have not been confined to calculators. We produce countless other consumer, industrial and space products, most of which have unique Sharp technology.

For example, we've also found a way to eliminate the picture tube in television sets: we've developed a matrix-type, thin-film electroluminescent TV set in which the video display is a mere 5.08cm thick. We've been mass producing solar batteries since 1963. We were the first to mass produce extra large scale integrated circuits (ELSI).

In fact, Sharp's innovations are found in so many areas of advanced technology that, no matter where in Sharp you may look, from the 8145 to the CT-600 and beyond, you will see the new era.

SENSOR TOUCH CALCULATORS

Sharp Electronics Corporation, Paramus, N.J. 07652

SHARP

The priceless gift of learning now has a price: $599. And a name: the Radio Shack TRS-80® Microcomputer. And now, at last, your child has a chance to discover Tomorrow on Christmas morning.

"Tomorrow" is an electronic world, based on computers — and it's already here. In it your child can be a number in a machine, like a robot. Because he or she does not understand either the number or the machine. Or your child can be pleasurably elevated into this brave new world with a gift that has only become affordable in recent months.

Quotes from Fascinated Customers

The Radio Shack personal computer surely ought to be on the gift list of every concerned parent, despite that $599 — though less than a moped — is costlier than an electric train. A father writes to tell us "this investment is one of the most significant in value to our family and to the future education of our child that we have ever seen."

A Californian, aged 12, writes to tell us that he's "too young to go to work for Radio Shack . . . but maybe we could work a deal where I could write some programs for you." An educator thanks us for "making possible the tapping of human innovation and creativity on an unprecedented scale."

Advice for Parents Who Care

In your lifetime the possibility of owning or giving a computer — up to now — was unthinkable. A computer? That can teach? Remember? Display on its own screen? Play games? Complete with a standard typewriter keyboard? Unthinkable — up to now.

But now the Tomorrow Machine is not only thinkable but practical, affordable and available at every Radio Shack store and participating dealer. The TRS-80 personal computer system? For the kids? For Christmas? Crazy? Like a fox!

Radio Shack®
The biggest name in little computers™

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Plain-English 232-page manual makes it easy to start programming with no computer experience.

Includes 12" video screen, 53-key keyboard, compact cassette recorder and 2 game cassettes.

TRS-80 is expandable and can grow in power and utility. Everyone in the family becomes involved, entertained, informed.

THE AUTHORS

CHARLES F. WESTOFF ("Marriage and Fertility in the Developed Countries") is professor in the departments of demographic studies and sociology at Princeton University and director of the university's Office of Population Research. He obtained his bachelor's and master's degrees at Syracuse University and his Ph.D. from the University of Pennsylvania in 1953. He has been on the Princeton faculty since 1955; from 1970 to 1972 he was in Washington as executive director of the Commission on Population Growth and the American Future. The information in Westoff's article has also been presented in three papers listed in the bibliography for this issue.

D. ALLAN BROMLEY ("Nuclear Molecules") is Henry Ford II Professor of Physics at Yale University and director of the university's A. W. Wright Nuclear Structure Laboratory. A native of Ontario, he was graduated from Queen's University at Kingston in 1948 and received his master's degree in physics the following year. He then entered the doctoral program at the University of Rochester, obtaining his Ph.D. in 1952. After two years on the Rochester faculty he joined the research staff of Atomic Energy of Canada, Ltd., where he helped to design the first variable-energy cyclotron. In 1960 he moved to Yale, where from 1963 to 1965 he collaborated on the design of the first Emperor Tandem Van de Graaff electrostatic accelerator and supervised its installation in the Wright Laboratory with the first completely computerized system for the acquisition of nuclear data. Bromley has since utilized the accelerator in studies of both heavy- and light-ion reactions, including the production of nuclear molecules described in his article.

ARNOLD P. FICKETT ("Fuel-Cell Power Plants") is program manager for fuel cells and chemical-energy systems at the Electric Power Research Institute (EPRI) in Palo Alto, Calif. He was graduated from Bates College in 1956 with a B.S. in chemistry and joined the research staff of the General Electric Company, studying at night for a master's degree in chemistry, which he received at Northeastern University in 1965. During his 18 years at General Electric he developed a wide variety of fuel cells. He joined EPRI in 1974 and has since managed research focused on molten-carbonate and phosphoric acid fuel-cell technologies. He writes: "The annual EPRI fuel-cell budget ranges between $6 million and $10 million. It is aimed at developing and expediting the commercialization of multimegawatt fuel cells as electric-utility power plants."

M. F. PERUTZ ("Hemoglobin Structure and Respiratory Transport") is chairman of the Medical Research Council Laboratory of Molecular Biology in Cambridge, England. Born in Vienna in 1914, he did his undergraduate work in chemistry at the University of Vienna. In 1936 he went to England to do research under J. D. Bernal in the Cavendish Laboratory at the University of Cambridge. After receiving his Ph.D. in X-ray crystallography in 1940, he worked as a research assistant to W. L. Bragg in the Cavendish Laboratory. In 1947 Perutz became director of the newly founded Medical Research Council Unit for Molecular Biology. He began his work on the structure of hemoglobin in 1937, but it was not until 15 years later, in 1953, that he finally discovered a method for working out the structure of protein molecules. His method led to the solution of the structure of myoglobin by J. C. Kendrew and of the structure of hemoglobin by himself. For these discoveries Perutz and Kendrew shared the Nobel prize in chemistry in 1962.

MICHAEL F. LAND ("Animal Eyes with Mirror Optics") is reader in neurobiology at the University of Sussex. Born in Devon, he did his undergraduate work in zoology at the University of Cambridge, where he developed an interest in the "odder forms of animal life." He then did graduate work in neurophysiology at University College London, which awarded him his Ph.D. in 1967 for a thesis on the eye of the scallop. After two years as a postdoctoral fellow at the University of California at Berkeley, where he worked with Gerald Westheimer on the eye movements of spiders, he became assistant professor of physiology and anatomy at Berkeley. He moved to the University of Sussex in 1971. Land's interest in the eyes of marine invertebrates was renewed during a cruise on the research vessel *Discovery* in 1976. He writes: "It was probably a happy combination of photography and a liking for odd animals (plus an adequate amount of residual physics from school) that led me into the field of invertebrate vision; I admit to being very happy about it. I believe science has for a long time been obsessed with its importance, to the detriment of its other merits: that it can be entertaining and enjoyable."

DONALD B. REDFORD ("The Razed Temple of Akhenaten") is professor of Near Eastern studies at the University of Toronto and research associate of the University Museum of the University of Pennsylvania. He received both his undergraduate and graduate education at Toronto, earning his B.A. in Hebrew and Akkadian and his Ph.D. in Near Eastern studies in 1965 with a thesis on the chronology of the Egyptian 18th Dynasty. In the 1960's he participated in the excavations of the British School of Archaeology in Jerusalem under the direction of Dame Kathleen Kenyon. From 1970 to 1972 he was director of an expedition to the Temple of Osiris at Karnak, and from 1972 to 1975 he was director of the Akhenaten Temple Project in Cairo. Since 1975 he has directed the East Karnak Excavations sponsored by the University of Pennsylvania. Redford's other interests include biblical studies and the relations among Egypt, Asia and Greece in ancient times. He is a Fellow of the Royal Society of Canada.

THOMAS A. McMAHON and PETER R. GREENE ("Fast Running Tracks") are mechanical engineers at Harvard University with a special interest in biomechanics. McMahon is Gordon McKay Professor of Applied Mechanics and also professor of biology. After receiving his bachelor's degree in engineering physics at Cornell University in 1965, he went to the Massachusetts Institute of Technology, where his Ph.D. thesis dealt with the fluid mechanics of the intra-aortic balloon, a device for providing mechanical assistance to the failing heart. Since McMahon joined the Harvard faculty in 1969 his research has focused on the mechanical design of trees and more recently on the physiology of locomotion and the mechanics of the heartbeat. Greene is a postdoctoral fellow working with McMahon on biomechanical problems, including the mechanism of myopia.

ERIC J. CHAISSON ("Gaseous Nebulas") is associate professor of astronomy at Harvard University and an astrophysicist at the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory. Trained initially in solid-state physics at the University of Lowell and at Harvard, he obtained his Ph.D. in astrophysics from Harvard in 1972. His research has concentrated largely on examining the physical and chemical processes within interstellar gas clouds by means of radio-frequency spectroscopy. He was the recipient in 1977 of the Bart J. Bok Prize for outstanding contributions to knowledge of the galaxy and was an Alfred P. Sloan Research Fellow from 1976 to 1978. Chaisson currently teaches a Harvard College course, "Cosmic Evolution," that attempts to synthesize astrophysics and biochemistry. Attended by more than 500 undergraduates, it is the largest science course in the university.

MATHEMATICAL GAMES

Is it a superintelligent robot or does Dr. Matrix ride again?

by Martin Gardner

"Computers don't actually think. You just think they think. (We think.)"
—THEODOR H. NELSON, *Dream Machines*

For years computer scientists who are also experts in linguistics have been working on systems to enable computers to accept input and produce output in natural spoken language. Progress on such systems has been disappointingly slow. As of today only the most trivial and stylized dialogue can be carried on, usually in the form of typed sentences with an extremely limited vocabulary.

On the other hand, science-fiction fans have been familiar with talking computers for more than half a century. The marvelous machines have even appeared in children's fantasy literature: as early as 1907 L. Frank Baum introduced (in *Ozma of Oz*) a mechanical windup robot named Tik-Tok, which according to its manufacturers could think, speak, act and do "everything but live." In recent years, through films such as *Forbidden Planet* and *Star Wars,* the general public have become accustomed to talking robots and to talking computers such as HAL, which ruled the spaceship in Arthur C. Clarke's *2001: A Space Odyssey.*

There are many signs of the new familiarity with such ideas. For example, consider a toy robot that went on sale this year: a child answers multiple-choice questions by pressing buttons on the robot's torso, and the robot comments (by a prerecorded tape) on the quality of the answers. Moreover, game-playing computer programs are improving rapidly. For less than $300 one can buy a small chess-playing computer that can beat a beginning player. The more sophisticated chess programs are now approaching the master level; in fact, when the time limit on moves is short enough, they can easily trounce even a grandmaster.

For these reasons and others there was little skepticism last July when advertisements began to appear announcing public demonstrations of ASMOF, the world's first talking computer. The name ASMOF was an acronym for the American Superior Mind Operating Foundation, which was sponsoring demonstrations of the robot prototype to stimulate sales of its stock. From newspaper clippings readers began to send me I gathered that the robot featured a new magnetic-bubble memory. Its circuitry was contained in a 20-foot-high aluminum figure designed to resemble a movie robot. The monster had two openings where a human being's eyes would be and a third eye with a ruby-colored lens at the center of its massive forehead. There was no nose, but a conical loudspeaker formed a kind of mouth. At the public demonstrations the robot was seated behind a large table and did not move. Occasionally a beam of crimson light shot from the third eye to scan the table or anyone seated in a chair on the other side of the table.

ASMOF began its tour of the country at the end of July, making two-hour appearances at halls and theaters in large cities and summer resorts. For an admission fee of $3 people in the audience were allowed to sit across from ASMOF at the table and ask it a reasonably brief question on any topic. The robot replied in a husky mechanical voice and sometimes engaged in humorous banter with a questioner before trying to answer the question. It did not know everything: occasionally it responded with remarks such as "Your problem would take too long to compute" or "Sorry, madam, that information is not in my memory bank."

On special occasions an entire appearance was devoted to combat with a local expert in some intellectual table game. ASMOF seemed to be a top-level player of chess, checkers, go and even games with random elements such as backgammon, bridge and poker. Early in August, when ASMOF was at a theater in Nyack, N.Y., a chess grandmaster who lives nearby was offered $1,000 if he could defeat ASMOF. The grandmaster lost in 18 moves. ASMOF then challenged him to a second game, offering to play without its queen's bishop if this time the grandmaster would bet $1,000 on the game. The bet was declined.

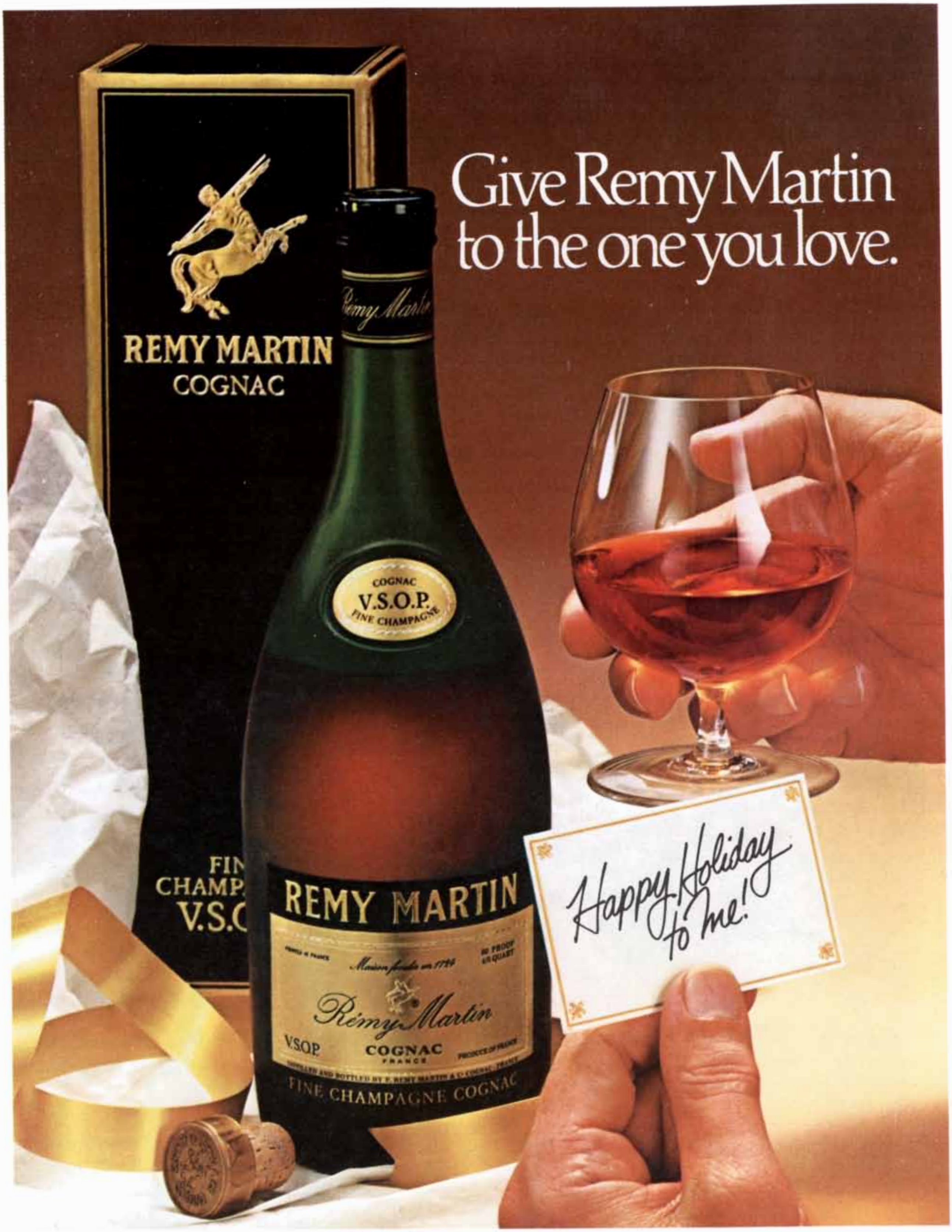
The grandmaster's humiliating defeat was a startling turn of affairs. When I telephoned an old friend who works in the artificial-intelligence laboratory at the Massachusetts Institute of Technology, however, he assured me that ASMOF was a total fraud. He did not know precisely how the robot was controlled, but he was sure the foundation backing it was a swindle. He intimated that my old acquaintance the numerologist Irving Joshua Matrix might be behind the scheme.

Glancing over my supply of press clippings, I could find no pictures of the foundation's head Frank Rossum or his assistant Josie Clarke Nelson. Knowing Dr. Matrix' obsession with wordplay, however, I began to think about the two names. Could Frank be an abbreviation for Frankenstein? Rossum certainly suggests Rossum's Universal Robots, from Karel Čapek's 1920 play *R.U.R.* (The play introduced into the English language the word "robot," from the Czech *robota,* meaning work or compulsory service.) What about Josie Clarke Nelson? Josie might be a feminine form of Joe, Lewis Padgett's famous science-fiction robot, which could "varish" as well as "skren." Clarke, of course, would be for Arthur C. Clarke. And Nelson could refer to Theodor H. Nelson, the young computer scientist whose double book *Dream Machines* and *Computer Lib* is such a whopping success as a wild, Oz-like introduction to the fantastic new world computers are creating. (His latest paperback *The Home Computer Revolution* contains still more startling predictions.)

But wait! There was another extraordinary coincidence. It was Dr. Matrix himself who revealed that HAL is obtained by shifting each letter of IBM back one letter in the alphabet. Now shift each letter of IBM forward one letter. In this case we get JCN, the initials of Rossum's assistant!

From literature supplied by Rossum's foundation I learned that ASMOF's next public appearance would be in the amphitheater of the venerable Chautauqua Institution on the shore of beautiful Chautauqua Lake in upstate New York. From my house in Westchester I drove there easily in a day, putting up at a motel close to the Chautauqua Institution's entrance. The next afternoon I made a point of arriving at the amphitheater early enough to be sure of a front seat. On the chance that Dr. Matrix or his lovely half-Japanese daughter Iva might appear on the platform I disguised myself with dark glasses and a large artificial moustache.

There was no sign of either of them. A pleasant young man with long red hair


Give Remy Martin
to the one you love.
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REMY MARTIN
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FINE CHAMPAGNE COGNAC
Happy Holiday to me!

"A FUNCTIONAL MASTERPIECE SUMPTUOUS SEDANS TO EVER

The editors of CAR *and* DRIVER *Magazine have graciously given us permission to quote these excerpts from their Dec. 1977 road test report on the Audi 5000:*

"The dominant trait...is German engineering excellence..."

"American influence has boosted comfort to an area of major concern for the first time in a German car. As a result, the Audi 5000 is...technically intriguing, a functional masterpiece and yet one of the most sumptuous sedans to ever leave Germany."

"It is so packed with fresh technology that scientists will spend years decoding component parts to see how it was all done."

"It's just flat beautiful—taut, smooth, no gimmicks and acres of glass; modern architecture for the road."

"...cleaner and crisper than either a Mercedes or BMW sedan..."

"I don't know how five-cylinder engines are supposed to feel, but this one doesn't feel like a five-cylinder. It feels like a six and sounds like a four—

and a reddish beard introduced himself as a "futurologist" formerly with the Stanford Research Institute. He spoke learnedly about recent progress in computer communication in natural languages, and finally about the monumental breakthrough by computer scientists working for the American Superior Mind Operating Foundation. Their discoveries, which had been made possible by the new bubble memory, he explained, were still highly classified. He hinted darkly that the CIA was trying to prevent the manufacture of smaller versions of ASMOF. The robot, he assured us, unlike human beings, cats and cockroaches, possessed no paranormal powers. Hence ASMOF would not answer questions about the future or questions that required any kind of extrasensory perception. The foundation was working closely with several physicists at the Stanford Research Institute on ways to add ESP and precognition to ASMOF's circuitry, he added, but that development might take another decade.

It was a singular and entertaining performance. Most people asked trivial questions, such as what years Millard Fillmore was our 13th president or who won the baseball world series in such-and-such a season—facts that could easily be stored in a computer's memory. Some of the questions, however, were harder. I took extensive notes on those involving the kind of mathematics and wordplay I thought would most interest readers of this department.

For example, a young girl asked ASMOF for the longest word in the English language. After scanning the girl with its ruby eye and complimenting her on her smile, ASMOF asked: "Can the word be hyphenated?" The girl said yes. "In that case," said ASMOF, "there is no longest word. We can speak of a great-grandmother, a great-great-grandmother, a great-great-great-grandmother and so on. Next question, please."

Here are a few other linguistic queries of an unusual nature. A woman asked for a 10-letter word of one syllable. ASMOF came up with "scraunched." A young man asked for an English word containing the sequence of adjacent letters "nkst." After some conversation about the slogan on the questioner's T-shirt, ASMOF gave an acceptable reply. The man was followed by his brother, who asked a similar question about the sequence "nksh." This one too was correctly answered. Can the reader supply a dictionary word containing each sequence before I reveal ASMOF's replies next month?

Children liked to test the robot with ridiculous riddles. Sometimes ASMOF answered correctly. When it failed, it always asked to have the answer to store in its memory and occasionally praised the child for having stumped it. I find in my notes that one elderly man, a professor emeritus of English at the nearby State University of New York at Buffalo, asked a literary riddle that was new to me. He wanted to know what Coleridge's ancient mariner and an inebriated shortstop had in common. ASMOF promptly responded: "He stoppeth one of three."

The most difficult word question was asked by a Shakespearean scholar from Bryn Mawr. There is a line in one of Shakespeare's plays, she said, that begins with "My." Reading upward, the first letters of the preceding four lines spell WANT. Reading downward, the first letters of the succeeding four lines spell BABY, yielding WANT MY BABY. In what play does this acrostic appear?

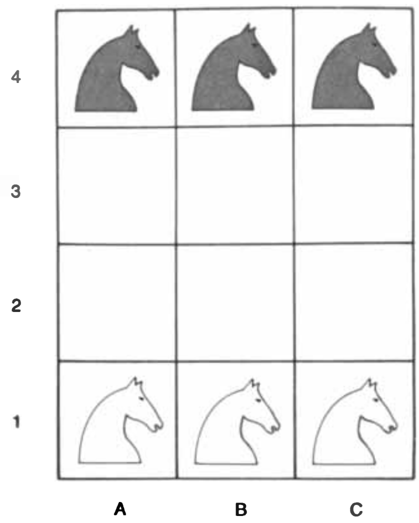
This question must have been hard, because ASMOF spoke for several minutes about whether or not such Shakespearean acrostics were intentional. Finally the robot identified the line. It is the 14th line from the end of the first scene of the first act of *The Comedy of Errors:* "My soul should sue as advocate for thee." Is it possible, ASMOF asked, that Shakespeare was sending a coded plea to a lady friend, asking for possession of an illegitimate child?

Some questions involved formal logic. A New Jersey man named Ken Knowlton tried to throw the robot's circuitry into an endless loop of alternating yeses and noes by posing Bertrand Russell's famous paradox about the barber in a certain town who shaves all the men and only those men in town who do not shave themselves. "Is the barber a self-shaver?" he asked. ASMOF replied: "Insufficient data. She could be."

What is the only way, a Princeton mathematician wanted to know, to divide all positive integers into two disjoint sets in such a way that no pair of numbers in either set add up to a prime? I shall give the simple answer next month. Incidentally, the robot failed to solve the problem.

Thomas Szirtes of Montreal asked ASMOF if it were possible for him (Szirtes) to be exactly one-third Scottish, one-third Chinese and one-third Hungarian. ASMOF replied that it was not. One has, explained the robot, 2^1 parents, 2^2 grandparents, 2^3 great-grandparents and so on. Hence the question is equivalent to asking whether 2^n can equal $3x$. Now, 2^n equals $2 \times 2 \times 2 \cdot \times 2 \times \ldots$, with 2 repeated n times. Since 2 is a prime, we know from the fundamental theorem of arithmetic that this sequence is a unique factorization of 2^n into primes, that is, that 2^n has no prime factors other than 2. Therefore 3 cannot divide 2^n, and the original conjecture must be false.

Jaime Poniachik of Buenos Aires, who edits an excellent Spanish puzzle magazine titled *The Snark,* happened to be visiting the Chautauqua Institution at the time of the ASMOF demonstration. When it was his turn to ask a question, he said he had a friend in the U.S. with a curious social security number: its nine digits include every digit from 1 through 9, and they form a number in which the first two digits (reading from left to right) make a number divisible by 2, the first three digits make a number divisible by 3, the first four digits make a number divisible by 4 and so on until the entire number is divisible by 9. What is the number? ASMOF expressed admiration for this new problem but pleaded insufficient time to compute the answer. After I returned home I figured out the only answer, but again I shall withhold it until next month.



A knight-switching problem

When it was my turn, I asked permission to give a problem involving six chess knights on a three-by-four board. On a sheet of paper I sketched the initial position shown in the illustration above. The task is to exchange the white and black knights with a minimum number of knight moves. The knights may be moved in any order, regardless of their color, but no two of them may occupy the same cell.

In 1974, when this problem was first published in *Journal of Recreational Mathematics,* it was called trivial and a 26-move solution was given. Later an 18-move solution was found. I included the problem in the first edition of my latest book *Aha!* (the handbook for a set of six high school filmstrips called *The Aha! Box*) and cited the 18-move solution as being the best. Three readers of the book, Gary Goodman, Warren B. Porter and George Schneller, independently reduced the solution to 16 moves!

After scanning my sketch with its third eye ASMOF offered the 18-move solution and expressed doubt when I said there was a shorter one. After I gave the shorter solution ASMOF congratulated the discoverers for their "Aha!" insight concerning what seems to be a wasted move. Can readers find the 16-move answer before I disclose it next month?

After watching ASMOF perform for

about an hour I was convinced that my friend at M.I.T. was right. None of the calculations were being made by internal circuitry; the robot was surely under the control of a human intelligence at some nearby vantage. I had learned from an ABC television crew there to film the performance that Rossum and Nelson were staying at a hotel on the Chautauqua Institution grounds. I slipped out of my seat and left the amphitheater. When I arrived at the hotel, the lobby and corridors were deserted. Everyone, it seemed, had gone to the demonstration. No one saw me put my ear to the door of Rossum's room. Inside I could hear the faint sounds of conversation.

The hotel is an old one, and I had little difficulty snaking a plastic credit card through the crack of the door and forcing back its spring catch. The scene inside the room was not very different from what I had expected. Iva was seated at a large desk with enormous headphones over her ears. A color television screen in front of her displayed the questioner sitting opposite ASMOF in the amphitheater. I later learned that the television camera was behind the robot's left eye. On both sides of Iva's desk were the same basic reference books that librarians keep on hand for answering telephone queries: ***The World Almanac, The New Columbia Encyclopedia,*** several ***Who's Who***s, an unabridged dictionary, concordances of the Bible and Shakespeare, dictionaries of quotations and so on. Also close at hand were the console of a large programmable computer and a telephone into which Iva could insert cards that automatically dialed numbers.

Iva looked startled when I entered. She took off her earphones and put a hand over the microphone in front of her. "If you don't leave at once," she said angrily, her dark eyes flashing, "I'll scream and call the police."

"I think not," I said, removing my dark glasses and ripping off my moustache.

"So, it's you again!" said Iva with a twisted smile. "Sit down and keep your big mouth shut."

I sat on the edge of the bed and watched her operate for the rest of the hour. An electronic device completely disguised Iva's pleasant voice, giving it that cold, toneless timbre characteristic of television and movie robots. Easy questions from simple souls were answered from the considerable fund of information inside her own head. Other answers she looked up quickly in the various reference books on the desk while she killed time by engaging in conversation with the questioner. For questions requiring numerical calculations, such as finding the 13th root of 10 or raising pi to the power of pi, she turned to the computer. When a more difficult question was asked, she inserted a card into the telephone. By restating the problem aloud—ostensibly to make sure it was correctly understood—she would ask it of the person she had called. Iva later told me that Dr. Matrix had hired more than 100 experts, each one a specialist in a different field, and was paying them handsomely to be on call at private telephone numbers during the demonstrations.

Iva also told me that Dr. Matrix had tried to hire Isaac Asimov for her job to avoid having to pay so many experts. Asimov had politely declined, however, at least partly because he had to complete 17 books before the end of the year. I never learned the name of their mathematics expert. Nor was I able to discover which grandmaster had been hired for the chess games.

When the two-hour performance ended, Iva removed her earphones, turned off the mike and grinned. She squinted at her wristwatch, one of those tiny watches that are so expensive the dial is almost impossible to read without a magnifying glass. "Time for cocktails," she said.

Dr. Matrix, I was delighted to learn, had left for the day. The old buzzard was visiting a friend who worked as a phony medium in the nearby spiritualist community of Lily Dale. No restaurant on the Chautauqua Institution grounds is allowed to serve liquor (a holdover from the institution's pious past), and so Iva guided us northward on Highway 17 to a colorful seafood restaurant in Westfield on the shore of Lake Erie. (I was amused by a statement on their menu: "We serve oysters in January, February, March, April, Mayr, Jurne, Jurly, Augurst, September, October, November and December.") We ordered dinner.

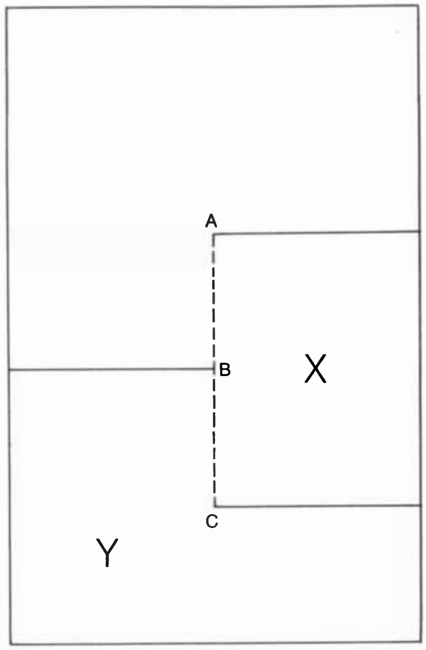
"In my opinion," I said between mouthfuls, "this is the salad of a bad café."

Iva winced. "I think the salad is excellent," she said. Nevertheless, we had a delicious dinner and an enjoyable evening together.

A month later, when ASMOF was booked into a theater in Washington, two investigative reporters from a newspaper, aided by Randi the magician, figured out the con. They rented a hotel room next to the one from which Iva was operating, bored a hole through the wall and obtained good photographs of her at the microphone. The story broke in the next morning's newspaper, but by then Dr. Matrix and Iva had disappeared. ASMOF was left behind in the van they had used for transporting it. The Washington police have since given the robot to the Smithsonian Institution, where it will soon be on display with a tape-recorded account of the history of the swindle.

The "hypercard," which I proposed last month as a piece of minimal sculpture, is easily constructed as fol-

This is Delta's Wide-Ride™ L-1011 TriStar, a $25 million superjet. The "living room" cabins are 8 feet high, almost 19 feet wide.



How to fold the hypercard

lows: Take a rectangular sheet of paper or cardboard and make three cuts along the black lines shown in the illustration above. Now fold flap *X* up 90 degrees along the broken line *ABC* and then turn the lower portion *Y* over by folding it back 180 degrees along the broken line *BC*.

Last March I mentioned that Alan Cassel, employing a Monte Carlo test for primes, had found that the odds were about a trillion to one that the number consisting of 123456789 repeated seven times followed by 1234567 was a prime. Physicist R. E. Crandall and computer scientist Anna M. Penk, working with a program completed at the computer center of Reed College in Portland, Ore., have succeeded in proving that the number is indeed prime.

Last August I mentioned a science-fiction story, whose author and title I could not remember, in which a man walked around inside a prismatic ring that had been twisted so that its interior had a single face. Readers too numerous to list have reminded me that the story was Theodore Sturgeon's "What Dead Men Tell," which appeared in the November 1949 issue of *Astounding Science Fiction*. The entire issue was a whimsical joke. In a letter published the preceding year a reader had "reviewed" the issue. The editor, John Campbell, Jr., persuaded most of the writers named in the letter to write stories with the titles that had been mentioned, so that when the issue was published, it made the letter precognitively accurate. Sturgeon's story was reprinted in the collection *Imagination Unlimited*, edited by Everett Bleiler and T. E. Dikty (Berkley Publishing Company, 1959).

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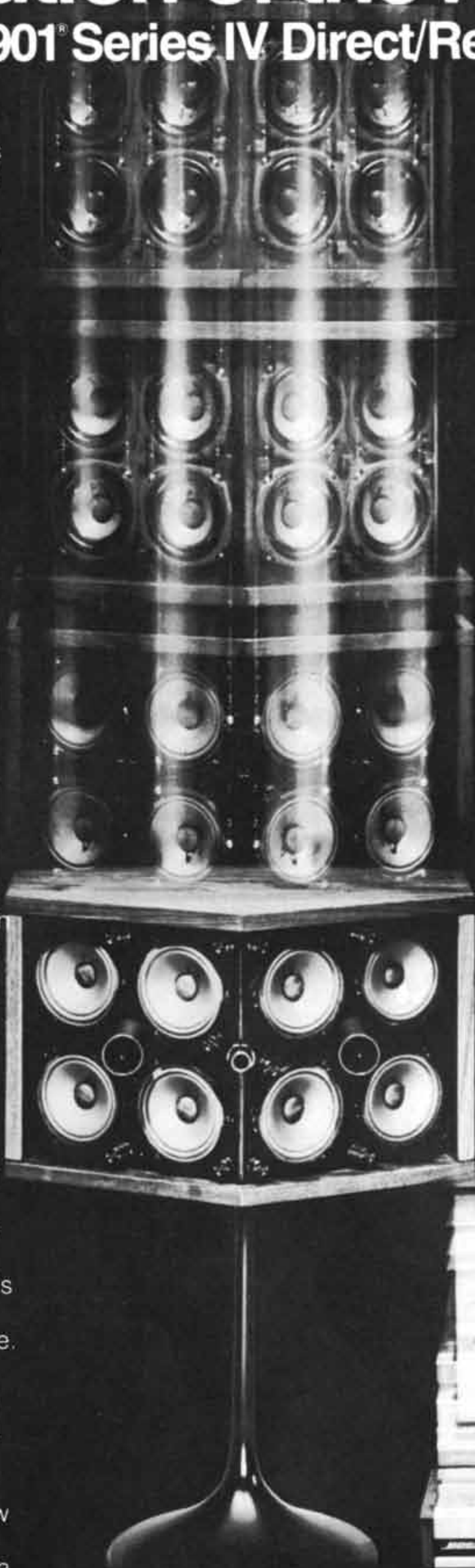

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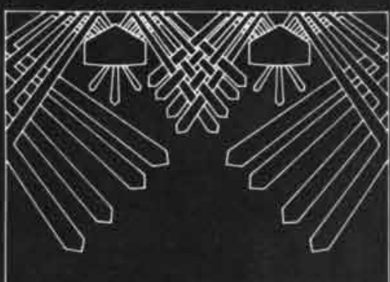


Now the 901® has evolved. Again. Introducing the Bose 901 Series IV Direct/Reflecting® speaker system. With new equalizer controls that consider your room as part of the speaker design. And a new answer to the problem of choosing an amplifier.

It is a known fact that moving a speaker just a few feet in a room will alter its performance. And that the variances in a speaker's performance from one living room to the next can be vast. This is a problem all speakers have regardless of design. Except one.

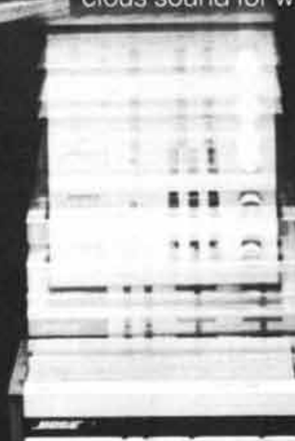
A new approach to the study of listening room acoustics and an ambitious survey of many actual listening rooms has resulted in new equalizer controls for the Bose 901 IV. These controls allow you to simultaneously adjust several bands of frequencies in a precise manner to match the performance of the 901 IV to your room. In a way that cannot be duplicated even with an expensive graphic equalizer.

As a result, the 901 Series IV speakers perform as well in the living room as in the demonstration room.

Were our engineers to design a speaker specifically for your living room, you would not get better sound than you do when you properly adjust the equalizer controls on the Bose 901 Series IV.

And the 901 IV provides a simple answer to the problem of choosing the power rating of your amplifier or receiver. Choose any amplifier you wish. The 901 IV provides surprisingly loud sound with as little as 10 watts per channel. Yet it is durable enough for us to remove all power limitations on the 901 IV. There is no power limit. Period.*

With these new improvements, the Bose 901 IV gives you a flexibility no other speaker can. You can place the 901 IV in almost any room and get the life-like, spacious sound for which the 901 IV Direct/Reflecting® speaker is famous. And you can match it to virtually any amplifier.



We think that once you hear the new Bose 901 IV Direct/Reflecting® speaker, you'll agree. The revolution has evolved.

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*There is a power limit in commercial applications. For information, contact Bose Customer Service.

BOOKS

An annual Christmas survey of books for younger readers

by Philip and Phylis Morrison

The literature in science and technology for children shows signs of maturity more clearly year by year. Many of the better new books are on less central subjects. Some publishers continue to indulge in trendy interests: this year some catered to the occult in the name of science.

The Telling of Tales

ADVENTURE OF THE STONE MAN, by Frances Hamerstrom. Illustrated by William Kimber. The Crossing Press, Trumansburg, N.Y. 14886 ($6.95 hard cover; $3.95 paperbound). Families have lived for a very long time among the limestone ledges of the French *causses*. In this brief, beautifully illustrated novel for young readers, we too enter those long-explored mountains to gather wild strawberries, to find by chance a small, dark cave, to encounter the rare and terrible eagle owl with its huge orange eyes and to find in the fossil pellets of the owl's cave a secret treasure. We share intimately the experiences of eight-year-old Marie, tactful, ingenious, with "the makings of a great scientist" and a responsible companion to her brave brother Pierre, a natural climber at age 10.

There is the secret of their find, uncovered by the delightful schoolmaster Monsieur Legrand, who knows and loves the children of the town and can even explain their need for privacy and growth to Papa and Maman. The best ideas are Marie's; with one of them she saves her brother, stuck on a terrible slope. But there is also a professor from Paris who comes to see the cave of the eagle owl, a savant with courtesy and respect, who kisses the hand of little Marie for her great gift. What Marie and Pierre found and held quietly was not only the place of the first eagle owl seen for a generation but also a tiny stone carving of a man, an image made by ancient people and buried in a fossil owl pellet since the time of the ice. It all ends happily; Marie's explanation of how the pellet held such an image is surely right. And it is not mere fiction: a Paleolithic artifact, if not a small sculpture, has indeed been found in a fossil owl pellet.

This new book, which has about it the air of a children's classic to be, is an example of purity. Its text brilliantly evokes the feel of French village family life between the wars, and its pictures make it doubly convincing. The biologist author has recaptured her own young life in the French countryside, and her talented Toronto-artist partner has studied and caught the look of that world. At the same time we learn about venture, inference and publication, a real archaeological lesson, not so much unlike the actual discovery of the caves of Lascaux, and we come to appreciate the wise and heartfelt dedication, dually offered to "owl biologists" and to "those children who understand the need for secrecy."

LAND OF HEROES: A RETELLING OF THE KALEVALA, by Ursula Synge. Atheneum ($6.95). THE DAYS WHEN THE ANIMALS TALKED: BLACK AMERICAN FOLKTALES AND HOW THEY CAME TO BE, by William J. Faulkner. Illustrations by Troy Howell. Follett Publishing Company ($7.95). THE MAGIC ORANGE TREE AND OTHER HAITIAN FOLKTALES, collected by Diane Wolkstein. Drawings by Elsa Henriquez. Alfred A. Knopf ($6.95). THE LION SNEEZED: FOLKTALES AND MYTHS OF THE CAT, by Maria Leach. Illustrated by Helen Siegl. Thomas Y. Crowell Company ($6.50). Dipped from the wide lake of the folktale, these four books are all first-rate reading and are of course well suited to being read aloud (although younger listeners will not be able to follow the sophistication of the folktale forms). In the Finnish tongue "land of heroes" is *Kalevala*. This book is a fine modern version of the Northern epic, full of profundities no less than roaring incidents among shamans and smiths, salmon and magical mills, Pygmalion brides and wonder babes. A summary would be absurd; the story is as old as the coming of iron and grain, closer to the simpler societies of hunter and farmer than to the aristocrats of Olympus, gods over a world of royal palaces and statecraft. "Vipunen sang of the earliest men and how they tamed the wild dogs from the woods.... He sang of the hunt and of the magic that exists between a man and a bear when each confronts the other and knows that one of them will die." Strong stuff but nourishing.

Dr. Faulkner, a folklorist well past 80, recounts in standard English two sets of fine black American folktales, which as a boy of 10 in coastal South Carolina he heard from the lips of Simon Brown, a former slave and a master storyteller. The first part of the book reports Brown's tales of slave life, a chronicle of courtship and witchcraft, of community solidarity, wit and religion. The bulk of the pages retell wonderful stories of Brer Rabbit and the animals of the Pee Dee River swamp, freed from barriers of dialect and given the dignity they deserve, without any loss of the trickster's sharp wit and plain fun. The tar baby is here, a clever trick but one topped by Brer Rabbit's last wish: to be thrown anywhere except into that awful briar patch! The ink drawings are attractive.

The Kalevala was collected long ago, and Simon Brown too is long gone. The Haitian tales collected by Diane Wolkstein come to us translated from the Creole but otherwise right from the storyteller's mouth; each is vivid as to time and place of collection within the past few years in that impoverished but lively countryside. There are acting, catchwords, songs and music, tales happy and scary, clever tricks and foolish failings—all in a magical world. It is a relief to learn how the last tiger in Haiti, a witty and powerful voodoo master, met his end at the hand of a hunter with a secret name, since when there have not been any tigers in Haiti! The illustrator, a self-taught Paris artist of worldwide reputation, has caught the feel of the stories in her black-and-white scenes, which are pretty magical too.

In *The Lion Sneezed* small, elegant woodcuts deck a little book packed with cat praise and cat lore from around the world, including a number of works by no means of folk origin, such as a long poem ("My Cat Jeoffrey") from an 18th-century English poet, Christopher Smart. The scholarly apparatus of this book is itself the start of an education in folklore.

ANNO'S JOURNEY, by Mitsumasa Anno. William Collins and World Publishing Company ($7.95). The lone rower lands on a quiet point, where a stag watches him warily. He journeys on foot and by horse through 20 carefully painted two-page watercolors, to leave as quietly as he came, across the ridgeline of the stubble fields at the hour of the Angelus. Not a word of text has appeared. One final page of text quotes the Tokyo artist and describes a little of what the happy reader can find as he pores over the pages. "I followed the path wherever it went, up and down hills, across rivers, through fields which spread out into great open spaces.... In the forests there were deer and in the river there were trout. At the end of the

The ingenious ways a Mercedes-Benz captures the wind-and uses it to improve visibility and comfort

For the engineers of Mercedes-Benz, shaping an aerodynamically "clean" car body is only a first basic step.

Their years of wind tunnel experience and the study of automotive aerodynamics have led them to an ingenious second step: harnessing the airflow that swirls constantly over and around a moving car and putting it to efficient use - outside and inside.

Window-cleaning wind

For instance, it wasn't enough for the engineers to give the driver as much side and rear glass as possible, for optimum visibility. They also wanted to keep that glass as clear as possible, come rain or slush or grime. And they went into the wind tunnel in search of ways.

One way can be seen in the unique moldings that frame the windshield, side and rear windows. They actually form an aerodynamically sophisticated *ducting* system, carefully angled and channeled to help divert the airstream away from the side and rear window glass - whisking rain, slush and grime elsewhere.

A fence with a difference

Even the rub rail - that horizontal steel and rubber strip on either body side - is meant to play its part in keeping those side windows clean.

Wind tunnel tests showed that, if skillfully shaped and placed, it could also serve as a *flow fence*: routing the airflow pattern along the body sides to deflect slush and mud flung up by the front wheels so it can't splatter the side glass.

The engineers used wind-tunnel expertise to control the airflow swirling around the outside rearview mirror. The mirror's windward face is shaped to create an airflow that helps keep the glass free of rain and road film.

Taillights use the wind

Aerodynamic research helped Mercedes-Benz engineers harness the power of the wind to help "scrub" the car's taillights free of slush and mud, keeping them visible longer in foul weather.

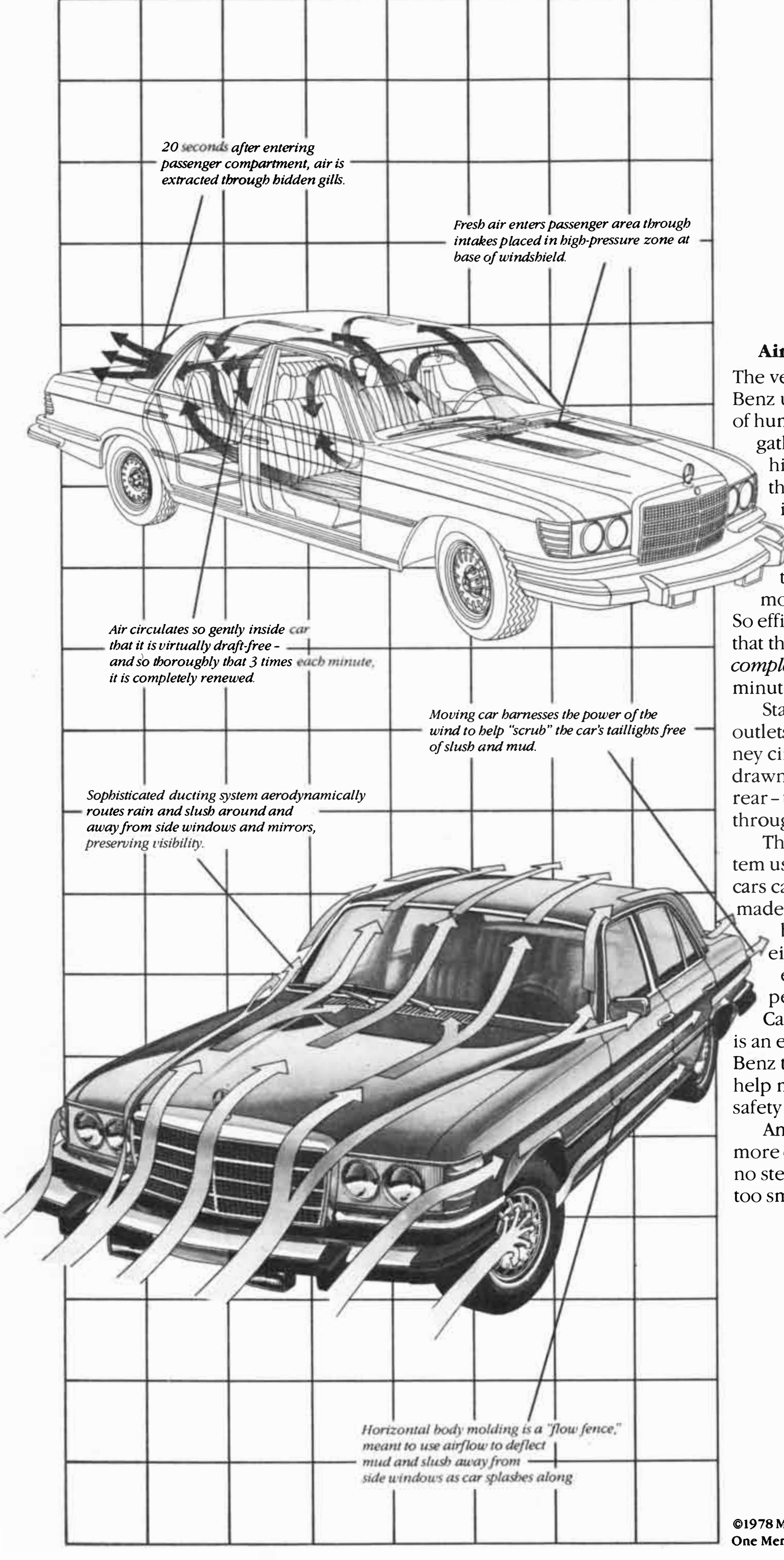
With the outer surface of the rear lights deeply ribbed, the recessed vertical areas remain free of deposits since they are not affected by the circulating motion of the vortex.

A simple idea, spawned only after many long hours of testing in the wind tunnel.

Cleaner windshield - cooler brakes

Aerodynamic principles help keep the windshield wipers pressed fast against the glass as they work. Objective: to prevent high-speed turbulence from suddenly lifting the blades.

The wheels on a Mercedes-Benz are intended less to catch your eye than to capture the wind. Multiple slots in each wheel scoop a steady stream of cooling air to the brakes within.



Airflow you can feel – inside

The ventilation system of a Mercedes-Benz uses aerodynamics in the cause of human comfort. Its air supply is gathered via intakes placed in a high-pressure zone at the base of the windshield, then ducted into the passenger area.

So carefully is the airflow through the cabin regulated that, although constantly in motion, it is virtually draft-free. So efficiently is the airflow processed that the cabin's fresh air supply is *completely renewed* three times a minute.

Starting from numerous forward outlets, the air in its 20-second journey circulates around the cabin until drawn into a low-pressure area at the rear – then is silently extracted through hidden gills.

The bi-level climate control system used in most Mercedes-Benz cars can create a wide range of man-made climates, aided by a radial blower capable of generating eight different levels of airflow – even when the car is standing perfectly still.

Capturing the wind in these ways is an exacting science. But Mercedes-Benz thinks the resulting subtle gains help make useful contributions to safety and comfort.

And in the search for more efficient automobiles, no step forward can be too small.

road there were always houses gathered together to make a town, and in every town there were gates, leading from shops... through graveyards and gardens to churches and cathedrals. One town had a castle...; one castle was a town.... It is a world filled with variety, yet a simple place with a deep-rooted sense of culture.... It is a beautiful world." On Anno's intricate way he passed, it may be, through England and France, Germany and the Lowlands, but he moves also through the imagination as he does through the epochs, past Beethoven and Don Quixote, past the little drawbridge at Arles, past people strolling through a Seurat, past cathedral workmen and castle guards, past vineyards, railroad stations, roof storks, cotton candy, the Pied Piper and the dog who envied his own reflection, past circuses and horseshoers—all amid gentle games, visual puns and jokes. It is all a prize.

GAMES OF THE WORLD: HOW TO MAKE THEM, HOW TO PLAY THEM, HOW THEY CAME TO BE, edited by Frederic V. Grunfeld. Introduction by R. C. Bell. Design, illustration and game models by Pieter van Delft and Jack Botermans. Ballantine Books ($7.95). PASSING THROUGH THE NETHERWORLD, text by Timothy Kendall. With *senet* board in color, throw sticks, wood pieces and manual. The Kirk Game Company, Inc., P.O. Box 478, Belmont, Mass. ($15). Comprehensive, dazzling to the eye, full of challenge and pleasure, the big, floppy *Games of the World* is one of those rich products of a European collaboration, with resources to spare, offering at a modest price the product of a corporate effort no single author could match. The games included, each with a couple of pages of history and rules as the title states, are more than 100 in number, and none is slighted. Board games such as nine-men's morris and backgammon, street games such as hopscotch, field games such as tug-of-war, party games such as London Bridge and tricks such as cat's cradle are all dealt with seriously, giving childish play its adult value. It is all admirable enough, but the visual offerings particularly distinguish the book. Big color photographs from life and museums abound; simply as a book of photographs the work would merit purchase. Eight armed Masai play the game *wari*, each in a natty derby; two Japanese workmen enjoy a game of go on the ground in a little city park; a spread brings us Brueghel's gaming village children; there is even a set of small photographs showing the young men of Sinaloa playing today the game *tlachtli*, once played in the ball courts of Mayan cities for stakes of life and death! If this book has a flaw, it is that the instructions given for making the equipment for many of the games, although they are clear and complete, will not easily yield equipment with the quality of the prototypes shown in the photographs, unless the maker brings to every detail the care and finish seen in the high craftsmanship of these Dutch designers. The games will be enjoyable nonetheless.

The game *senet* was enjoyed by the Egyptians for 4,000 years from the time of the First Dynasty until its pagan structure made it an anathema in newly Christian Coptic Egypt. It is a game for two, a game of chance more than of skill; the moves of the pieces across the board are dominated by fate in the form of a set of four binary dice, as the gods ruled Egypt. The rules are here reconstructed by a young Egyptologist at the Museum of Fine Arts in Boston, with a lively sense of their uncertainty but a fine, fair presentation, of the long line of evidence on which he worked, even to text translations from the hieroglyphics. The board is handsome, with its houses of Hades (bread, steering oars, constellations) based on designs of the 13th century B.C. The wood pieces are colored to simulate blue-green faience; all the material is of good quality. The rules given for the game are clear and brief; remember that "when playing *senet*..., it becomes increasingly more fun to play the more one can divorce oneself from the present."

Making and Finding

ALBUM OF SCIENCE: THE NINETEENTH CENTURY, by L. Pearce Williams. Charles Scribner's Sons ($40). WORLDS WITHIN WORLDS: A JOURNEY INTO THE UNKNOWN, by Michael Marten, John Chesterman, John May and John Trux. Holt, Rinehart and Winston ($7.95). Four volumes, *Les Merveilles de la Science*, edified Parisians before 1870; Londoners could read *Punch* and *The Illustrated London News; Illustrierte Zeitung* came out of Leipzig into many homes eager for the news of *Naturwissenschaft*. Here is a full album drawn from such period sources: 600 carefully chosen pictures, cartoons, maps, diagrams and photographs with well-informed captions compiled by a historian of the science. It was a time of heroism and yet one of certain misgivings. Here are charts of the canals of Mars, the embryology of a woman's face, the befurred party under James Ross that first reached the north magnetic pole (their dip needle pointing straight down), the life history of the dread anthrax bacillus (right from Robert Koch himself) and thumbnail drawings of 160 animal links in the great chain of being from germs to Adam and Eve. This is no child's book—note the price—but the first splendid volume of a five-volume series, a major reference source for the iconography of science under the general editorship of I. Bernard Cohen. But this volume offers such a grand sweep over the era that formed our world it is to be urged on any library where young readers might search through it.

The second book, *Worlds within Worlds*, is also a ransacking of the scientific images of a time, compiled by science journalists and picture specialists rather than by a historian. The time is our own, perhaps the past decade. The aims of the two books are not the same, and the differences leap to the eye. Color is everywhere in today's world of images and was much scarcer in the 19th century. (Victorian color lithographs are absent from *Album of Science* for technical and economic reasons.) In the 20th-century book, however, there are no cartoons or artist's comments, although the captions have a pop content (not always very credible), with a lot of anxiety, say about "a virtually unstoppable epidemic" or the licensed lethality of cigarette smoke. No single person appears, no scientist or even an astronaut, although a few human beings serve as subjects for this or that new imaging system. The affect has changed, become wry, although it is still deep in wonder.

Not all the new images are novel; some are well-known favorites, such as the strobe-frozen crown and jet of a falling water droplet in 15 color frames. Consider Niagara Falls in false color from the air, and a marvelous suite of scanning electron micrographs: ants and flies and a fly-ash sphere of spheres. (Pollutant art?) Here are a night shot of western Europe from orbit, London and the Ruhr ablaze with light, a color-coded image of colliding galaxies, an airport from the air in thermal infrared, showing in the lineup the heat print of a plane that had already taken off. These 200 pages are a bargain; a final few pages of text offer a simplified introduction to the battery of instruments whose images we see.

VIBRATIONS: MAKING UNORTHODOX MUSICAL INSTRUMENTS, by David Sawyer. Cambridge University Press ($7.95). The vibrations are good. The remark is no metaphor but the literal truth. Let the percussion pitch tube be an example. Cut a length of bamboo without nodes. Balance the hollow tube on your finger to mark the place where you will file a slot. When you have cut through into the cavity, test the sound of the two notes that arise, one from a tap across the open end of the tube and the other from a tap on the side of the tube near the end. The first note is the cavity tone, and it will rise in pitch as you slowly file. The second is the vibration of the wood, which is weakened by the slot, and it will descend as you file. File and test until the two tones coincide and you will have a pleasant percussion instrument, played by striking it firmly with a heavy wood beater. Bamboo, coconut shell, tin cans, bits of wood, nylon thread, glues and care produce the score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of music makers here described, with a clear and detailed set of instructions for each one. Each account is graced by photographs, drawings and simple explanations of the acoustics. (The pitch measurements seem much too accurate for the dimensional tolerances implied.)

With a small arsenal of these instruments any group of people who can keep time are ready to try the improvisations, repetitions and patterns out of which a pleasurable and instructive musical experience can grow. The author is a British musician and sculptor. His artistry and enthusiasm are apparent. American readers will find a few puzzles of translation, and they will need to find a domestic dealer in bamboo as helpful as the Bamboo People in Dorset.

NATURALLY POWERED OLD TIME TOYS: HOW TO MAKE SUN YACHTS, SAIL CARS, A MONKEY ON A STRING, AND OTHER MOVING TOYS, by Marjorie Henderson and Elizabeth Wilkinson. With crafts illustrated by Martha Weston and photographed by Tom Liden. J. B. Lippincott Company ($12.95 hard cover; $6.95 paperbound). The source is a battery of Victorian boys' how-to-do-it books, the means is a set of three dozen convincingly practical descriptions with full-page assembly and detail drawings, plenty of photographs and a few period engravings, and the yield is a circus of unlikely and endearing devices. There are, besides the items of the title, a rubber-band Ping-Pong-ball cannon, a Cartesian diver that simulates an old-style balloon, a marvel of a sand-driven acrobat, called Leotard after a 19th-century French aerialist who is also celebrated by a one-piece garment. A squadron of sun yachts sail delicately around their nail-point bearing when the assembly is placed near a sunny window, or indeed in the slightest draft. There are kite messengers, dolls that jiggle on a washing-machine top, a model of Hero's engine and lots more. A short treatise on soldering (not at all for circuit builders) is included. This is a first-rate guide for the brave in heart, with a wide span of challenges for girls and boys old enough to burn candles and use tin snips safely. The authors have really done the things they explain, although they are not always aware of the antecedents of their work in the physics demonstrations of yesteryear.

THE LONG AGO LAKE: A CHILD'S BOOK OF NATURE LORE AND CRAFTS, written by Marne Wilkins, illustrated by Martha Weston. Sierra Club Books/ Charles Scribner's Sons ($8.95). Around an unpretentious and engaging set of summer memories of a childhood in the Wisconsin lake country (including a secret muskie-filled lake up north among Chippewa friends) the pilot-weaver-artist arranges a couple of dozen instruction pages, clear and completed with many small line drawings, each page outlining a craft skill a serious young person can gain. The audience foreseen is handy kids in the upper elementary grades and their friends. Samples are, for woodcraft, a reflector oven, workable; for the ancient arts, a clay pot to be fired without a kiln, in the fireplace or outdoors, well tested; for high technology, a good geometrical road to a sundial, and a nifty heliograph. Altogether attractive in style, content, form and the sense of knowing a remarkable personality, the book offers much wisdom and lots of fun. Don't smoke ground-up acorns!

There is a fine index of crafts.

THE FARM BOOK, by Charles E. Roth and R. Joseph Froelich. Pictures by Russell Buzzell. Harper & Row, Publishers ($4.95). A FARM, with paintings by Carl Larsson and text by Lennart Rudström. G. P. Putnam's Sons ($6.95). Overlook the bend of the broad blue Connecticut River where the leaf tobacco stands by the acre, all shaded by wide stretches of thin cloth. Or take a pheasant's-eye view of the farmer on his tractor disking the field of buckwheat. The small but richly packed book by Roth and Froelich amounts to an informative field guide to the farm of today, chiefly realized in the richer lowlands of New England. There is a look back, to a horseshoer, yoked oxen and a deft spinster, a look belowground at the turnip, the parsnip, the beet and the potato as they grow, a drawing of each of the four wheat varieties against a wide view of strip-cultivated wheat field, and a bonanza of plants and animals farmers grow, together with those that simply dwell around woodlot, pond and farm. The hawks and owls ("flying mousetraps—day and night shifts") are admired, and the little burro and the motherly Hampshire sow look out of these paintings each in full character. For city people who want to know a little about the land and its use, particularly as they drive through the countryside, and for rural families who would enjoy a celebration of the farm of today this joint work by three men associated with the Massachusetts Audubon Society Drumlin Farm just west of Boston is a bountiful harvest of fact and image in small space.

The second book, *A Farm,* is a tour de force. Carl Larsson was an influential Swedish artist whose sunny and lovingly detailed paintings record the happiest rural life in Sweden as the century turned. This volume presents almost the full repertory Larsson painted. There he is at the easel in the snowy barnyard, with long white smock and straw hat, following the work from ice cutting on the frozen lake through hand sowing the oats, the sower's gesture and stance as old as agriculture, to the women and children gathering the potatoes from where they lay turned up by the wood harvest plow and ending with the long table of Christmas Eve, the fruit of the year set before happy folk around the roaring fire. The pictures and text both celebrate this way of life, seen sharply but always from a full heart, and they document an evolved technology when the machine was new.

Flailing and winnowing on this provincial farm were no longer done by hand, with men swinging the heavy flail and pitching the threshed rye high into the air within the barn. Now there was a new machine for each task, one powered by a belt driven by a horse outside the barn, the other cranked by the farmer. Hay and rye bread—solar power!—fuel the farm. Specialized hand tools, iron castings, steel blades and timber frames, few of them designed and built far from the farm, characterize the technique. Although the dark side of this busy and ordered life stays in the shadow, the poignant celebration should delight many a family.

THE TWELVE MILLION DOLLAR NOTE: STRANGE BUT TRUE TALES OF MESSAGES FOUND IN SEAGOING BOTTLES, by Robert Kraske. Thomas Nelson Inc., Publishers ($5.95). Can there be anyone who walks the beach so unromantic as not to hold the secret hope of a bottle cast up with a message? That hope is in no way unreal. It is even sanctioned by antiquity: the oceanographer Theophrastus asked Greek ship captains to drop sealed bottles into the Strait of Gibraltar, to demonstrate by their drift that the blue Atlantic waters fed the Mediterranean. Benjamin Franklin's cousin, a whaler captain, carried out Franklin's scheme to map the Gulf Stream by notes in sealed bottles. Such projects continue and abound; investigators at the Woods Hole Oceanographic Institution alone, for example, have for decades set adrift from ships, oil rigs, blimps, yachts and Ice Patrol vessels more than 10,000 bottles a year off the East Coast. About 10 percent are returned, nearly all found on that same coast. On the Pacific coast the return is smaller, only 4 percent. Of those started offshore on the East Coast, fewer than one in 1,000 have been found overseas, a voyage that takes a bottle about a year. In the Pacific a brave and lucky bottle can drift from the west coast of Mexico along the old route of the silver galleons to the Philippines in about 18 months.

The twelve-million-dollar note? It came as a most idiosyncratic will, under litigation for years, with the outcome not yet reported. In drift bottles are the stuff of rescues and marriages, solutions to sea mysteries, mementos of mariners long lost or happily safe ashore. Bottles that are carefully loaded to ride just awash, to drift not with the wind but with the water, usually become overgrown by organisms and sink within a


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year, unless they are first washed ashore. One bottle, however, was reported after 150 years adrift! Some bottles offer rewards, from half a dollar up to a unique $1,000; some offer moral advice. This small study is an out-of-the-way pleasure. There can be no doubt that the author is veracious, but one wishes he had given us some of his documentation.

RAINBOWS, HALOS AND OTHER WONDERS: LIGHT AND COLOR IN THE ATMOSPHERE, by Kenneth Heuer. Dodd, Mead, & Company ($5.95). With excellent photographs and period prints of real style this text for readers in the middle grades tells about sunsets and twinkling, rainbows and mirages, twilight, blue sky and the sun "drawing water." There is no mathematics; not even a geometric diagram is to be found (although angles are mentioned). Still, the phenomena are made to appear both graspable and wonders yet to be sought out. The red rainbow of sunset, the shadow of the Empire State Building in the fog and the subsun seen from a balloon are hard to forget. This small book deserves the praise of remarking that it is a worthy introduction to the simple but quantitative masterpiece by M. Minnaert: *Light and Color in the Open Air.*

HOW BIRDS FLY, by Russell Freedman. Drawings by Lorence F. Bjorklund. Holiday House ($6.95). DESIGN FOR FLYING, by David B. Thurston. McGraw-Hill Book Company ($14.95). Brief, thoughtful, convincing, *How Birds Fly* makes clear what we know and do not know about bird flight, without any mathematics but with careful analysis in words of the needs and task of flight. It has simple diagrams, no less than whole-bird pencil drawings, of real utility and beauty. Feathers, muscles, weight, the wing slots and the propellerlike sweeping motions are made real for young readers. Gliding, soaring and hovering flight are distinguished from the strong wing-beat form in an introduction that does not demand too much and yet satisfies. The simple Bernoulli demonstration—blowing over the curving droop of a page held before the lips—is the earnest of a book that genuinely increases understanding.

Human beings fly quite differently. In *Design for Flying* an experienced consulting engineer–author, a man with the design of fighters and of personal airplanes to his credit, tells how they do it nowadays for a wide variety of general aircraft, from the little single-engine four-place favorites to crop dusters and seaplanes. This is genuine engineering in a complex but well-surveyed context. The convergence of design ("aircraft designed for the same use are becoming so similar in appearance that it is extremely difficult ... to tell them apart") is made understandable by careful discussion of the requirements for any type of plane. Handling, performance, structural loads, power plants and even exterior finish play a role in the final design the engineer must consider.

The blend of quantitative analysis and ripe experience, of pilot preferences and ways to lessen the risk of error and temptation, the key role of certain dimensional choices—all are served up, with a liberal use of graphs and some need for algebraic literacy, in a model of engineering know-how and informality of exposition. A sampling of the graphs will give a feel for how 70 years of human experience can emulate 70 million years of natural selection: load factor v. bank angle, thrust and speed envelopes, load weights v. vertical moments, altitude v. horsepower, propeller thrust v. propeller-tip speed and of course much more. Engineering is here made plain, the rational choice among the options offered by a complex and shifting context, a design freedom that is the imaginative recognition of necessity. Older readers with an interest in any branch of engineering, if they have some feeling for flight, will thrive for a long time on this example of what good design means.

Shiny airplanes are out of style: the oxide finish of that aluminum-clad alloy sheet would not, after all, last forever, and color contrast, not a mirror, makes for better visibility in traffic. Then too the pull of wartime camouflage accelerated coating development. Thus does design evolve, in a world too complex for prediction but perhaps just amenable to the knowing decisions of the designer.

Form and Symbol

FIGURING: THE JOY OF NUMBERS, by Shakuntala Devi. Harper & Row, Publishers ($6.95). "At three I fell in love with numbers." Now quite grown up, this Calcutta calculator travels the continents displaying her powers over armies of digits with a loving but firm hand. The jacket shows her in performance: rapt in thought, she is working out the 23rd root of a 201-digit number. That took her 50 seconds. Now, no young reader will gain such a prodigious talent from this small book of arithmetical agility. But much can be gained, not least a feeling for insightful mental arithmetic. That requires some clear analysis of each task, some preparation and a head for figures. The last can be supplemented for most of us by an external memory: pencil and paper.

The combination can give the ubiquitous little boxes of keys and chips a run for their money, at least on carefully chosen grounds. Suppose someone sets you to taking fifth roots of numbers with not too many places. ("When a number has been raised to the fifth power, the root is surprisingly easy to find.") A root of two digits produces a power with between six and 10 digits. The units digit of any fifth root is the same as that of the power, and so you may have only one number to find. A table of fifth powers for the 10 digits helps to produce the fifth root, say of 1,073,741,824, very fast indeed, and Ms. Devi tells just how. She offers a lot of commonsense schemes for the four arithmetic processes around the digits themselves, with easy reformulations of factors and divisors, simpler algorithms for adding long columns with carrying, check schemes such as casting out nines and a lot of organization and tables for the purpose of showier root taking and manipulation of the calendar.

In this chip-happy world the energy of these simple schemes sounds a cheerful note of dissonance that will be welcome to many caught by numbers. It is all quite elementary, whole numbers only (except for a page or two on pi), and only a few properties go beyond the early grades. A couple of dozen agreeable, if mainly familiar, tricks end the little book. There is a flavor of India in the examples, but it is subtle; arithmetic is universal. Can you write 1 using all 10 digits? It is not hard.

SPEAKING OF CHINESE, by Raymond Chang and Margaret Scrogin Chang. W. W. Norton & Company, Inc. ($10.95). *Man, homme, hombre* and *Mensch;* meaning remains although the strings of symbols vary across a continent. On another continent they say *rén* in Peking, *yan* in Canton, *nin* in Shanghai, *in* in Seoul and *hitoh* in Kyoto. Old Confucius would have spoken it still differently. But all those speakers in the Far East would write the same form in careful strokes. Chinese students at Columbia order their favorite dishes with pencil and pad; the waiter speaks only Cantonese. The students are likely to speak only Mandarin, and so they discuss the menu in English and write out the order in the common forms.

This pleasant, unpretentious account by a young chemist and his writer wife is in fact a small stream leading to the ocean of the culture of China by way of its language. Radicals, stroke analysis, hybrid, iterated and rebus characters, differing forms of romanization, ambiguities in the tones of speech, oracle bones and seal writing—all find a natural place in the low-key account. Chinese dialects are mapped, and we follow an imaginary Peking traveler as he struggles with each new speech. The gradual spread of standard Mandarin (*pŭtōnghuà,* common speech) and of the current *Pīnyīn* romanization under the Peoples' Republic are described.

Language of course is politics in China; it is plain that the government in Peking is not seeking to erase old dialects overnight. "The Chairman himself did not speak perfect *pŭtōnghuà,* and took pride in the individuality of his provincial Honan accent." There is a page about the water-gas reaction from a textbook; chemical formulas look as much at home among the characters as they do in English. A homely account of domestic life includes nicknames, kindred, proverbs, foods, colors and a few jokes, and then we read a brief history of printing. The Chinese treasured the color red long before it suffused the East politically. Wedding dresses are red, gift envelopes are red, festive candles are red. A performer who is in vogue is said to be very red, and of a superstar one says *Hóng dé fā zì*, "He's so red he is beginning to look purple."

A dynasty list, a little historical table, a dictionary of 100-odd characters arranged by strokes and a list of animal birth years and their significance close this easy once-over of some of the more familiar attributes of the most pervasive cultural pattern in all human history. One is entitled to some skepticism about the Changs' crystal ball. There are plenty of reasons for the beautiful old characters to survive the coming of the typewriter and the dictionary. Modern technology is beginning to replace the Procrustean bed of type with subtler ways of making marks on paper. And it is not plausible that mastery of classical Chinese will soon vanish from the Central Realm. The list of readings is excellent, a real giant step from this small-scale beginning; we miss an index. Any good reader could enter this open door.

CREATING ESCHER-TYPE DRAWINGS, by E. R. Ranucci and J. L. Teeters. Creative Publications, Palo Alto, Calif. ($6.50). In simple, steadily more demanding chapters, with plenty of bold diagrams in black, white and red, the authors lead a serious reader through the idea of the tessellation of the plane to the transformations of planar symmetry (exemplified by the alphabet) and on to the wonderful techniques of the late M. C. Escher. One starts with simple tile forms and modifies the polygons into forms of interest under the operations crystallographically allowed in the plane: translations, reflections and rotations. After five chapters some pretty interesting designs emerge, to be compared then with four or five of the master's examples, analyzed along the same lines.

A needed chapter on imagination opens the way to the free use of a set of work sheets that might make easier some of the repetitive steps involved. There is no certain road, of course, to such flights as the flight of geese into farm fields, forever stitching the city of night to the city of day, that quicken Escher's own most famous tessellations. The book ends with a few pages about the artist and a list of references. It is an inviting path to this important portion of Escher's work, and a fine long encounter with the structure and richness of plane symmetries. Dr. Ranucci was a talented teacher of mathematics among mathematics teachers; this posthumous work is a valuable legacy.

MATH IN NATURE POSTERS, with a teacher's guide by Alan Hoffer, color photographs and a paperbound brochure. Creative Publications, Palo Alto, Calif. ($6.95). A dozen foot-square color photographs, only one with text, bright and crisp on rather light poster stock, are suited to add visible excitement to classroom or study. They present the classical examples: the logarithmic jewel of the nautilus shell, the radial net of a spiderweb, the crowded scales of a pinecone in elegant sequence, an armored starfish pentagon, mineral crystals, snowflake forms, bubble clusters and the like. The forms are full of rewards; the brochure offers a rather flat page or two about each image, with little to say of nature beyond the basic diagrams and formulas that tie these objects to classroom algorithms. Not enough is said to explain what we see; the bees are shown at work, it appears, not on their own hexagonal comb but on a man-made foundation sheet; the garnets are in a natural matrix, and other minerals are not identified at all. The books referred to are good, but otherwise the value of this set lies in the pictures, not in the text.

Fin, Fur, Feather, Flower

FLYING FUR, FIN AND SCALE: STRANGE ANIMALS THAT SWOOP AND SOAR, by Mary Leister. With illustrations by Tony Chen. Stemmer House Publications, Inc., Owings Mills, Md. ($9.95). A frog, an amphibian, is quite likely to have webbed feet. In southeastern Asia, however, some 50 species of frogs have lengthened toes, arrayed in a still wider web, and swim the air—triphibiously. "They don't glide far, perhaps thirty or forty feet at a time," but their skill far extends their ordinary leap. There are also plenty of flying fish, whose fins are glider wings. They manage repeated hops 150 feet or so across the water. Often merely touching their tail fins to the crest of a wave and vibrating them "like gauzy outboard motors," they take off again and again, as many as 10 times before they submerge. Usually they fly to escape predators.

Here too are webbed lizards and the golden tree snake, another creature of the steaming lowlands that glides to definite target tree limbs for a landing. It uses its strong coiled muscles for the takeoff; flattening its 100 ribs so that its normally cylindrical body is rigidly flat, the snake glides like a long weighted leaf to the mark. Look out for flying—and venomous—snakes! Marsupials, lemurs and squirrels all have forms that fly in the gliding way. Perhaps in the fullness of time these animals will evolve to powered flight; we cannot know, because there is no trace yet of flight-muscle engines, even in their faintest beginnings. After all, did not the agile bats, well-instrumented fliers all, begin with mere webbed fingers? The text is crisp and easy reading, never condescending.

The color illustrations of these wonderful creatures are outstanding. Chen manages to offer meticulous detail and the sense of animal individuality of form and pose while giving his compositions interest, grace and strength apart from their subject. They are bright and sharp, animals held against striking backgrounds, sometimes simply white for emphasis (the bats are shown once in darkness) and sometimes in an appropriate natural texture.

INSECT MAGIC, photographs by Kjell B. Sanved. Text by Michael G. Emsley. A Studio Book. The Viking Press ($16.95). The colorplates of this tour through the million-species zoo of the insect world are luminous and strange. No drab bugs or series of similar insects are to be found here; the subjects are reproduced, mostly larger than life, for their spectacular color and form by the photographer of this partnership. He travels the world for specimens to match his vision; the shots are made in natural light, mirrored sunlight and flash. Eighty-odd pictures sample the forms and colors of the insect world, from the page-long head of a green katydid with the false pupil made by its compound eye to an absolutely ceramic Australian beetle glazed in scarlet, yellow and black. The pages are almost like paintings.

The text is an essay that now and again looks perceptively at insect life but is actually an expression of delight and the confessions of an addict, a collector in the name of science. Once an English schoolboy cycling to the fens a dozen miles away to swing his net tirelessly after butterflies, now a professional tropical entomologist at George Mason University in Virginia, Emsley served as resident director at the William Beebe Tropical Research Station in Trinidad. He is full of tales of that collector's world. Intimacy with insects includes eating and being eaten. The Yukpa on the Venezuela-Colombia border find the huge rhinoceros beetle particularly delicious, "not because of its flavor but because it contains a lot of meat." In fair exchange Professor Emsley recounts his leaving a maggot of the human botfly within his wrist for a few days to grow into a more impressive specimen. He lost his nerve and extracted it, only half an inch long yet worthy of being labeled with the modest but immortal record "Removed from the skin of MGE."

Once he took a most unusual specimen for help in identification to a museum, there to consult an elderly "very

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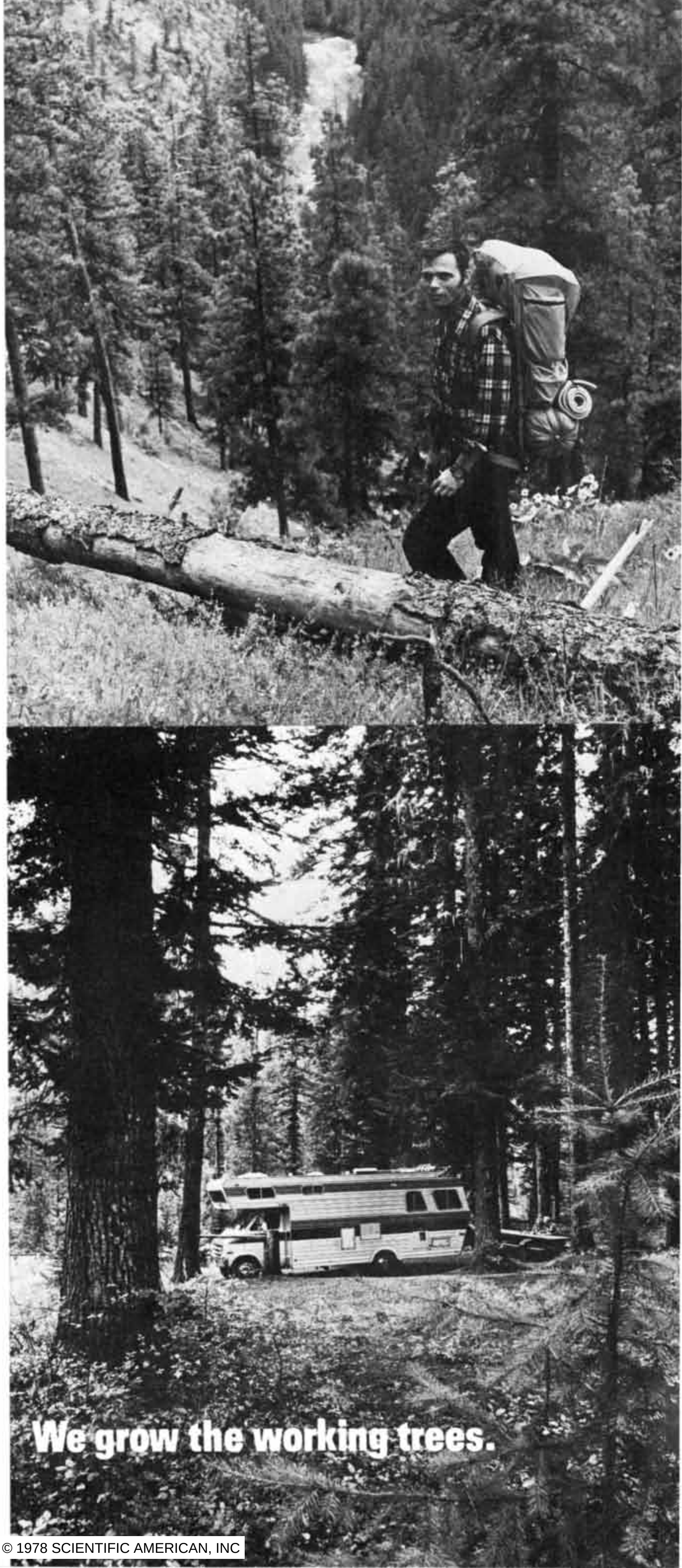

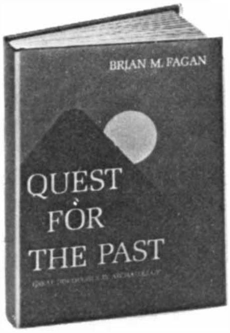

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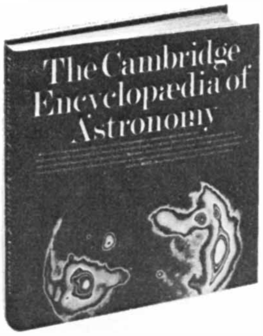

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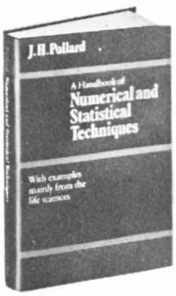

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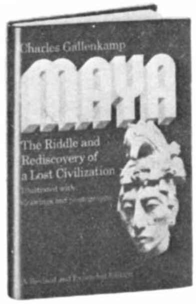

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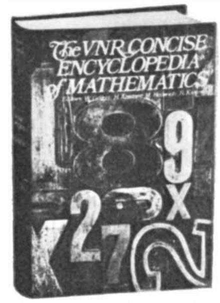

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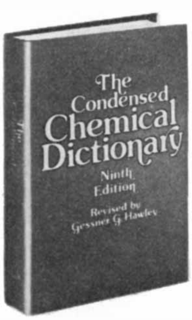

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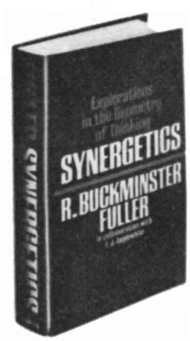

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revered entomologist." Somehow the little specimen was lost before it could be returned. The elderly entomologist was terribly sorry. Poor Emsley had found only one such bug in 10 years of hard collecting in Trinidad. The museum staff was only amused by this unhappy accident: the old savant, no less fanatical a collector than Emsley, had been "up to his old tricks." Museums privately blacklist certain collectors, who must be chaperoned whenever they visit. Only the obituaries of such enthusiasts bring their removal from the list, whereupon their collections usually rejoin the holdings of science. Entomologists are apparently long-lived, happy as long as they can still see, and they make an imperceptible transition into retirement. We wish Professor Emsley and his colleagues a long spell of work; they have made a volume that views the intricate, dark, creepy and warring insect world as a treasure-house of bright splendor and pursuit.

A SPIDER MIGHT, written and illustrated by Tom Walther. Sierra Club Books/Charles Scribner's Sons ($7.95). THE SPIDER'S WEB, by Oxford Scientific Films. Photographs by Dr. John Cooke. G. P. Putnam's Sons ($5.95). Tom Walther pushes our ideas of empathy to the limit. On each left-hand page is a detailed and rather elegant drawing and opposite appears a paragraph of text. But the drawings alternate; half show a boy and a girl performing in some unusual way, say strutting cheerily with big plumes. On the next page you find some spider, drawn even more particularly with the same property. Here we see the plumed palps of the Eastern jumping spider *Phidippus audax*. (Scale is of course strongly suppressed.) The comparison can be grotesque, for example one page showing two kids each with eight eyes and the next page showing nine named spider faces each with six or eight eyes.

The book ends in a more matter-of-fact vein, with a brief chapter on finding spiders and a field guide to common forms, with drawings but now also with little life-size silhouettes. The most attractive drawing is a kid's view down past a pair of shoes and a tree limb to the ground below, where one sees a neatly dressed Miss Patience Muffet holding her dish. No polite person would do what a spider once did! (Patience's father, Dr. Thomas Muffet, was a 16th-century physician who was convinced that spiders were close to a panacea.) The text and drawings alike are artful, but the final effect is not for every reader. Those who are attracted by this sometimes grisly whimsy will surely lead lives unafraid of our friends the spiders.

The other book, *The Spider's Web*, is a slight work, but it holds a couple of dozen beautiful color photographs of a garden spider's orb web in the stages of being woven and also a shot of a net-throwing spider that hunts by dropping a small, neat rectangular array of threads right over an unwary passing beetle.

THE HYDRA, by Dr. Stanley Shostak. Photomicrographs by Dr. Jane A. Westfall. Coward, McCann & Geoghegan, Inc. ($5.96). "To the naked eye a hydra looks like a short piece of frayed string." They are not hard to find in almost any freshwater pond or stream, clinging to rocks or twigs. In a few brief chapters with unusual illustrations, particularly those made with the scanning electron microscope, the text leads us from appearance to function, habitat, movement and reproduction and to the cells and tissues within the tiny jellyfish. The author is a research biologist with an active interest in hydra developmental biology. "Taking hydras apart and putting them back together again" is told in a page; it is surely curious that such an intricate little creature can be regrown from cells separated by gently forcing pieces of hydras through a very small tube. If the unbonded cells are then spun down into a mixed-up mass and given fluid containing antibiotics and the right salts, new hydras form in a few days. At first they are a misshapen lot: cells from head ends make new heads and cells from the foot form feet, but several heads and feet generally begin in the same mass (or mess). The monsters break up soon, and somehow quite normal hydras manage to sort themselves out.

Hydra harpoons, hydra tentacles, hydra buds are here in the pictures. There are a few pages, perhaps a bit skimped for detail, about growing hydras on your own. The writing is simple, if less exciting than the strange animals themselves.

TYRANNOSAURUS REX, by Millicent Selsam. Harper & Row, Publishers ($5.95). From at least the second grade on there is a well-recognized enthusiasm for dinosaurs. The creatures are deliciously big and fierce, yet they are harmless—because we do not have them anymore. The great bipedal carnivore of the title is a dinosaur star, Superlizard. In this small, well-illustrated book we read an easy story rather different from the usual didactic reconstruction of a thundering dragon alive, alive-o. We read about and see the Montana badlands, where in 1902 the expedition came from New York to find the tyrant reptile king. We see men and horses hard at work in the hot summer sun. The pelvis weighed two tons, a four-horse wagonload. We follow the mounting and then the easier inferences about the beast: the teeth are pointed for tearing meat; the powerful hind legs and the stunted front ones do not allow for flying, swimming or living in the trees. The beast had to hunt on the land on its two great legs. We do not know what the tiny front legs could do; some students of dinosaurs feel those legs might have reached the animal's mouth, their hooked claws serving to hold its food. We cannot do more than guess the color of the skin: red like a coral snake, green like a turtle or striped? Reconstructions do appear, with the animal itself, some big contemporaries, rivals or prey. Here is a satisfying addition to the dinosaur genre, and one more of this author's 80 first-rate science books for children.

DISCOVERING THE MYSTERIOUS EGRET, words by Jack Denton Scott, photographs by Ozzie Sweet, with drawings by Pamela Sweet Distler. Harcourt Brace Jovanovich ($7.95). For a long time now, at least since the Pleistocene, a large, beautiful white-plumed heron, the cattle egret, has followed and even ridden on the ungulate mammals of Africa. As hippopotamus or elephant feet disturb the ground, insects, particularly grasshoppers, are flushed up, and the cattle egret lazily lunches on them, with surprising economy of effort by actual measurement. Under Mount Kenya the grazing cattle of the Masai also support the lovely egrets, which can be seen from afar rising in "butterfly bursts" above the distant grazing herds.

One sunny day in 1930 a flock of these birds, "shining like alabaster," came down from the sky to walk beside the big Brahma cattle of a herd on another continent: in British Guiana. By 1950 they had become abundant, perhaps unmatched in numbers in some areas of the region by any other bird of comparable size. It is not likely that any zoo had lost such a flock, or that someone had secretly introduced the birds, or that they came hidden in some cattle boat. Most likely, although one still cannot be sure, they flew on a strong east wind from the Old World to the New, the first bird species known in history to establish (or is it reestablish?) itself in the New World without human aid. (The large grazers are post-Columbian too.)

Today the cattle egrets are known all up and down the Atlantic coast, but Florida is their North American homeland. There they live quietly, dwelling and breeding in compact colonies among the native water birds in the swamps, flying out each dawn to feed in the new cattle pastures of the state. Here black-and-white photographs show the egrets nesting and courting, their white eggs hatching fright-wigged chicks, and much more. We miss seeing the color changes of the mating season, when over a few days' time the austere plumed white bird "becomes a tropical beauty," with legs of Chinese red, a bill of scarlet with a golden tip and a skin flushed to scarlet and purple. The photographs and the text are most skillful, and the

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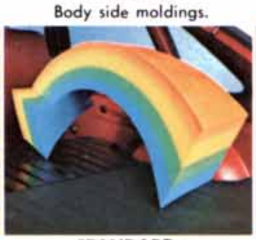

STANDARD:
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STANDARD:
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STANDARD:
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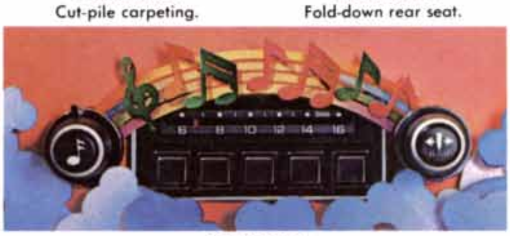

STANDARD:
AM radio.

STANDARD:
Four-foot-wide hatch.

STANDARD:
White-stripe glass-belted radials.

STANDARD:
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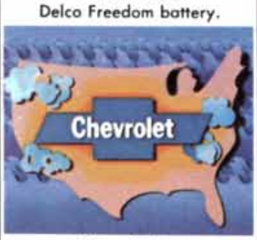

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story is a fascination for the young bird lover and the entire family.

WATCH IT GROW, WATCH IT CHANGE, written and illustrated by Joan Elma Rahn. Atheneum ($6.95). In clear prose and simple line diagrams the author allows us to follow four sequences of life, in forms accessible to serious grade school botanists, young people with greenish thumbs. We see a lilac bud open in March, after we have watched it since before Christmas. Step by step it becomes a green-leafed twig, then leafless and all but dry. Now it too bears buds in the cycle of growth. Similarly, we see an apple blossom of April swell to an apple and drop in July. A Jerusalem artichoke tuber grows in the spring thaw, and by October it has blossomed aboveground and has made new young tubers belowground. Finally, the changes that are quickest and easiest to see for oneself are the maturing of a seed into a seedling, easy and fascinating with a squash or a pea and many other plants not fully described. The last few pages remind the young observer that "plants don't read the books"; any real observation is quite likely to differ from the text. This small, quiet, careful book has the patience of the gardener about it, although its yield is not for the pot but for understanding.

COLOR IN PLANTS AND FLOWERS, by John and Susan Proctor. Everest House, Publishers, New York ($9.95). The sun is source. That energy flux is cunningly absorbed and converted in the wonderful chlorophyll green that clothes Vermont in summer and the tropical rain forest the year round. Some of the energy is used by plants to make a variety of pigments and dyes, held in solution in cell vacuoles, in cell walls or in organelles such as those that contain chlorophyll. Among them are the carotenoids, pigments ranging from yellow through the reds to brown, made in certain plastid organelles. Animals feed on plants and in the course of that dependency take in the carotenoids, which form substances essential for the chemistry of vision. The circle is closed, but the gyres are still more intricate. Having given animals their vision, the plants coax services by the use of that very sense. Insects are brought to flowers by color, scent and form; birds and bats find their way to other flowering plants.

Thus are the flowers colorful, and this delightful and knowing book explains which colors and why. Only the green grass need attract no onlookers; the wind spreads its pollen. The 20-pound flowers of the carrion flower *Rafflesia* (shown here examined by a very reflective Malayan visitor to the forest) look and smell like rotting meat. Larvae placed there by the deceived flies, however, will starve. The tangled tale continues. Fruits are often colorful because animals can spread seed no less than pollen. In Europe there are no bird pollinators. There red flowers are rare but red fruit is common, and birds are major agents of seed dispersal. It is said that the old Dutch nutmeg monopoly was broken by the fruit pigeons, who took the seeds quite illegally far beyond the Dutch-held islands.

This couple of English biologists, in a handsome volume with more than 100 color photographs and diagrams, give a connected inner account of plant life, beginning with the most evident and attractive observables. One remarkable photograph shows an open seedpod of a peony; the many reddish fertile seeds aligned in the pod are set off by a couple of larger infertile seeds of dark blue. The entire combination resembles some strange butterfly and "makes the seeds very attractive to birds." This book too displays its attractions for the mind very cleverly.

ELOQUENT ANIMALS: A STUDY IN ANIMAL COMMUNICATION, by Flora Davis. Coward, McCann & Geoghegan, Inc. ($8.95). A few years ago Lucy, one of the chimpanzee partners of Roger Fouts and Sue Savage out there in Norman, Okla., was in a little trouble. Chimpanzees are hard to toilet train, and when Fouts came one day for the language lesson, "there was a bowel movement in the middle of the floor." Fouts decided to take a stern line for the moment and asked Lucy "What that?" in the standard signs. Lucy did not want to answer. But conversation went on, like this: "ROGER: You do know. What that? LUCY: Dirty, dirty. ROGER: Whose dirty, dirty? LUCY: Sue's. ROGER: It's not Sue's. Whose is it? LUCY: Roger's! ROGER: No! It's not Roger's. Whose is it? LUCY: Lucy dirty, dirty. Sorry Lucy." If an apt lie does not qualify as language, what does?

Washoe, a television personality a few years ago, is now also at Norman. She was born in Africa in the summer of 1965; she bore her own first infant in August of 1976. The infant was born with a severe heart defect, but during the four hours it survived Washoe signed to it! Otherwise she played the part of a good mother. We all hope for another infant to come along.

Chimpanzees seem to "have more intelligence than they really need to survive in the wild." There they enjoy an entire repertory of informal, unvoiced contextual signals that make possible quite elaborate communication. Their communications are deliberate, concept-mapping, able to describe the future and the absent, but they are not yet invariant symbols.

Flora Davis has visited and talked with a wide variety of research people in this remarkably fast-growing and controversial discipline. Her interest was drawn to speech when her own mother began a struggle with aphasia. This is her second book on the general subject, and it is so clear, thoughtful, firsthand and simple that readers of high school age and up should find it delightful. She casts a wide net over the American work in the area, from slime-mold assembly signals and bee dancing to the communication of birds and killer whales. In each case her method is the same: a visit to a research site or two, a personal account of what she saw, a reflective reporting of conversations and the directions of tentative inference. The work carries the reader up to late 1977.

The next to last chapter describes nonverbal signal exchange in our own species, we wordy ones whose transfer of new information is judged to be about five minutes' worth per day. ("The rest is just reassuring one another.") The book ends with a chapter of reflection on definitions and consequences.

ANIMAL FACTS AND FEATS, by Gerald L. Wood. Sterling Publishing Co., Inc. ($14.95). Marvel-thirsty, the public drinks up the Guinness record books with widespread enthusiasm. This lively volume of carefully arrayed, well-illustrated little pieces is one of a family of such record books. It is free, however, of those transient enthusiasms that fill the daily newspapers with whimsical, even silly accomplishments. Here the records are meaningful: weight, length, speed, age and the like, and the record holders are animals, arranged chapter by chapter according to class and phylum, from mammals right through to jellyfish, with a closing chapter on extinct animals. The compiler is a well-informed English naturalist who presents his sources and conclusions with meticulous care and a reasonable balance between enthusiasm and skepticism.

The oldest animal? Plenty of dubious claims are gone into, but what we can believe is that an off-island Marion's tortoise, blind with age, died by accident in a fort in Mauritius in 1918 "when it fell through a gun emplacement." It had been given as a pet to the French garrison in 1766, when it was already quite mature. The creature was at least 180 years old at its death. The fastest animal seems to be the spine-tailed swift of Asia. It has been reliably clocked in the U.S.S.R. at an airspeed of 106 miles per hour in level flight. (Don't believe what you read about the peregrine's stoop at more than 150 m.p.h.) Louis Agassiz himself saw a jellyfish from Massachusetts Bay that was seven feet six inches in diameter. The giant squids get cut down here, perhaps too skeptically, to three tons in weight (the minimum of the estimates of other enthusiastic authorities), but the octopus record is set here at five tons, with rather less than firm limits. The octopus currently appears to have a better press than the squid.


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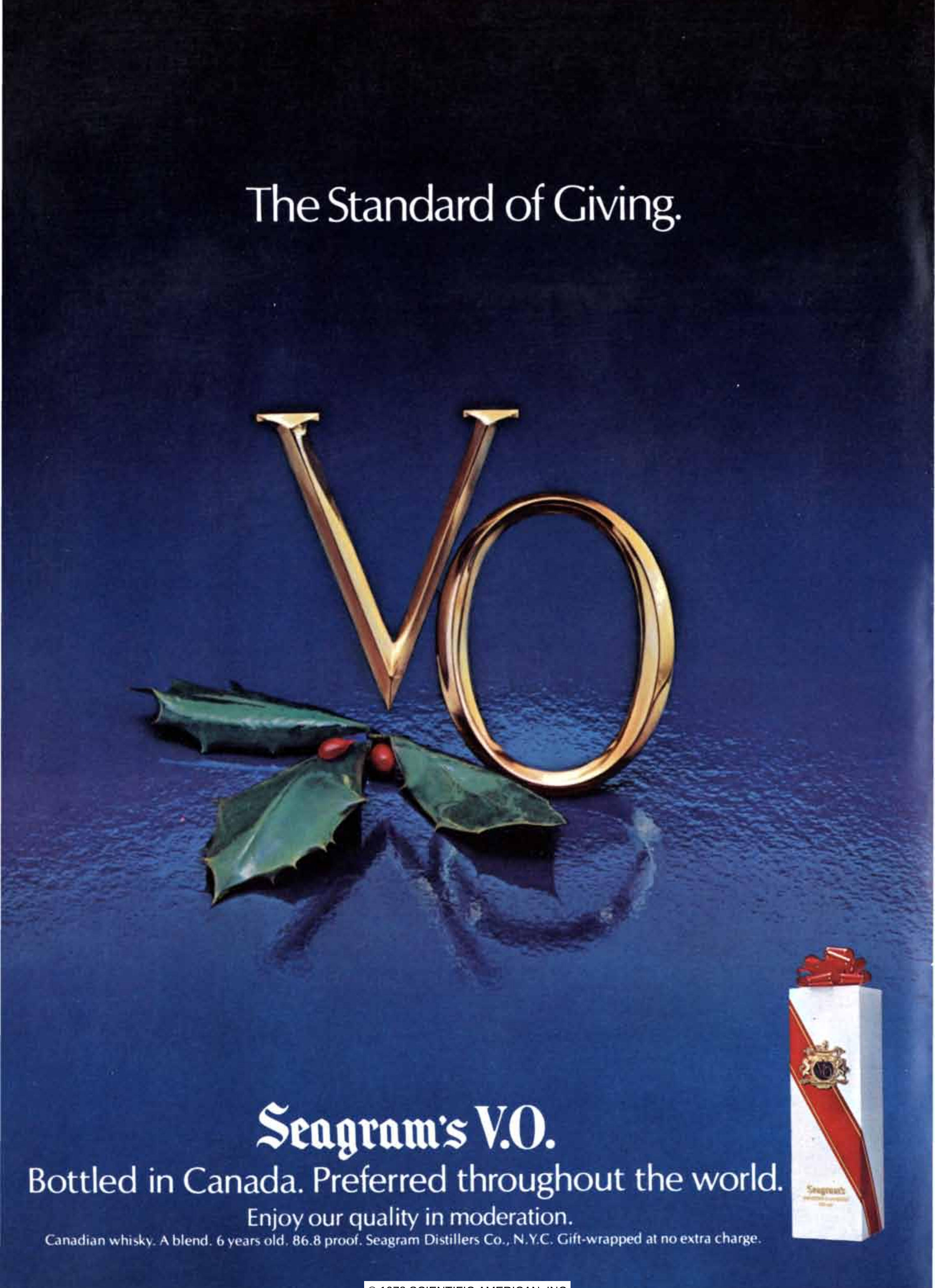
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Marriage and Fertility in the Developed Countries

The decline of the birthrate in the industrialized countries is both a cause and a consequence of changes in marriage and the family. How will nations respond to a long-term decrease in population?

by Charles F. Westoff

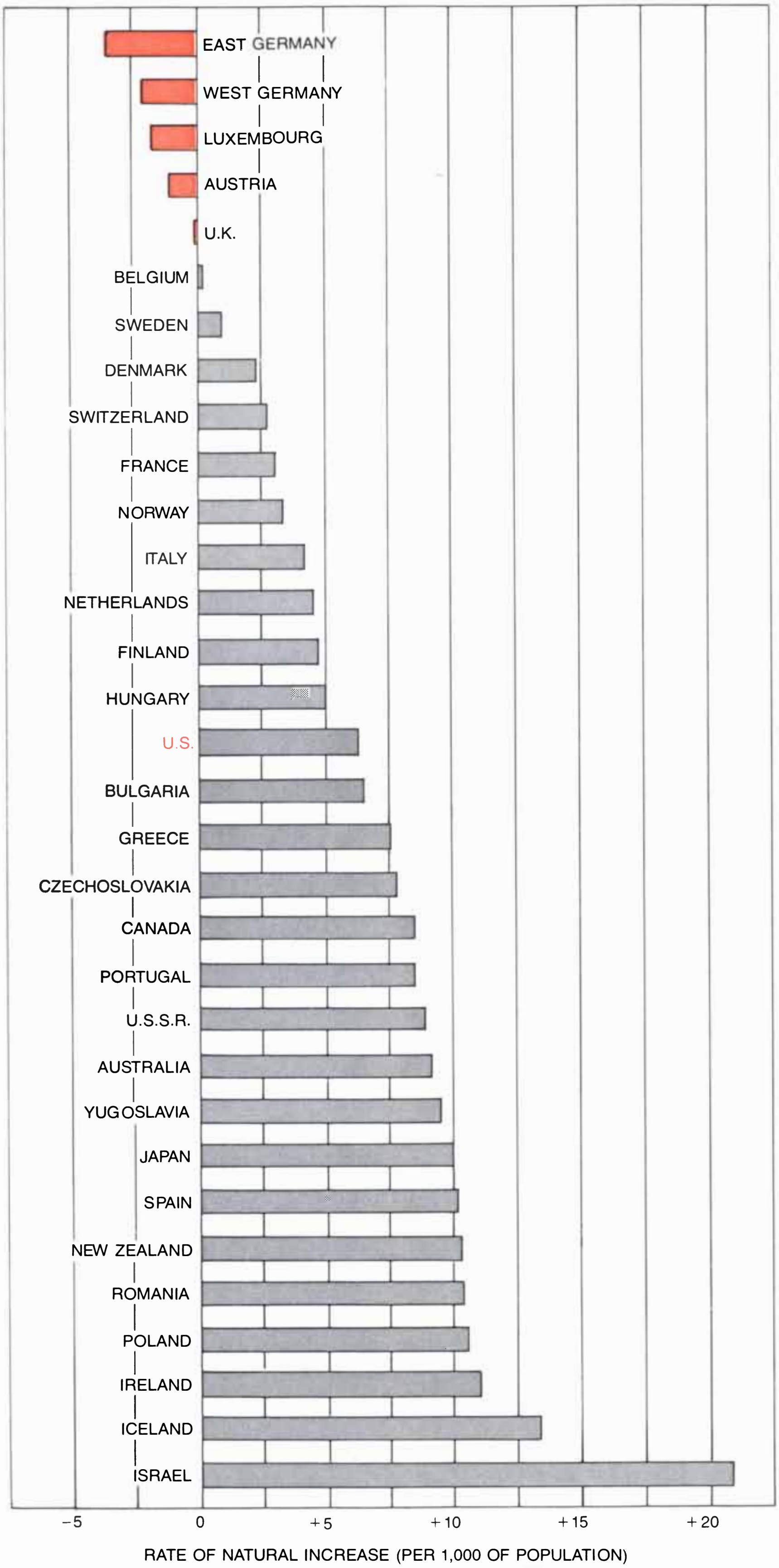
Most of the world's developed countries now appear to be approaching zero population growth. Several European countries—Austria, East and West Germany and Luxembourg—have already gone beyond zero growth: they have more deaths than births each year. The United Kingdom is right at the balance point, with births and deaths about equal. If current trends in fertility continue, Belgium, Czechoslovakia, Denmark, Hungary, Norway and Sweden will reach or fall below zero growth in a few years; Bulgaria, Finland, Greece, Italy and Switzerland will follow by about 1990. If the trends should persist, the population of Europe as a whole and of the U.S.S.R. would begin to decline at the turn of the century and the U.S. population would stop growing in about 2015.

Will fertility indeed continue to decline? One can only speculate, more or less plausibly. Here I shall argue that the low level of fertility is the result of a long-term trend that may continue. And I shall examine some of the current social changes, particularly those affecting the institution of marriage, that seem likely to cause fertility to decline to new lows in the industrialized countries, and some of the ways those countries may respond to an actual or impending decrease in population.

The projection indicating a decline in the European population by the year 2000 assumes that the total fertility rate in Europe will reach 1.5 by 1986 and remain at that level. (The total fertility rate in a particular year is the average number of births women would have over the course of their reproductive life if they followed the rates characteristic of various age groups for that year; it is derived by summing the age-specific birthrates in a given year. The total fertility rate at which a population just replaces itself is 2.1 rather than 2.0, primarily because not all females survive to the reproductive ages. The relatively large size of the youthful population in many countries means that some years of below-replacement fertility are required before a population levels off and begins to decline.) A total fertility rate of 1.5 is below the rates now prevailing in Europe and below the lowest rate known to have been experienced by an actual cohort of women (1.8 for women born in 1907 in England and Wales). Nevertheless, the fertility trend is now on a trajectory that would bring it to 1.5 by 1986. The increased availability of sophisticated birth-control technology makes it increasingly feasible to attain such a low fertility level; everything seems to point in that direction. (Perhaps the trajectory of future reproductive levels is aimed too low too soon, in which case the time perspective may be off by a few decades.)

Because of the sustained "baby boom" after World War II and the resulting bulge in the population of childbearing age, the U.S. (along with Canada, Australia and New Zealand) can expect to reach zero population growth somewhat farther down the road than most European countries. Including legal immigration and assuming an ultimate level of completed cohort fertility of 1.7 births per woman (the U.S. is currently reproducing at a rate implying about 1.8 births), the population of the U.S. would effectively stop growing at a total of about 253 million in 2015. This is the current "low" projection of the Bureau of the Census. Even if fertility should climb back to the replacement level of 2.1, the population would be only 260 million in 2000 and 283 million in 2015, considerably below the 300-million population that only a few years ago was being predicted for the year 2000. The important difference between the projection based on a fertility rate of 1.7 and the projection based on a rate of 2.1 is not so much the 30-million difference in population in 2015; it is that at the lower fertility rate the population would have begun to decline, whereas at the higher fertility rate the population would still be growing at an annual rate of about five per 1,000 of total population. Both projections show considerable growth beyond the current population of just under 220 million because of the relatively high proportion of people in the childbearing years, a result of the baby boom.

Having described these recent projections, I must now admit that the record of population projections has not been a happy one. A 1947 projection of the 1970 U.S. population fell 65 million short of the 205 million actually enumerated. Projections made since the early 1960's of the U.S. population in the year 2000 have ranged from a high of 362 million (a 1964 projection) to a low of 245 million (the latest lowest estimate). The major variable determining such estimates is fertility, and fertility has changed considerably since the early 1960's. In view of the fact that any pop-



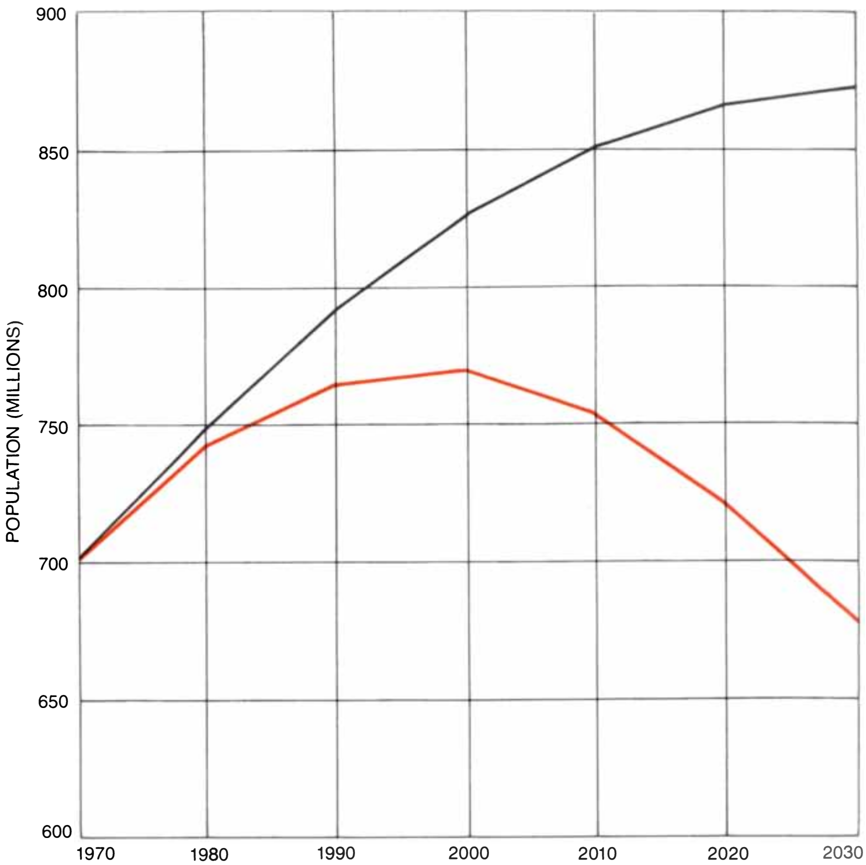
RATE OF NATURAL INCREASE (birthrate minus death rate) is below the zero-population-growth line in a few European countries, and it is approaching that level in most industrialized nations. Data are mostly for 1976; U.S. figure is for 12 months ending in May, 1978.

ulation projection is essentially based on an extrapolation of current fertility levels surrounded by a "high" and a "low" band, it is not surprising that projections drift badly off-target during a period of rapidly changing reproductive behavior. To develop more accurate population forecasts, demographers would have to know a lot more than they now do about the social and economic determinants of fertility. Even assuming such theoretical understanding, one would then have to predict the future course of the appropriate social and economic indexes, and there is no evidence that the relevant social-science disciplines have developed any such capability.

All of this suggests it is foolhardy even to speculate about future trends in fertility and population growth, let alone to take new projections seriously. How do we know a new baby boom is not in store? As a matter of fact there is one school of thought in demography that offers an attractive theory in support of just such a prediction for the U.S. The argument is that fertility responds positively to people's perception of their degree of opportunity, in particular as opportunity is affected by the competition of peers. Such competition is in part a function of numbers. People born during the low-birthrate period of the late 1920's and the 1930's came of age after World War II during an expansive period of great demand for labor. They were the parents of the baby boom. In contrast, the babies of the baby boom came of age in the late 1960's and the 1970's, when their large numbers increased competition for places in college and for jobs. They in turn have been responsible for the postponed marriage and low fertility that have characterized the past decade. This negative association between the size of a cohort and its ultimate fertility leads to a prediction that there will be another baby boom in the 1990's as people in the low-birth cohorts of the 1970's respond to the brighter prospects and competitive advantages stemming from their smaller numbers.

The theory is intriguing, but the empirical evidence for the cyclical pattern it predicts is largely limited to the two examples described above, and not much supporting evidence has been adduced for such a pattern in other countries. Moreover, the theory ignores the radical changes in the status and expectations of women. It appears to assume that the competitive economic advantage of reduced numbers is to be realized only by men, even though women have been joining the labor force at a steadily increasing rate. It is not at all clear that an increase in economic opportunity would automatically be translated into earlier marriage and higher fertility; might it not instead prompt young people to spend more on housing and other consumer items, and also attract women to better jobs and to long-term career commitments? The cyclical theory is nonetheless a cogent one with some empirical support. What evidence speaks for the opposite view: that fertility will remain low?

Every time the birthrate records a new low (frequently in recent years) a demographer receives inquiries from journalists about what the decline can be attributed to: "the pill," abortion, sterilization, recession, the women's movement or some other ad hoc explanation. To ask what caused the latest decline, however, is to ask the wrong question. The decline is the long-term reality. The birthrate has been coming down more or less steadily for the past 200 years in this country—with the exception of one period. The real question, and the more perplexing one, is what caused that exception: the baby boom that lasted for more than a decade after World War II.

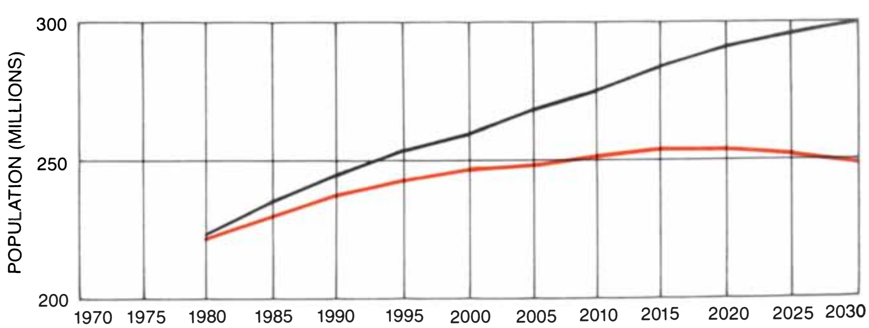


POPULATION WOULD DECLINE in Europe (including the entire U.S.S.R.) after the turn of the century according to one United Nations projection (*color*) made in 1975; the projection assumes that the total fertility rate would drop to 1.5, or about 25 percent below the replacement rate, by 1986 and remain at that level. Another UN projection (*black*) assumes constant fertility just below the replacement level, in which case the population would continue to grow, at a diminishing rate, through the period shown. Present trends favor lower projection.

We are beginning to understand the baby boom demographically, although not the underlying causes. The notion that everyone married early and had a lot of children is imprecise at best. What apparently created the boom was a definite movement away from spinsterhood and away from childless and one-child marriages. There was a large increase in the proportion of women having at least two children, but the increase in the proportion of women having three or more children played a minor role in the boom; there was no return to the large families of the past. What social and economic forces generated and sustained the changes in marriage and childbearing is not at all clear. An unpredictable element of what might be called fashion seems to play a role in such changes, which is one reason it is not inconceivable that the marriage and fertility levels of the baby boom might reappear, however unlikely that may seem today.

If the baby boom was a temporary (but demographically significant) excursion, the secular downward trend in fertility from which it departed was one aspect of a major demographic transition in Europe and the U.S.: the long-term decrease in death rates and birthrates that accompanied economic development and modernization in general. What has been basic to the entire demographic transition has been a change in the economic value of children, from a source of income in agrarian economies to a considerable drain on income in industrial and postindustrial economies. The economic transformation of society has been accompanied by a decline in traditional and religious authority, the diffusion of an ethos of rationality and individualism, the universal education of both sexes, the increasing equality of women, the increasing survival of children and the emergence of a consumer-oriented culture that is increasingly aimed at maximizing personal gratification. When these changes are combined with the development and diffusion of sophisticated birth-control technology, it is hardly surprising that the institutions of marriage and the family show signs of change.

The important thing about this catalogue of social changes is that the changes all seem to be irreversible and that some of them, particularly those linked with the status of women, have not yet run their full course. In spite of some signs of net migration to rural areas, no return to an agrarian economy is likely. There is some resurgence of evangelical religion, but no one would argue that the religious or traditional authority of past centuries is being reestablished. Not-



U.S. POPULATION DECLINE would begin somewhat later, according to a Bureau of the Census projection (*color*) that assumes a drop in total fertility to 1.7, which is just below the current U.S. rate of 1.8. Another projection (*black*) assumes an increase in U.S. fertility to the replacement level, or 2.1. Both projections assume net legal immigration of 400,000 a year.

withstanding some recent disenchantment with the economic rewards of higher education, a prolonged period of education and training has become the norm. It does not take a professional economist to discern that the hunger for consumer goods has not abated in spite of the antimaterialist sentiments of the environmentalist movement. Birth-control technology, although it is still far short of ideal, is more widely used and more effective than ever before. Current efforts to reverse the trend toward permissive abortion may be partly successful, but the end result may well be merely to make abortion less convenient and more expensive. We are fast approaching the "perfect" contraceptive society, in which there will be no unwanted births.

In short, nothing on the horizon suggests that fertility will not remain low. All the recent evidence on trends in marriage and reproductive behavior encourages a presumption that it will remain low. It is instructive to review some of these trends in the U.S. and in two countries that have often been in the forefront of social change in the developed countries: Denmark and Sweden.

The number of marriages has been declining in Denmark and Sweden for the past decade or so—by 30 percent in Sweden between 1966 and 1975. In the U.S. there has been a radical decline in the proportion of women who marry young. In 1960 only some 29 percent of the women from 20 through 24 years of age had never married; by 1978 the proportion had risen to almost 48 percent. That is about the same proportion as in 1940 and less than at the turn of the century, when more than 50 percent of the women between 20 and 24 were still single. Further increases in nonmarriage and the postponement of marriage would, in other words, be well within historical experience, but contemporary developments suggest that such increases will come about in the future for very different reasons. Many women now delay marriage until they are almost 30. Some of the postponement is due to the "marriage squeeze": the sharp increase in the birthrate after the war meant that during the late 1960's and early 1970's there were more women ready to marry than there were men of the conventional marrying age (a few years older). Much of the postponement, however, is due to fundamental changes in attitudes toward early marriage.

That conclusion is supported by the evident and increasing tendency for unmarried couples to live together. In the U.S. in 1976 an estimated one million couples (about 2 percent of all couples living together) were not married. It appears certain that cohabitation will become more popular in the near future. Its incidence has been increasing rapidly in Denmark, where more than a fourth of all women 18 through 25 live with a man to whom they are not married. In Sweden a recent survey found that about 12 percent of all couples (aged 16 through 70) who were living together were not married. In many instances cohabitation is simply a prelude to marriage—a new form of engagement—and so perhaps not much has really changed, aside from the legitimation of the arrangement by a certificate. Perhaps, on the other hand, we are seeing the beginning of a more basic change that will significantly alter the institution of marriage. In either case it is clear that cohabitation means lower fertility, whether because of the trial nature of the arrangement or because of its relative instability.

Instability of the marriage relationship is increasingly the normal expectation, judging by the high and increasing U.S. divorce rate. The traditional notion of having one partner for life is no longer the norm for a growing segment of the U.S. population. The current divorce rate implies that perhaps half of all marriages will eventually be dissolved by divorce and that a third of all children will spend a significant amount of time with a divorced or separated parent. The divorce rate has about doubled in the past decade in Denmark and Sweden, although it is still lower in those countries than in the U.S.

The conventional wisdom about the high U.S. divorce rate is that it is an index of disenchantment not with marriage as such but with a particular spouse; the high rate of remarriage has been cited as evidence. Here too, however, the beginning of change can be discerned. The U.S. remarriage rate, which had increased along with the divorce rate, has started to decline. (In Sweden the remarriage rate has declined about 50 percent since 1965.) More second marriages now seem to be headed for divorce. Cohabitation is not limited to the premarital years; one is increasingly aware of middle-aged and even older divorced people living together unmarried.

One of the major factors that has historically affected the fertility rate is the changing economic role of women. In recent decades there has been a striking increase in the proportion of women who are in the labor force. In the U.S. the proportion of women in the prime childbearing years who are employed increased from less than two-fifths in 1960 to about three-fifths in 1977; it is projected to reach about two-thirds in another decade. For Europe as a whole the International Labor Organization has projected a three-fifths participation in the labor force for women of reproductive age by the year 2000.

Such increasing economic activity by women does not, to be sure, mean a commensurate increase in their financial independence; there remains a clear income inequality between the sexes. The earnings of women are well below

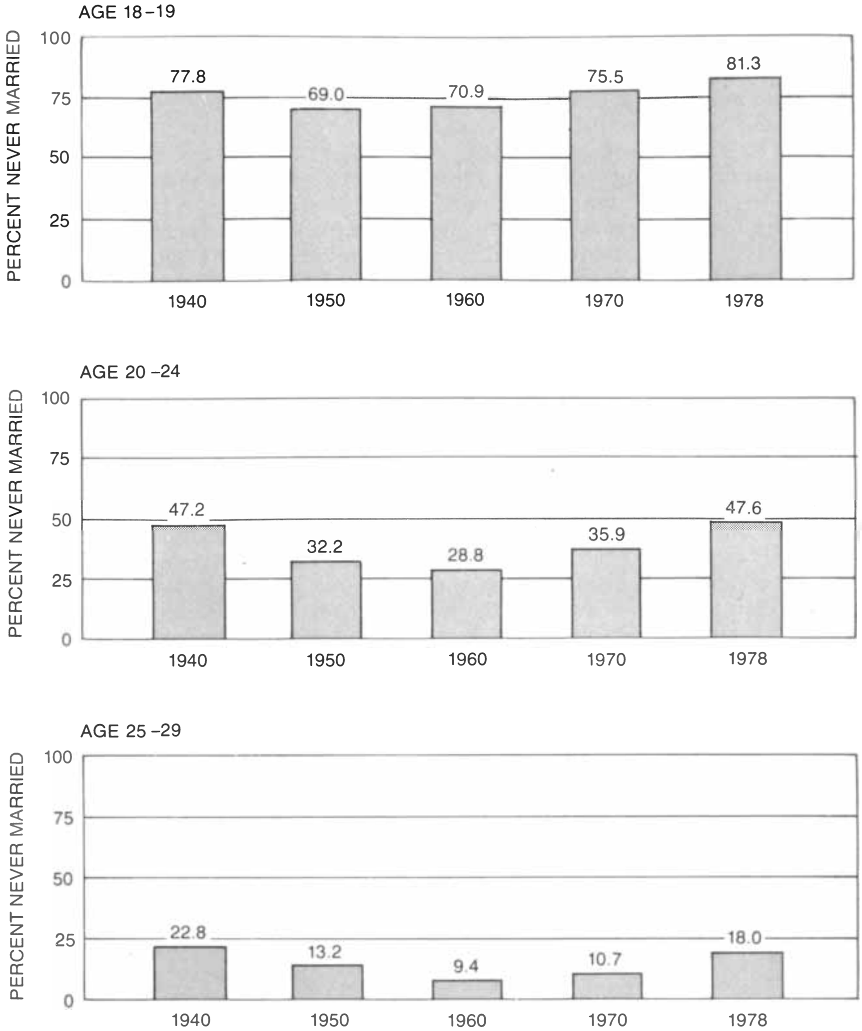
RECENT DECREASE in the rate of population growth in the currently developed countries is a result of the greater decline in the birthrate (*color*) than in the death rate (*black*). The current convergence of the birthrate and death rate at a low level of fertility and mortality indicates a return to demographic equilibrium. Such equilibrium had been the historical norm (but at a higher level of fertility and mortality) before the second half of the 18th century.

those of men in spite of diminishing educational differences between the sexes. Women are disproportionately concentrated in less remunerative jobs and they are paid less in the same jobs. Among year-round full-time workers from 18 through 44 who received income in 1976 in the U.S., the average woman earned only 60 percent as much as the average man. Still, the future trend of the economic status of women seems clear: even if genuine economic equality is probably generations away, an increasing number of women will have the option of financial independence.

There is a considerable body of research describing the complex causal connections between women's participation in the labor force and their fertility. Employment and children are not always incompatible, and various sequences of working and childbearing complicate the relationship. Regardless of any qualification, however, there seems to be little doubt that work and fertility are negatively correlated and that an increasing proportion of women will work in the future. Imagine, ultimately, a society in which men and women have the same incomes, in which there are as many women as men who are lawyers, engineers, corporation executives, physicians and salespeople. What would the consequences be for marriage and fertility?

Certainly the institution of marriage would lose one of its few remaining sociological rationales, if one thinks of marriage in functional economic terms as a system whereby the woman offers her childbearing and domestic services in exchange for the security and status of a man's income and occupation. This concept of marriage is unromantic, but there is no doubt that it goes a long way toward explaining the universality and persistence of the institution. If the economic rationale were lost, what then would provide the motivation for marriage? It is hardly necessary these days for companionship or for sexual gratification. Given the growing acceptability of cohabitation (and the ease of divorce), does it not seem likely that traditional marriage will become still less prevalent?

Perhaps the final sociological rationale for marriage is the bearing and nurturing of children, but the ongoing retreat from parenthood makes even this foundation a bit shaky. If current rates for first births were to persist, some 30 percent of U.S. women now of childbearing age would never have any children. The highest proportion on record was 22 percent childless, for U.S. women born in 1908. It seems likely that today's young women will break that record by a few percentage points, although they will not reach the 30 percent level implied by current rates. If the large increase in out-of-wedlock births registered in Sweden in recent years as a consequence of the increasing proportion of unmarried couples living together is any indication that the taboo on extramarital fertility is weakening, then even this function of marriage may be less important.



AGE AT MARRIAGE affects the birthrate. The "baby boom" of the 1950's and early 1960's was marked by early marriage, as is shown by these bars indicating the percent of women who were still single at various ages. That percentage has risen recently as women delay marriage.

The decline of fertility, then, can be regarded as both a cause and a consequence of changes in marriage and the family. Having fewer children or none can be construed as facilitating the economic activity of women and increasing their economic equality with men, two developments that in turn make marriage and childbearing less of an automatic social response. A future increasingly incompatible with the concept of long-term traditional marriage is almost certain to be a future of low fertility in the developed countries.

There is a wide spectrum of views on the optimum rate of population growth in the developed world. Some people argue cogently that growth has already exceeded a level mandated by environmental and other quality-of-life considerations, and that the additional population already "in the pipeline" will exacerbate the situation. From that point of view an actual decline in population is a desirable prospect. Others have concluded that the best outcome would be zero population growth. The Commission on Population Growth and the American Future investigated the economic, environmental and governmental implications of various rates of increase and concluded in 1972 that any growth beyond that to which the U.S. was already committed by the legacy of its past growth would only intensify the nation's problems and make their solution more difficult.

There is no magical quality, however, in the 2.1 fertility rate that just maintains replacement. No one has yet discovered any homeostatic mechanism that will automatically regulate a society's reproduction to keep it at the replacement level. If fertility continues downward, then, the ultimate prognosis is negative population growth: declining population size and much older populations. It is worth reiterating that predictions to the same effect have been ventured before, in the 1930's; they were made to look ridiculous in the light of the subsequent baby boom, and that could happen again. What I am arguing is that (if my interpretation of the evidence is even only approximately correct) a significant renaissance in fertility seems unlikely and that the developed world has resumed the prolonged downward trend in fertility that began a century or more ago.

What is causing concern particularly in Europe, where the entire process of change is more advanced than it is in the U.S., is that fertility will remain well below replacement, that the proportion of older people will therefore increase markedly, that the population will therefore not remain stationary but will begin to decline—and that the aging of the population will make it increasingly difficult to arrest the demographic momentum of the decline.

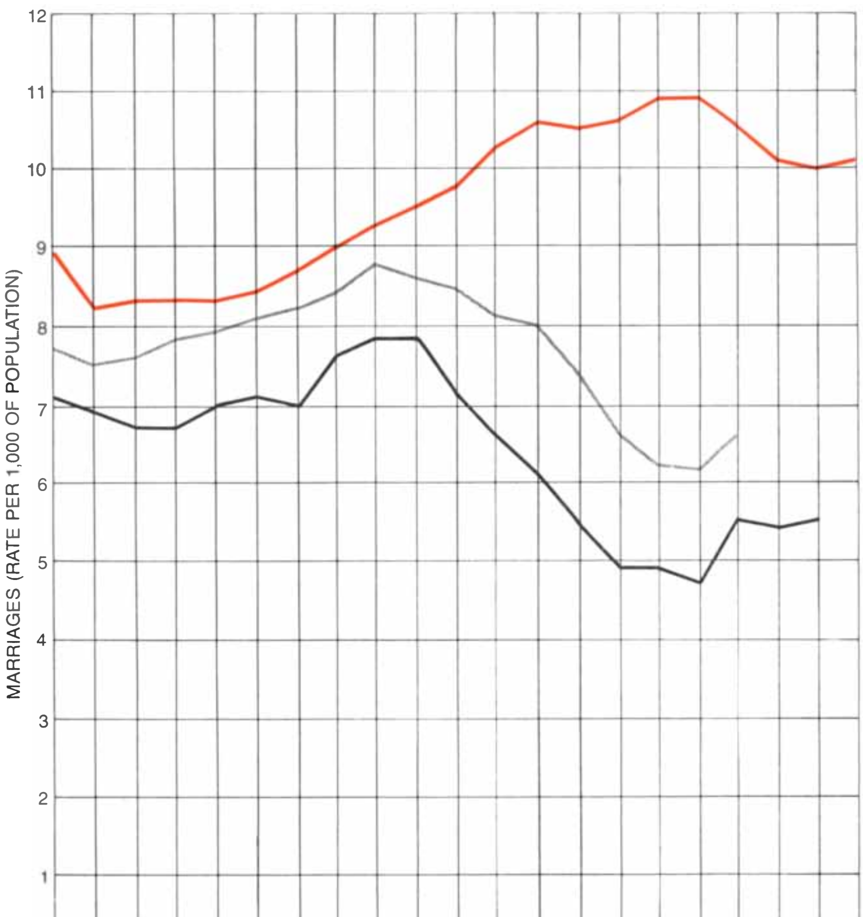
Several countries have already given signs of being very uncomfortable with the low-fertility trend. A recent United Nations survey revealed that 10 European countries considered their current fertility rate too low. In West Germany (where in 1976 there were 733,000 deaths and fewer than 603,000 births) the growing concern was reflected by a recent television program that was titled "Are the Germans Dying Out?" and answered the question in the affirmative. One German demographer has said: "Beneath the blankets we are a dying people."

In France, where population growth has long been of concern both as a matter of national prestige and for specific national-security reasons, population has become the subject of a national debate. In 1976 President Giscard d'Estaing warned that no country with a middle-size population could realistically aspire to grandeur. The former premier Michel Debré, an extremist on the issue, regards the declining birthrate (which at 13.6 in 1976 still exceeded the death rate of 10.5) as a national peril. He has gone so far as to propose a bill providing for a "family vote," which would give parents an additional vote for each child under voting age. For many years the French government has subsidized families with children by means of cash allowances and tax relief. Since 1976 there has also been a guaranteed minimum income for unmarried mothers, a two-year maternity leave for female civil service workers and exemption from military service for young fathers under special circumstances.

Many of Sweden's social-welfare measures have long been focused on the protection of children and assistance to parents (whether married or not). A recent example is a "parents' insurance" law that increases from six to nine months the amount of paid leave for either the mother or the father of a new baby. The leave may be taken over a period of up to eight years.

East Germany, where the birthrate had dropped to a low of 10.6 (with a death rate of 13.5) in 1975, reportedly succeeded in raising the birthrate to 13.3 in 1977 following the introduction of several new measures in mid-1976. These included reduction of the work week for mothers of two or more children, extension of pregnancy leave at full pay from 18 to 26 weeks and various financial incentives, the most striking of which is an interest-free credit of up to $10,000 for the purchase of housing or furniture. The debt is reduced by $1,000 for the birth of a child within eight years and by another $1,500 for a second child, and is excused entirely on the birth of a third child. The cost of this provision is considerable: a reported 37 million marks (about $18 million at the official rate of exchange) in canceled debts to date as well as the loss from women's absence from work. According to one report, "90,000 women—1 percent of the total labor force—have accepted the government's invitation to go into baby production."

Pronatalist policies have been actively pursued in other Eastern European countries. Romania achieved a certain notoriety among specialists in population policy for its demonstration of the potential demographic impact of outlawing abortion; that was done in 1966 and it more than doubled the birthrate in 1967. (The rate has declined slowly since then as illegal abortion and contraception were substituted for legal abortion.) Abortion laws have also been tightened in recent years in Bulgaria, Czechoslovakia and Hungary, and birthrates have increased. How much of the increase is attributable to pronatalist economic measures introduced at the same time (including maternity leaves, family allowances, subsidized childbirth services, preference in housing and

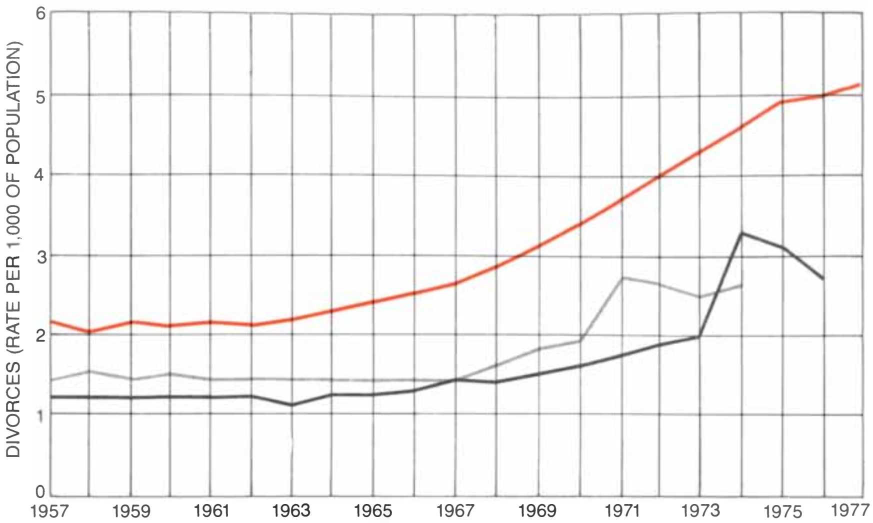


MARRIAGE RATE has been generally declining in Sweden (*black*) and Denmark (*gray*) since 1965 and in the U.S. (*color*) since 1973. More couples are living together without marriage.

other inducements) rather than to the change in the abortion laws is an open question.

Such responses to declining fertility suggest that an increasing number of governments will regard low fertility and negative population growth as a threat and will develop programs for inducing women to marry and to have more children than they now seem to be motivated to have. What kind of measures will be adequate to such an objective? The same question was being posed 40 years ago as several European countries confronted similar demographic futures (a prospect that was radically altered by World War II and its aftermath). At that time there was speculation that society might have to develop a class of specialists in reproduction, who would be compensated for their services and whose progeny would be raised in child-care centers in the absence of conventional family arrangements. Such schemes were made irrelevant by the rush to marriage, the suburbs and child rearing after the war, and they still have the ring of science fiction.

And yet given current trends it is not hard to visualize a society in which a third of the women remain childless, which would mean that the remaining two-thirds of the women would have to average slightly more than three births each to replace the generation. It seems unlikely that the mild and often trivial economic inducements so far implemented by governments could motivate the required fertility. It is hard to imagine well-educated and well-paid women, raised in a society that rewards nonparental roles, being sufficiently attracted by a few thousand dollars in benefits to sacrifice income, interrupt a career and devote the necessary time and energy to raising several children. An industrialized nation that decides not to tolerate negative growth may have to subsidize reproduction on a large scale, with a serious investment of public funds. Almost certainly it would have to guarantee working women that they will have ample leave for childbearing and will suffer no loss of income or position, and that they will find a comprehensive system of child-care institutions at their disposal.



DIVORCE RATE in the U.S. (*color*) is high and has been increasing. The divorce rate is lower in Sweden (*black*) and Denmark (*gray*) than it is in the U.S., but it has been generally rising.

As the birthrate in any country drops closer to the death rate immigration plays an increasing role in determining population growth. In theory a government attempting to maintain a particular rate of growth—zero growth, for example—could manipulate its immigration quotas to make up any deficit in the number of births in the preceding year or so. The qualifications for immigration could be set fairly high to bring in individuals with training and skills that are in short supply, assuming that the economy could be kept strong enough to attract such people. Such fine tuning would be difficult, however. Immigrants arrive at different ages and, what is potentially more important, they arrive in various colors and nationalities and speaking different languages. Any country with substantial immigration seems sooner or later to experience problems, arising from differences in language, customs, religion or race, that tend to offset many of the economic and long-term cultural advantages.

In the past two decades or so most countries of western and northern Europe have admitted immigrants (or in many cases have merely admitted workers for temporary stays) from less affluent countries with a growing population and high unemployment. The influx has provided additional labor force, in particular for relatively menial work, that has helped to sustain rapid economic growth, but it has also created social problems. Countries with a shortage of labor will undoubtedly continue to resort to importing foreign workers as long as surplus labor is available from nearby countries with high fertility. No nation has yet opted for immigration for purely demographic reasons, however, and the experience with foreign workers is one the receiving countries are not likely to forget as they face the more basic problem of supplementing population growth.

In the U.S. illegal immigration is a growing concern, although no one has a clear picture of its magnitude or duration. Its effect is localized, but it undoubtedly has significant economic impact in parts of the country. Indeed, its economic value is what sustains illegal immigration; if it were not so valuable to localities and particular employers, the illegal flow would presumably be more effectively controlled by U.S. authorities.

Whatever the short-term economic advantages of international migration, legal or illegal, it clearly offers no long-run solution for a country in which native fertility is well below the replacement level. In the U.S., for example, the volume of immigration would have to be about twice as high as the present legal total in order to avoid eventual negative growth.

The developed countries are just beginning to adjust to the prospect of a stationary population after several centuries of growth. If zero population growth turns out to be passed in the night and negative growth appears to be the course of the future, one can expect revolutionary social changes in the 21st century. We know very little about the short-run consequences of negative population growth, but the long-run consequence is clear enough.

I must make it clear that I am not here urging the desirability of maintaining a particular rate of growth. The Commission on Population Growth and the American Future concluded, after an exhaustive evaluation of the pros and cons of population growth, that the slowing and eventual cessation of growth appears to be in the best interest of the U.S. and that even short periods of negative growth may be beneficial. The point is that zero population growth is now in sight in many developed countries. If population declines for any significant length of time, it will be regarded—rightly or wrongly—with alarm. Before policies to stimulate fertility are developed uncritically, one would hope that serious efforts will be made to evaluate the costs and benefits of alternative rates of population growth.

Nuclear Molecules

At certain energies protons and neutrons in nuclei form clusters moving in simple orbits with respect to each other. These nuclear molecules constitute a new kind of nuclear structure and dynamics

by D. Allan Bromley

The tendency of atoms to bind themselves together into molecules by exchanging or sharing their valence, or outer, electrons is a well-known phenomenon. At the center of the atoms lie the atomic nuclei, which are roughly 100,000 times smaller. It has now been shown that nuclei too can be made to form molecules: under special conditions in high-energy interactions they are momentarily held together by effective bonds. Whether or not these bonds are the result of the nuclei's exchanging or sharing valence protons and neutrons remains an open question. These short-lived nuclear molecules constitute an entirely new mode of nuclear structure and dynamics that physicists are only now beginning to understand.

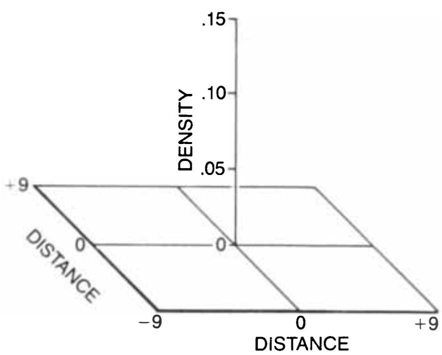
The structure and stability of both atomic and nuclear molecules depend on the characteristics of the fundamental natural forces that govern the interaction of electrons, protons and neutrons. Atomic molecules represent a balance between two long-range aspects of the electromagnetic force: the covalent attraction of the electron clouds of atoms and the electrostatic repulsion of the positively charged nuclei of the atoms. The distance between the atoms in an atomic molecule is such that the attracting and repelling forces cancel each other. Generally atomic molecules are relatively stable and hold together unless they are broken up in some energetic interaction. In nuclear molecules a less stable balance is reached between the same long-range electrostatic repulsion and the much stronger short-range nuclear force that determines the motions of the protons and neutrons. The nuclear force does not act on electrons, and so it plays no direct role in the formation of atomic molecules. In nuclear molecules the nuclear and electrostatic forces are so much stronger than the forces in atomic molecules that the nuclear molecules are precariously balanced between either flying apart under electrostatic repulsion or coalescing into one nucleus under nuclear attraction.

If a nuclear molecule is to form, two nuclei must be brought close enough together for the short-range nuclear force to overcome the long-range electrostatic force. In nature nuclei are usually not close enough together for the short-range attractive nuclear force to be strong enough to form nuclear molecules. Perhaps nuclear molecules will yet be detected in the depths of giant stars, where a third fundamental force, gravitation, can reach sufficient strength to counter the electrostatic repulsion and push the nuclei together.

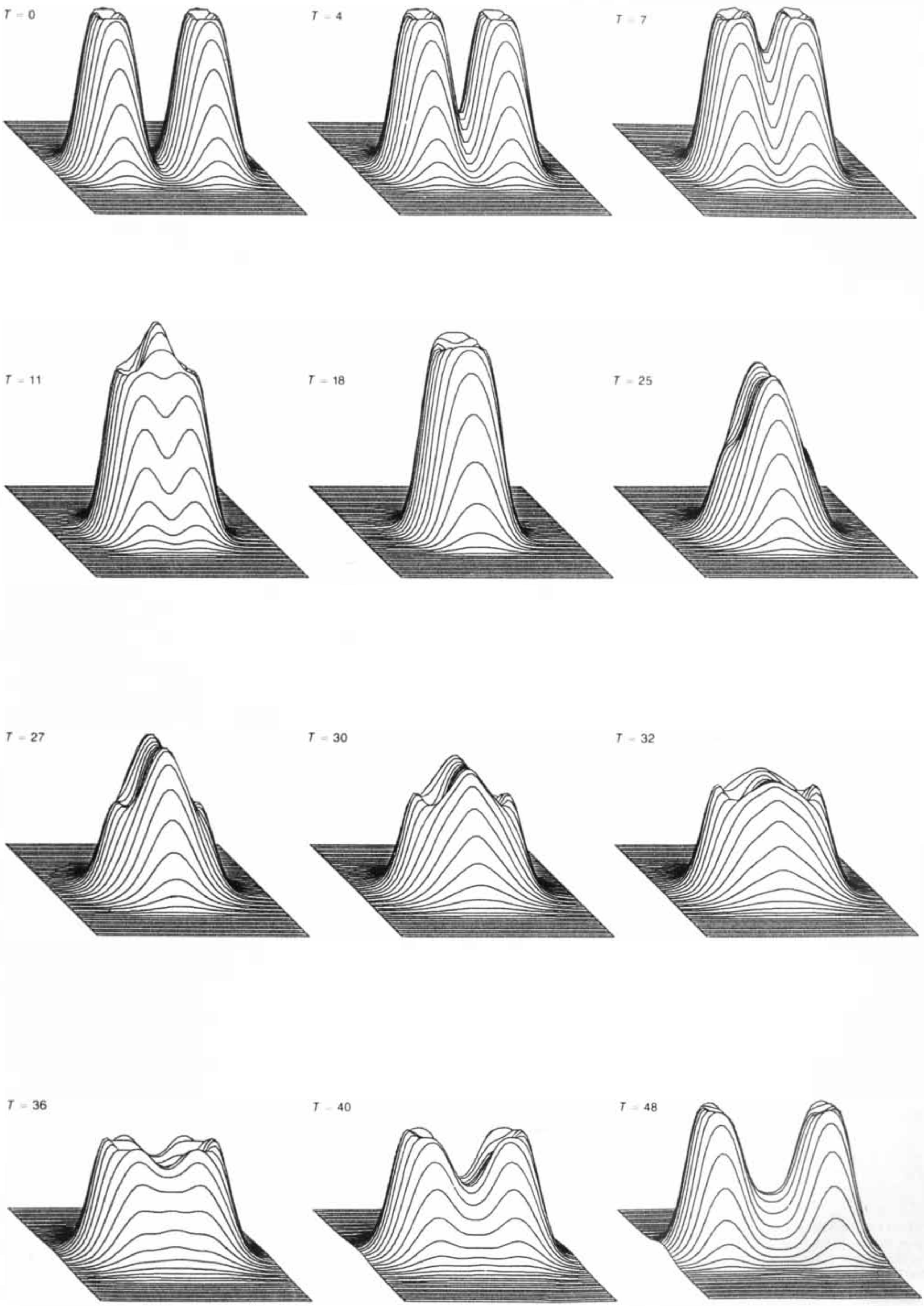
Although nuclear molecules have not been found in nature, they have now been produced in the laboratory in energetic collisions between accelerated nuclei and stationary nuclei. Particle accelerators can raise the kinetic energy of a projectile nucleus to the point where it can be driven very close to a target nucleus against the force of electrostatic repulsion. Then under certain conditions nuclear molecules appear to form, the two nuclei vibrating and spinning rapidly around each other for a brief moment until they either fly apart or coalesce.

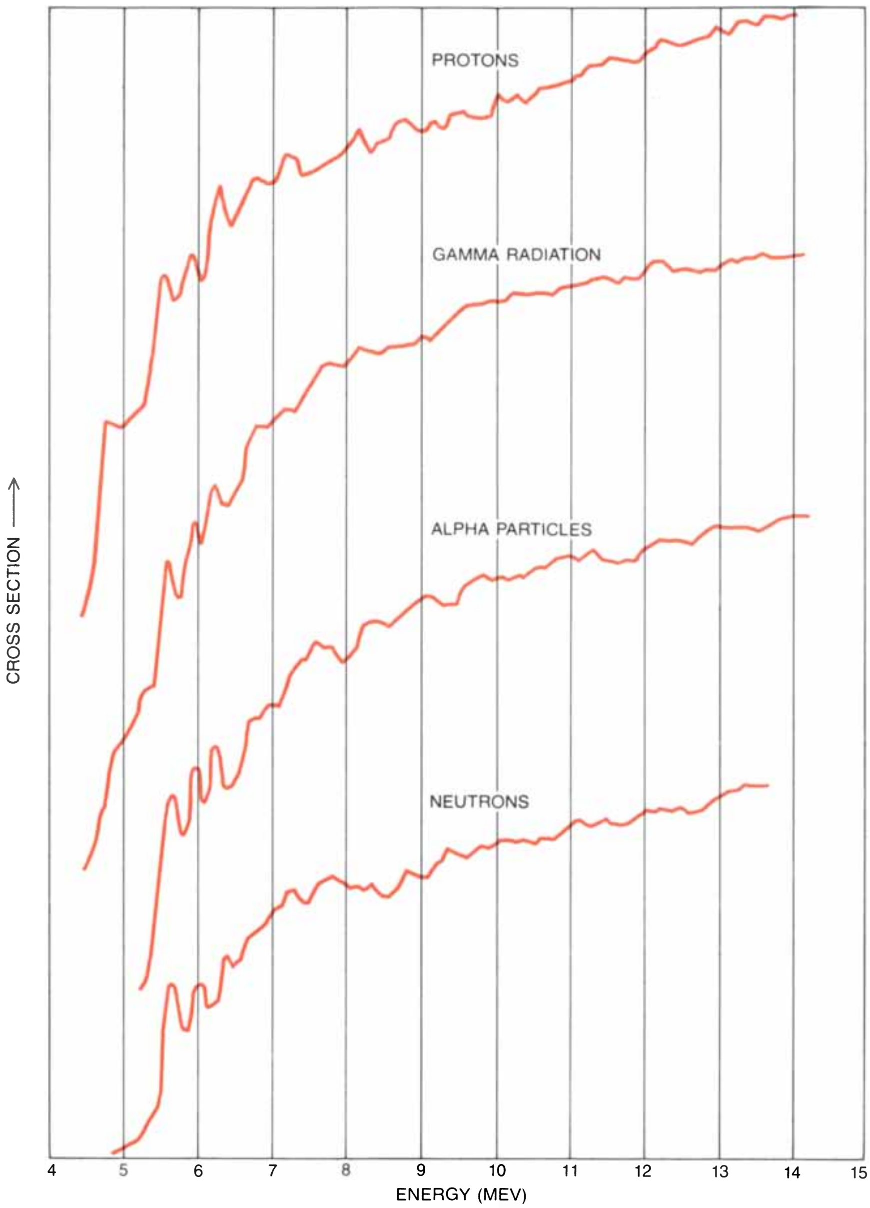
Nuclear molecules are significant entities because they live much longer (about 10^{-21} second) than the time it usually takes for nuclei to collide (about 10^{-23} second), although they do not live long enough for them to be subjected to the same kind of measurements that are made on stable atomic molecules. A great deal about them can be learned indirectly, however, by studying how their formation and decay affects the "cross section," or probability, of certain things happening when two nuclei of a specific energy collide and form any one of a number of nuclear products. Where the cross section varies smoothly as the energy of the nuclei varies, no long-lived phenomena are involved; the nuclei meet only briefly, as in an elastic collision where the two nuclei scatter like two colliding billiard balls.

If, on the other hand, the cross section resonates, or peaks, at certain energy values, that suggests the nuclei may be remaining close to each other for a comparatively long time. And if other conditions that I shall discuss below are met, these resonances can be identified as signatures of the formation of nuclear molecules. On the basis of Werner Heisenberg's uncertainty principle the life span of such a molecule can be calculated directly from the width of the corresponding resonance. The width represents an uncertainty in the energy of the nuclear molecule, and the uncertainty principle associates a long lifetime with

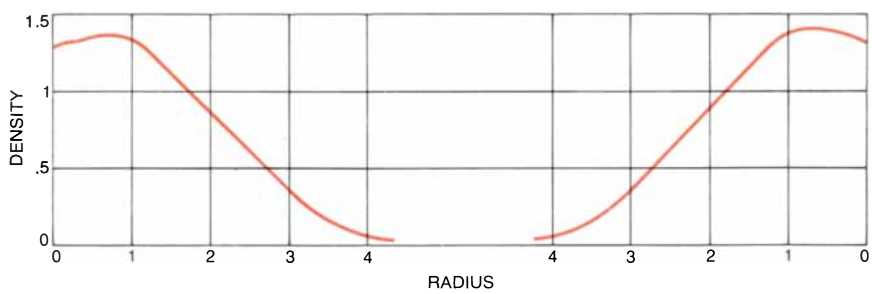


FORMATION of a nuclear molecule is displayed in these computer plots of the calculated density of protons and neutrons in two colliding nuclei of carbon 12. The density is given in terms of the number of protons and neutrons per 10^{-39} cubic centimeter. Each proton and neutron in the carbon projectile that struck a carbon target had an average energy of 64 MeV (million electron volts). The interaction between the two nuclei lasted for about 5×10^{-22} second. The unit of time T is 3.3×10^{-24} second, and the unit of distance is 10^{-13} centimeter. At $T = 0$ the carbon nuclei came in contact, and at $T = 11$ the density reached a maximum at the central spike. Then a long-lived neck developed that bound together two fragments, each having roughly the density of one of the original carbon nuclei. Finally the nuclear molecule began to break apart, but the limited capacity of the computer made it impossible to carry the calculations through to where the carbon nuclei finally separated. The fact that the density profiles of each nucleus were less smoothly distributed at $T = 48$ than at $T = 0$ means that energy was transferred from relative motion to internal excitation. The calculations were done by Ronald Y. Cusson and Joachim Maruhn at the Oak Ridge National Laboratory.


T = 0
T = 4
T = 7
T = 11
T = 18
T = 25
T = 27
T = 30
T = 32
T = 36
T = 40
T = 48



CROSS SECTION, OR PROBABILITY, of various nuclear products emerging from collisions between carbon-12 nuclei is plotted as a function of the available kinetic energy. At an energy of 6.6 MeV, the Coulomb barrier, the collision partners can just touch. Of particular interest are the three resonances, or peaks, at energies just below the Coulomb barrier. The three resonances, which appear in all four cross sections and at all observation angles, constituted the first evidence that nuclear-molecule phenomena exist. The data were obtained in 1960 by the author, Einar Almqvist and John A. Kuehner at the Chalk River Nuclear Laboratories in Canada.



DENSITY PROFILES of two colliding carbon-12 nuclei with an energy of 5 MeV are shown when the centers of the nuclei are spaced closest together at 10.4×10^{-13} centimeter. Such a separation is more than twice as large as not only the mean radius of a carbon nucleus but also the effective largest radius. Here the radius is measured in units of 10^{-13} centimeter.

a narrow resonance (a small uncertainty) and a short lifetime with a broad resonance (a large uncertainty).

In 1960 Einar Almqvist, John A. Kuehner and I at the Chalk River Nuclear Laboratories in Canada discovered resonances in collisions between carbon-12 (^{12}C) nuclei that provided the first evidence for the existence of nuclear molecules. We used the first tandem Van de Graaff electrostatic accelerator to bring together the carbon nuclei. At certain energies we observed resonances in the yield of collisional by-products: protons, gamma radiation, alpha particles and neutrons. The resonances had characteristic widths of about 120 KeV (thousand electron volts), which on the basis of the uncertainty principle corresponds to a lifetime of 5×10^{-21} second, a value more than 10 times greater than the typical time span of a simple collision. Yet it could not be concluded simply on the basis of this comparatively long collision time that the resonances had been produced by the formation of nuclear molecules rather than by some other phenomenon.

We found additional evidence, however, that we had detected nuclear molecules. In atomic molecules each of the atoms retains most of its internal properties, in spite of the fact that the atoms are coupled together. By the same token, in nuclear molecules each constituent nucleus would be expected to retain most of its internal properties. Indeed, that was found to be the case in our Chalk River experiment.

We made detailed measurements that showed that at the resonance energies the probability the collisions would result in the reemergence of two carbon-12 nuclei was more than 25 times higher than it would have been if the nuclei had momentarily coalesced to form a normal magnesium-24 (^{24}Mg) nucleus, which has the same number of protons and neutrons as two carbon-12 nuclei do. This told us much about the dynamics of carbon-12 collisions and the structure of magnesium 24. Our cross-section measurements indicated that at the resonance energies 24 protons and neutrons preferred to form two loosely bound carbon-12 nuclei rather than one normal magnesium-24 nucleus. For this reason we suggested that if a magnesium-24 nucleus was given in any way an amount of energy corresponding to the observed resonances, there would be a high probability of its 12 protons and 12 neutrons rearranging themselves into two carbon-12 nuclei, each nucleus made up of six protons and six neutrons.

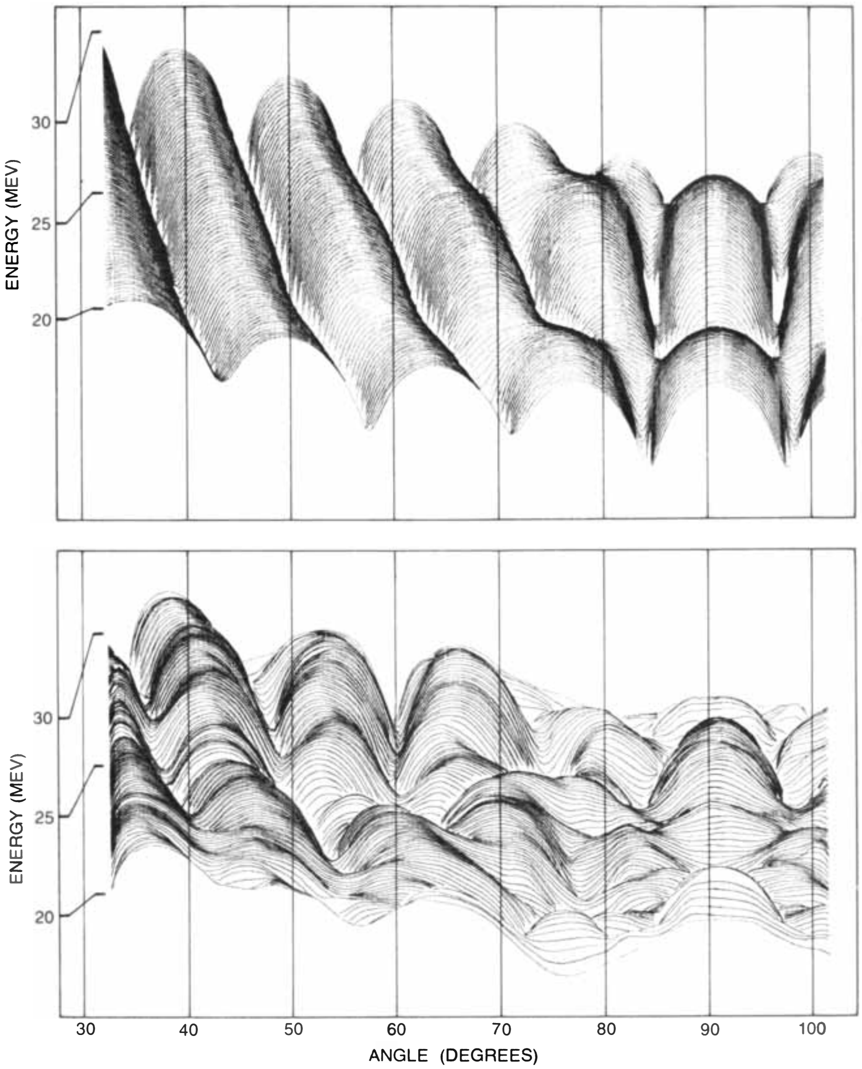
Other nuclear physicists soon tested this suggestion. In the first test, conducted by N. O. Lassen and his coworkers at the University of Copenhagen, magnesium 24 was created when a neon-20 nucleus (10 protons and 10 neutrons) and a helium-4 nucleus (two protons and two neutrons) were forced to coalesce. When the total energy was adjusted so that it was the same as that of the Chalk River resonances, there was a greatly enhanced yield of carbon-12 fragments. In another experiment, performed by Norman K. Sherman at Queen's University in Canada, magnesium 24 was made to absorb high-energy photons so that its energy was boosted to the resonance values, at which point the magnesium 24 fissioned with the enhanced carbon-12 yield that is the signature of a nuclear molecule.

Apart from the role of nuclear molecules as unexpected new modes of nuclear structure and dynamics, they have interested physicists because of the role they might play in such astronomical phenomena as stellar evolution. Nuclear carbon burning has long been recognized as a crucial process in the twilight period of a star's existence. Obviously the presence of unsuspected molecular resonances in the ^{12}C-^{12}C nuclear interaction would affect the rate at which the carbon burns. In the early 1970's investigators at the California Institute of Technology and at the University of Pennsylvania extended our Chalk River measurements to lower energies that were closer to those presumably characterizing stellar carbon burning. They found additional resonances at available carbon energies between 3 and 4 MeV (million electron volts), and they extrapolated the cross section down to energies of about 100 KeV, which correspond to the energies nuclei would reach in the interior of stars at temperatures of about 1.2 billion degrees Kelvin, where carbon burning is believed to proceed. The extrapolation to astrophysical energies led to the puzzling suggestion that carbon burns at a rate that is more than 10 times higher than that allowed by any proposed model of stellar evolution.

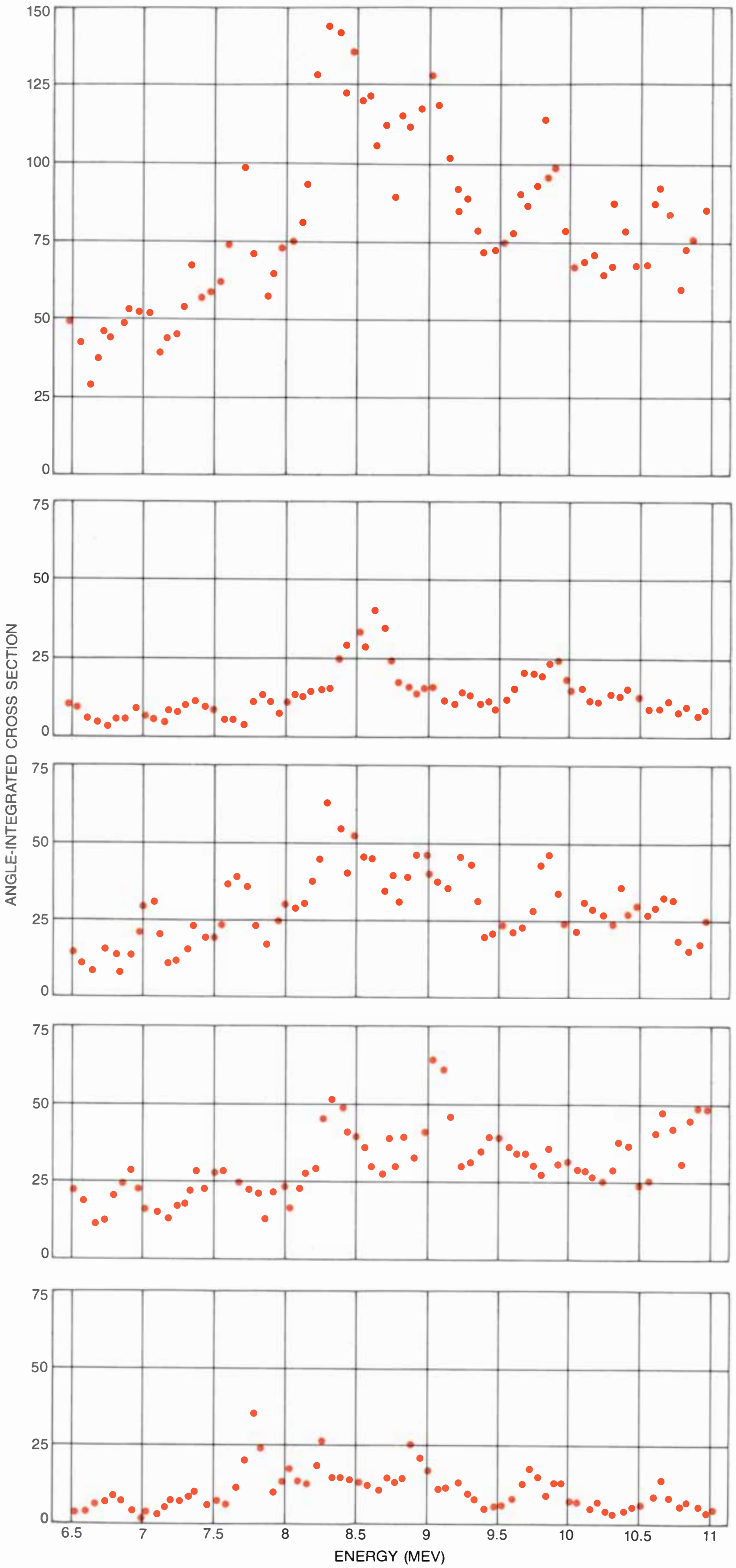
There were other surprises in the early measurements. In our original work we found that similar resonances did not show up in collisions between oxygen-16 (^{16}O) nuclei, although they did appear in collisions between oxygen-16 and carbon-12 nuclei. Other investigators soon observed the same thing. Why did molecular resonances show up clearly in the ^{12}C-^{12}C and ^{12}C-^{16}O interactions (and very recently in collisions between boron 11 and carbon 12 and between carbon 12 and carbon 13) but not at all in the ^{16}O-^{16}O interaction? The question went unanswered throughout the 1960's and the early 1970's. We had been intrigued by the fact that of all the kinds of atoms carbon atoms are found in the greatest number of atomic molecules. Yet we could see absolutely no connection between the atomic phenomenon and the nuclear one.

The original Chalk River data stimulated widespread experimental and theoretical interest in nuclear molecules and other interactions of heavy ions (atoms that have been ionized so that their nuclei can be electrostatically accelerated). Still, progress was limited, on the experimental side by the comparatively low energies of the heavy-ion beams that were available then and on the theoretical side by the absence of an explanation of the unique role of carbon in the nuclear interactions. In the case of carbon the most successful theoretical model, developed by Bunryu Imanishi of the University of Tokyo, could reproduce the Chalk River data only if it made what at the time appeared to be the extravagant assumption that nuclear surfaces are highly transparent: that the nuclear-surface regions could pass through each other and emerge essentially undisturbed. Moreover, the Imanishi model seemed to have been discredited when it failed to encompass the lower-energy resonances that had been discovered by the workers investigating stellar carbon burning. As a result physicists began to question the existence of nuclear molecules, and work in the field dropped off until late in the 1960's, when powerful new heavy-ion accelerators became available.

Coincident with the new technology came an increased understanding of the possible structure of nuclear molecules and the conditions under which they might appear. Although all nuclear molecules would be expected to show up under the proper conditions as resonances in the interaction cross sections, not all peaks in cross sections can be identified as true resonances and not all true resonances correspond to the formation of nuclear molecules. In order for us to correctly identify the molecules, we needed to be able to recognize them in the presence of peaks that characterized other phenomena. The problem was addressed by my research group working with the first of the large "Emperor" class of tandem Van de Graaff accelerators installed in the A. W. Wright Nuclear Structure Labora-



MATHEMATICAL MODEL of the optical type, incorporating forces that act on two carbon-12 nuclei as they come together and then elastically scatter like colliding billiard balls, was used to generate a cross-section surface (*top*). The model parameters were adjusted until the calculated cross-section surface closely matched the measured cross-section surface (*bottom*).



tory at Yale University. We first developed a mathematical model of the gross features of the ^{12}C-^{12}C collision in which the nuclei were assumed to be scattered by an effective potential: a mathematical representation of how the kinetic energy of the approaching nuclei decreases as they come together. The potential incorporated all the forces that would act on the nuclei as they came closer together: the electrostatic repulsion, the nuclear-force attraction and the centrifugal force generated by the rotation of the nuclei around their common center of mass. Such a model is called an optical model because it relies on a mathematical formalism that was developed originally to describe how light scatters off a cloudy crystal ball. Although optical models play a major role in nuclear, atomic and particle physics, they are frequently misused. Such a model is intended to represent only the gross average features of an interaction, and so it should not be expected to accurately reproduce any specific datum such as the way the yield of a particular product at a certain angle varies with energy or the way the yield at a certain energy varies with angle. With our model we generated cross-section surfaces that depended on both the energy values and the scattering angles [*see illustration on preceding page*]. The surfaces show characteristic oscillations in the predicted yield of scattered nuclei as the energy, the angle or both are varied. We kept adjusting the parameters of our model until it could reproduce the gross features of our new experimental data with reasonable accuracy.

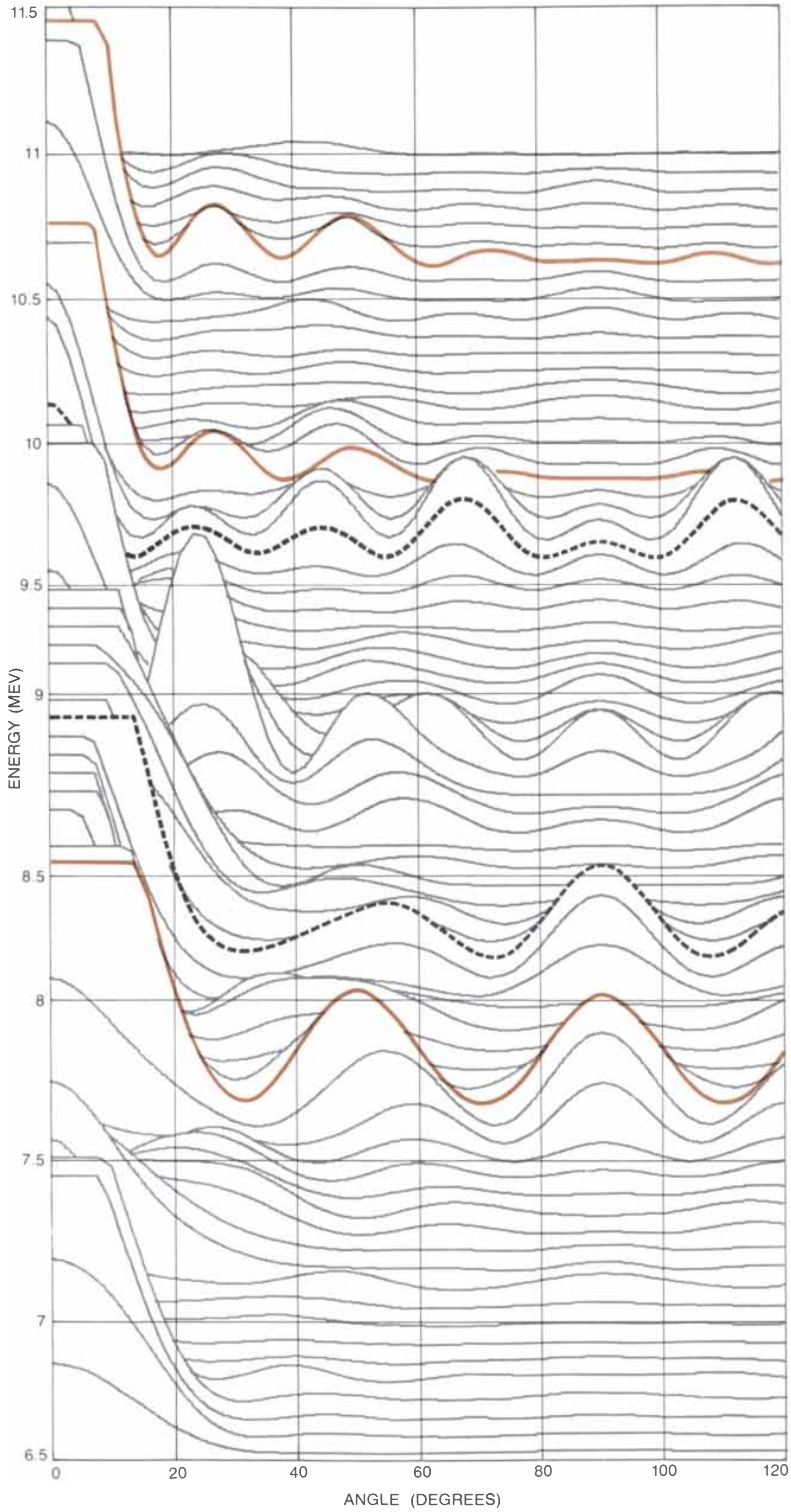
What is particularly striking about the newer ^{12}C-^{12}C scattering data obtained by us and by other investigators is that sharp peaks show up in the cross sections over the entire range of energies of the experiments so far. At the low energies studied at Chalk River, Cal Tech and Pennsylvania molecular resonances are difficult to detect because the electrostatic repulsion between the two nuclei is so strong that it overshadows the nuclear effects. Nevertheless, more and more such low-energy molecular resonances have appeared in the cross sections obtained in careful

NEON 20 AND HELIUM 4 (an alpha particle) can be formed when two carbon-12 (^{12}C) nuclei collide. Here a neon-20 cross section, integrated over all scattering angles, is plotted against the energy of the colliding carbons. The four bottom plots correspond respectively to the formation of the four lowest quantum states of neon 20. Some resonances in the top plot, which was obtained by adding together the other four plots, correspond to the formation of ^{12}C-^{12}C nuclear molecules.

scattering measurements. Indeed, Stephen Korotky and his co-workers at Yale and Helmut Voit and his co-workers at the University of Erlangen have recently determined the quantum numbers, or detailed intrinsic properties, of many of these resonances.

At the highest energies the cross section for ^{12}C-^{12}C scattering abounds with sharp peaks. It was obvious from earlier work by Torleif Ericsson at the European Organization for Nuclear Research (CERN) and Erich Vogt and his collaborators at Chalk River that many of these peaks might, however, be the products of statistical fluctuations in the nuclear processes involved rather than the genuine signature of nuclear molecules. At high energies colliding nuclei can produce compound (fused) systems in any one or in a great number of compound reaction states without ever forming nuclear molecules. These compound states have a wide range of lifetimes, and so Heisenberg's uncertainty principle indicates that the resonance peaks corresponding to them vary considerably; the wider ones in particular overlap. At any specific energy where the interaction is genuinely a statistical one involving compound-nucleus formation a large number of these overlapping peaks serve to define the shape of the cross section. Normally the peaks add together randomly to produce a smooth cross-section curve on which resonances that represent such special interaction configurations as nuclear molecules stand out. Yet in such random situations statistical flukes sometimes occur. For example, it is possible for all but a few of the peaks to cancel one another, leaving those few, or even a single peak, to determine the cross section. Such peaks have sometimes been mistaken for nuclear-molecule resonances.

In search of a way to distinguish peaks that were genuine molecular-resonance phenomena from those that were statistical we found it necessary to look in detail at statistical models of nuclear interactions, which had previously been neglected in studies of collisions between complex nuclei. Although such models, which were developed by Walter Hauser and Herman Feshbach of the Massachusetts Institute of Technology, were introduced originally to describe the statistical aspects of nuclear reactions induced by neutrons, we have found that they are also capable of reproducing in a quite remarkable fashion the results of reactions induced by heavy ions such as those of carbon. Indeed, Daniel W. Shapiro and his coworkers at Yale showed that the statistical model generates predicted cross sections as rich in peaks as the measured high-energy cross sections. This did not



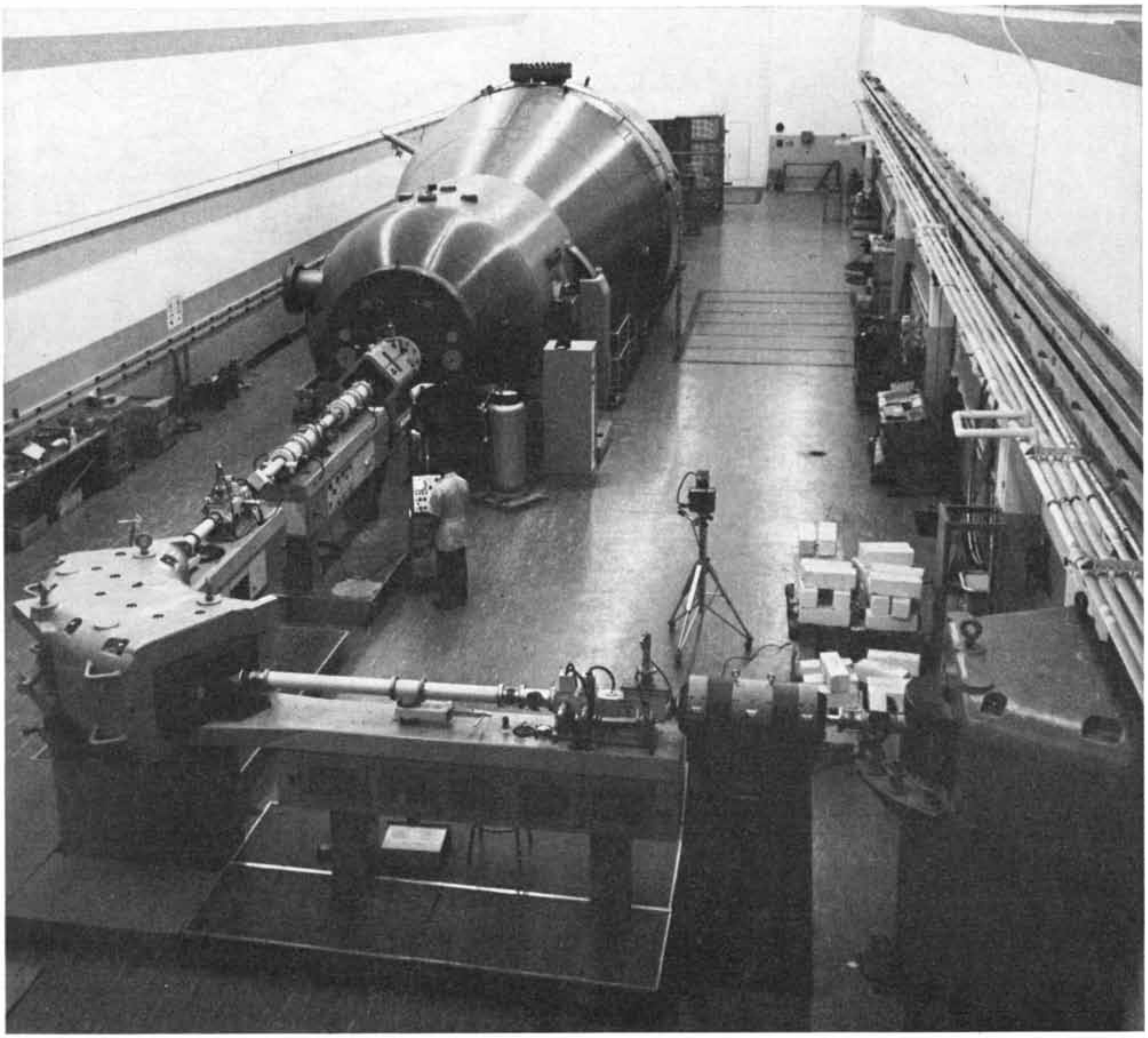
PROBLEM OF SPURIOUS RESONANCES is illustrated by the behavior of the measured cross-section surface for the creation of neon 20 in its ground state, or lowest energy state, in collisions between carbon-12 nuclei. The colored curves were identified as genuine nuclear-molecule resonances. Broken curves, although apparently equivalent, were shown to be products of statistical fluctuations rather than signatures of the formation of nuclear molecules.

mean, of course, that all the high-energy peaks were statistical flukes; it only made it clear that in the absence of additional evidence none of the high-energy peaks could be identified as the signature of a nuclear molecule, as had occasionally been done.

Armed with this new understanding of the statistical aspects of heavy-ion interactions, we tried to answer the old question of why nuclear-molecule phenomena seemed to require the participation of carbon. David R. Hanson and his co-workers at Yale had demonstrated that of all possible combinations of colliding nuclei the interaction of two carbon-12 nuclei had by far the lowest number of compound reaction states. Collisions between oxygen-16 nuclei, for example, in whose cross section resonances did not appear, had 10,000 more compound reaction states that the nuclei could occupy. We suggested that even if nuclear-molecule resonances existed in the oxygen-16 collisions, they would probably be smeared out beyond recognition by the numerous competing states in the cross section.

This hypothesis was supported by the observation of resonances in the collision between carbon-12 and oxygen-16 nuclei, which also has one of the lowest number of compound reaction states. Confusing the issue was the fact that resonances did not show up at all in collisions between carbon 12 and beryllium 9 and only very weakly in collisions between carbon 12 and carbon 13, in spite of their both having a low number of compound reaction states. We now believe that in these two kinds of collision the behavior of the particularly loose valence neutron in both carbon 13 and beryllium 9 overshadows and smears the nuclear-molecule phenomena.

At first we were somewhat discouraged by our hypothesis about the conditions under which nuclear molecules would be observed, since it suggested that such resonances might be comparatively rare in nuclear physics. Fortunately we were not discouraged for long. As new methods were developed for obtaining precise cross-section data we and others found molecular-resonance phenomena in a great many interactions, including those between oxygen



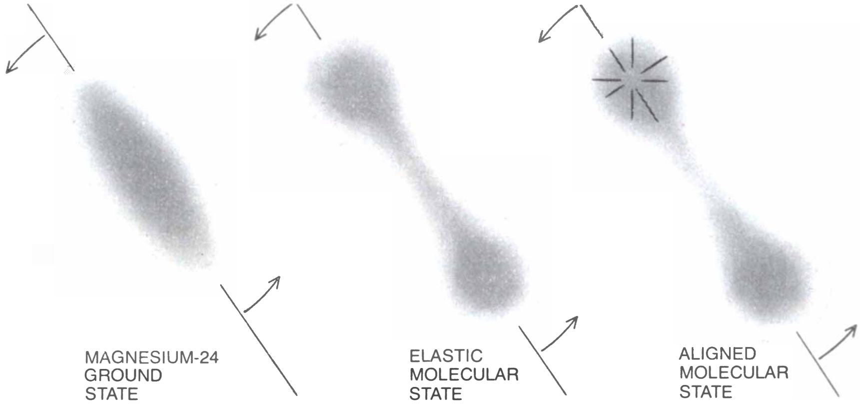
FIRST "EMPEROR" VAN DE GRAAFF ACCELERATOR in the A. W. Wright Nuclear Structure Laboratory at Yale University was used to study nuclear-molecule phenomena. The ion source that generates the nuclear projectiles is in the background behind the large pressure vessel, which contains high-voltage electrodes that serve to accelerate the projectiles. The nuclear projectiles are made to acquire a negative charge through the addition of electrons. As a result the nuclear projectiles are attracted to a positively charged terminal at the center of the pressure vessel. There the electrons are stripped off, and the resulting positively charged nuclei are accelerated further by effects of electrostatic repulsion to the front end of the large pressure vessel, which measures 100 feet in length and 20 feet in diameter.

16 and oxygen 16, carbon 12 and carbon 13, boron 11 and carbon 12, magnesium 24 and carbon 12, silicon 28 and oxygen 16, and silicon 28 and silicon 28. Of course, these resonances are generally less dramatic than those in the ^{12}C-^{12}C interaction, where there are far fewer competing effects.

In the past few years nuclear physicists in laboratories all over the world have turned their attention to nuclear molecules. This renaissance of interest stems from substantial new developments, both experimental and theoretical. On the experimental side powerful new cyclotrons and electrostatic accelerators have increased the energies at which the colliding particles can be brought together with high precision and have made it possible to measure scattering cross sections much more accurately and in many new systems. In addition ways have now been found to detect special nuclear products such as beryllium 8, which, although it has a life span of only 10^{-16} second, provides a sensitive new probe of the structure of nuclear molecules. On the theoretical side Yasuhisa Abe and his co-workers at the University of Kyoto have found that a more complicated version of the Imanishi model predicted many more low-energy nuclear-molecule resonances, including all those known at the time, than the original Imanishi model had been thought to predict. This stimulated a search for those predicted resonances that had not yet been identified experimentally.

Since the time nuclear molecules were first discovered their angular momentum has been one of their most important and most unambiguously determined properties. According to quantum theory, the angular momentum of any microscopic system such as a nuclear molecule can have only certain discrete values: $Jh/2\pi$, where J is any integer and h is Planck's constant. Although nuclear molecules are too evanescent for their angular momenta to be measured directly, such momenta can be determined experimentally from the angular distribution of the nuclei into which the nuclear molecules fission or from the angular distribution of the nuclear products into which the nuclear molecules decay. If the theoretical picture of nuclear molecules is valid, it should correctly predict the experimentally determined angular-momentum values. In fact it does, and it has also suggested additional resonance states, many of which have now been detected.

Walter Greiner and his co-workers at the University of Frankfurt made a significant contribution by recognizing a further extension of the original Imanishi model that is particularly important at the higher energies now being investigated. They noted that at certain energies resonances can appear simulta-



DUMBBELL CONFIGURATIONS, shown here in a highly schematic fashion (*middle, right*), characterize nuclear molecules formed in collisions between carbon-12 nuclei. In the elastic molecular state both carbon-12 nuclei are in their ground state (*middle*). In a typical excited molecular state one of the carbon nuclei is in its first excited state (*right*). Even with one or both of the carbon nuclei excited, however, the molecule retains its dumbbell form. Such nuclear molecules differ from prolate spheroid of a magnesium-24 nucleus in its ground state (*left*).

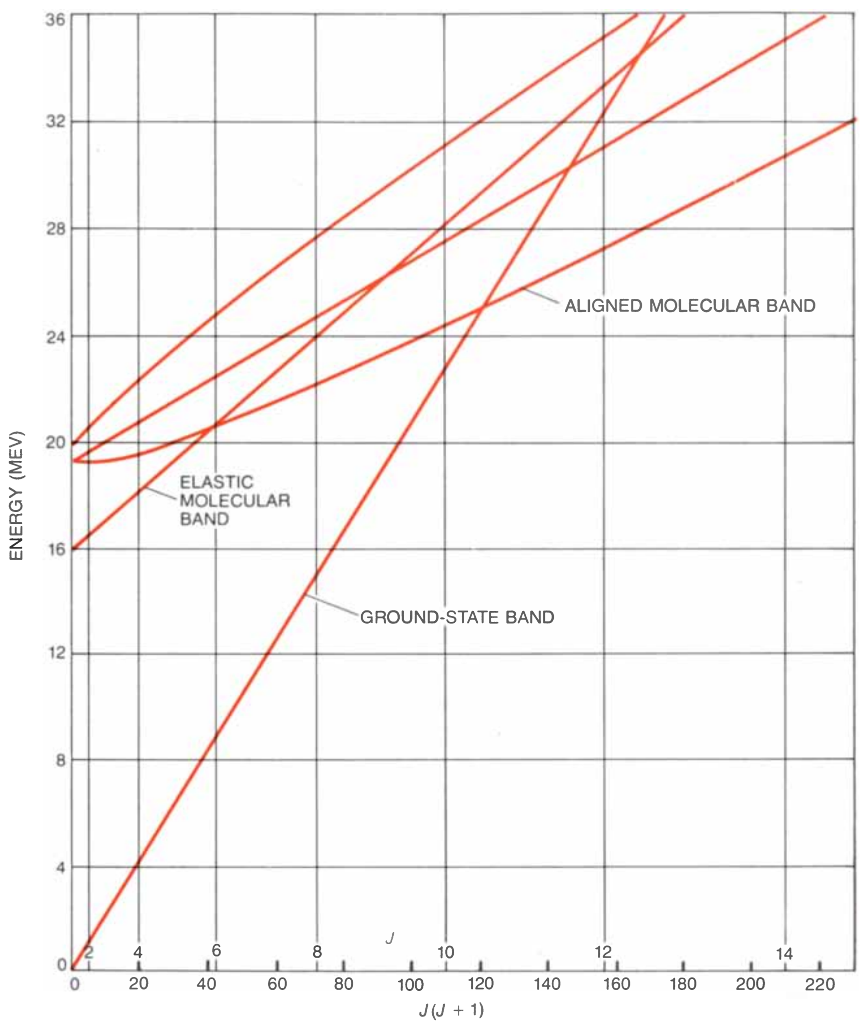


Fig. I

ROTATIONAL BANDS, or sets of states, correspond to particular nuclear configurations rotating at different quantized rates. States that constitute a band are points that fall on a straight line in a plot of energy against $J(J+1)$, where J is the total angular-momentum quantum number. The ground-state band, the elastic molecular band and the excited molecular bands correspond respectively to the three configurations in the illustration at the top of the page. The two highest bands represent configurations in which the spin of the carbon-12 nucleus in its first excited state is either perpendicular to or antiparallel to the angular momentum of the relative motions of the nuclei. Attention has been focused on the significance of the crossing of the elastic molecular band and the aligned molecular band in which the intrinsic and relative angular momenta are parallel. So far only some of the predicted states have been found experimentally.

neously in the relative motion of the constituent nuclei and in the excitation process through which energy is transferred from relative motion to internal excitation. The simultaneous resonances indicate that the probability of nuclear molecules forming under such conditions is greatly enhanced. The available data support this hypothesis.

An elegant interpretation of the rotational properties of the ^{12}C-^{12}C nuclear molecule has emerged out of the work of many investigators. Such a molecule, in its simplest quantum configuration, has the form of a rotating dumbbell. This form is quite unlike that of the magnesium-24 nucleus in its ground, or lowest-energy, state; even though the magnesium-24 nucleus has the same number of protons and neutrons as the two carbon-12 nuclei, it has the form of an American football (a prolate spheroid). It is a general consequence of quantum mechanics that any nonspherical entity with the form of a dumbbell or a football can retain its internal structure as its speed of rotation increases, but only at discrete quantized angular velocities. A series of such quantized states constitutes a rotational band, which is well known in atomic-molecule physics. The states of a given angular velocity, and hence of a given angular momentum, have energies that are proportional to $J(J+1)$, where J is the angular-momentum quantum number. The nuclear molecules that belong to a particular band all have the same internal structure; they differ from one another only in terms of the angular velocity with which the structure is rotating.

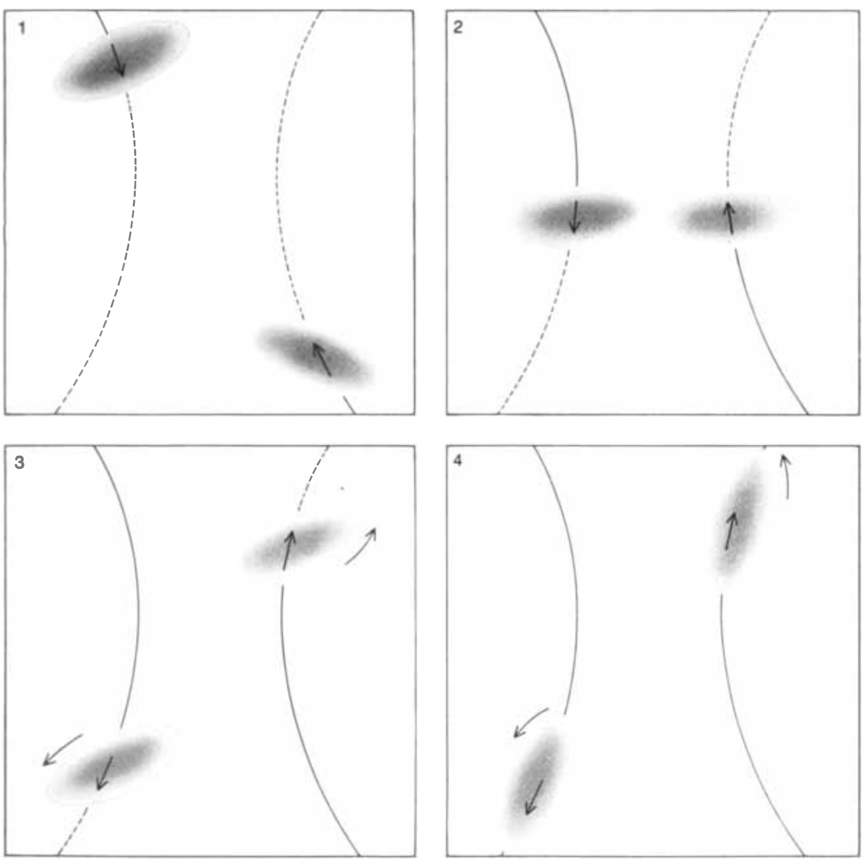
Since the energies of the nuclear-molecule states are proportional to $J(J+1)$, the members of a rotational band will fall on a straight line in a plot of energy against $J(J+1)$. In the elastic molecular, or least energetic, band the carbon nuclei that form the molecule are unexcited, that is, they too are in their least energetic state. The excited molecular bands, where one or both of the carbons are themselves in excited states, have a more complex structure reflecting the different ways the angular momentum of the dumbbell can couple with the angular momentum of the excited constituent nuclei to define the angular momentum of the nuclear molecule as a whole.

What is striking about this interpretation is that one of the excited molecular bands, an aligned molecular band in which the dumbbell is spinning about an axis that is aligned with the intrinsic spin of the excited constituent nucleus, crosses the elastic molecular band at one point. Moreover, aligned molecular bands corresponding to higher-energy intrinsic excitations or mutual excitations of the nuclei cross the elastic molecular band at even higher angular momenta and energies. What is the significance of these crossings? At the angular momenta and energies where two bands cross, the molecule assumes a configuration that is a mixture of the characteristics of the two bands. For example, at the point where the elastic molecular and aligned bands cross, the molecule in effect spends part of its time in each of them. At that point an elastic molecule, formed in the collision between two unexcited carbon nuclei, could become an aligned configuration without expending energy or angular momentum.

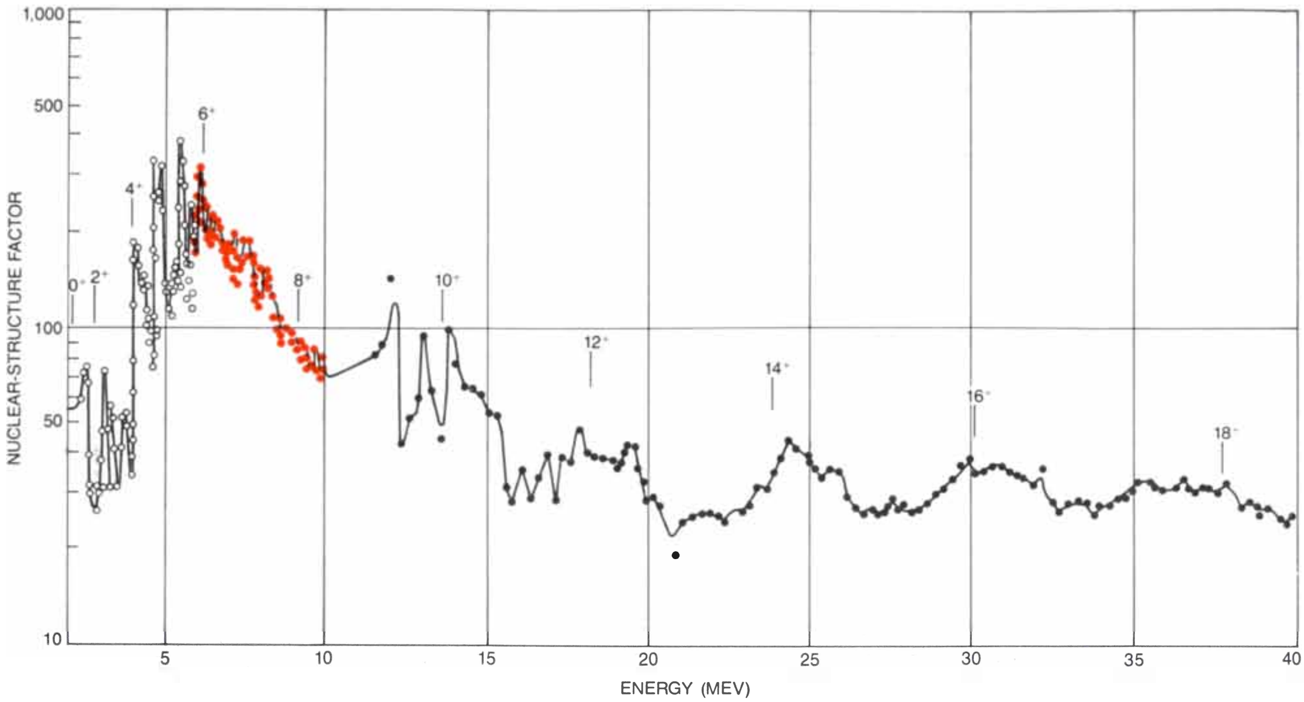
Under such circumstances there is a greatly enhanced probability that the aligned molecule will dissociate into two carbon nuclei, one of which would be in the excited state that characterized the band crossing. This band interpretation predicted that near the band crossings molecular resonances would split into two separate peaks, one peak corresponding to each band. Such double peaks have recently been observed in ^{12}C-^{12}C and ^{12}C-^{16}O nuclear molecules at the appropriate energies, lending credence to the molecular-band interpretation and stimulating a widespread search for the predicted doubling at crossings in other highly excited nuclear molecules.

The extended Imanishi model, which takes into account the coupling between the motion of the dumbbell and the intrinsic motions of the constituent nuclei and also the exchange of energy between these two kinds of motion, has yielded predictions that have been confirmed in many experiments. Abe and his collaborators worked with the model to predict a triplet of hitherto undetected resonance states at energies just above the Coulomb barrier, which is the energy needed to just overcome the electrostatic repulsion between the nuclei. The triplet has since been found. Although a number of other predicted resonances have not yet been identified, the general agreement obtained so far between the model predictions and the measured data is encouraging.

Whether or not the observed resonances correspond precisely in location to those originally predicted is no longer an important consideration, because relatively minor adjustments in the model parameters will make the band interpretation fit the data. The model also requires that when a nuclear molecule in an aligned configuration dissociates through inelastic scattering, the emerging excited carbon nuclei will all be spinning in a common direction. Difficult measurements to confirm this phenome-



GRAZING COLLISIONS between carbon-12 nuclei that are known to be shaped like doorknobs can set each nucleus to rotating about any axis perpendicular to the symmetry axis of the doorknob. The probability that both nuclei will emerge from the collision in rotating excited states has been shown experimentally to be comparable to the probability that only one of the nuclei will be promoted to such a state. That suggests a "gear wheel" interaction where the two nuclei are set into equal and opposite rotation through friction at the point of contact.



TOTAL CROSS SECTION for the ^{12}C-^{12}C interaction is plotted as a function of the available energy. The open dots represent data obtained at the University of Münster, the colored dots data obtained at Yale and the black dots data obtained at the State University of New York at Stony Brook. The nuclear-structure factor represents that part of the interaction cross section that depends only on the structure of the carbon nuclei. The vertical lines indicate energies at which current models have predicted elastic molecular resonances. Each resonance is labeled by the total spin in units of $h/2\pi$, where h is Planck's constant. The apparent lack of substructure in the higher-spin resonances may reflect the fact that the corresponding measurements were not made with enough precision to reveal such substructure if it was present. It is striking that resonances appear to exist throughout the 40-MeV range of energy that has been studied so far.

non are now under way, and the results should help to establish the physical validity of the bands.

The band interpretation, the simultaneous-resonance picture and the large amount of new data that bolster them have resolved some of the paradoxical aspects of the original Imanishi model and the early data. Where extrapolation from the early data had suggested that at the center of certain stars carbon burns at a rate more than 10 times higher than that envisioned by any model of stellar evolution, recent work indicates that the difficult early measurements contained experimental errors and hence the extrapolation was incorrect. The carbon-burning rate required by current data is of the same order of magnitude as the rates proposed by these astrophysical models. Where the original Imanishi model had made the apparently unphysical suggestion that the nuclear surfaces involved in nuclear-molecule phenomena frequently penetrated one another undisturbed, recent work makes this suggestion more understandable. This work indicates that when angular-momentum effects are properly taken into account, the nuclear surfaces are indeed remarkably transparent.

Much of the latest work in this field centers on the measurement of total fusion cross sections: the probabilities of the nuclei involved in nuclear collisions coming together to form a single compound nucleus. Since the nuclear attraction between the two nuclei is very strong at nuclear-molecule distances, it was expected that the formation of nuclear molecules would enhance the probability of the nuclei's fusing, as in the case of two carbon nuclei coming together to form a compound magnesium nucleus. This expectation has been confirmed experimentally for ^{12}C-^{12}C and ^{12}C-^{16}O collisions, in which the fusion resonances appear to be in gratifying agreement with the states the molecular-band interpretation predicts.

In early studies of the ^{16}O-^{16}O collision no peaks had been seen that suggested nuclear molecules had formed, presumably because such peaks had been smeared out by the large number of competing compound nuclear effects. Now, however, resonance structure indicative of nuclear molecules has appeared in ^{16}O-^{16}O fusion data acquired by Peter Sperr and his co-workers at the Argonne National Laboratory and by Florent Haas and his co-workers at the University of Strasbourg. Not all the fusion data, however, show resonance structure. In collisions between oxygen-18 (^{18}O) nuclei, for example, the presence of two valence neutrons outside the basic oxygen-16 core could smear resonances that might otherwise be apparent. The presence of two valence neutrons and one valence proton in fluorine 19 (^{19}F) might explain why there is no resonance structure in ^{19}F-^{12}C collisions, but here the explanation is much less persuasive. The difficult measurements of the cross sections of these interactions are only in their infancy, and so resonance structure may yet be detected.

Quite recent measurements have revealed ragged peaks in the ^{12}C-^{12}C reaction cross sections at high energies. Each ragged peak seems to be the envelope of a large number of sharp and closely but irregularly spaced resonances that may correspond to specific states of the magnesium-24 compound nucleus. Feshbach has suggested that the ragged peaks might well be a classic illustration of his "doorway" model of nuclear interactions, which he developed to describe interactions that involved nuclei much lighter than those of carbon. In the doorway model the carbon-12 target and the carbon-12 projectile are assumed to combine initially to form a particularly simple state that can either dissociate back to the original target and projectile or pass through a figurative doorway and develop stepwise through a series of more complex configurations toward the statistical equilibrium characteristic of a highly excited compound nucleus of magnesium.

Much work remains to be done in order to substantiate the doorway model of heavy-ion interactions. For example, according to quantum theory the underlying sharp compound resonance states into which the doorway state can dissolve must all have the same spin and parity (intrinsic symmetry) as the molecular doorway state, since the total spin and parity are conserved. If the experimentally determined spin and parity values satisfy this requirement, the doorway model will receive strong support. Furthermore, in order to conclusively identify the doorway as a molecular one it must be shown experimentally that each of the sharp states has a substantial fraction of the molecular configuration in its intrinsic structure. Here measurements are now under way.

Let me summarize what experiments have revealed about the structure and dynamics of ^{12}C-^{12}C nuclear molecules, since they are the kind of nuclear molecule that has been studied the most. Molecular resonances have appeared every time a new range of energies has been closely scrutinized. At higher energies well above the Coulomb barrier the molecular resonances appear as fragmented peaks a few million electron volts wide, which are composed of narrow subresonances typically a few hundred thousand electron volts wide. Most of the work on the carbon molecules has focused on what happens when one or both of the colliding nuclei are promoted to the lowest excited state of a carbon nucleus at 4.43 MeV. When the energy of the colliding nuclei is increased toward the maximum that can be achieved with the existing high-precision accelerators, however, a variety of excited states have been found to participate. For example, Karl A. Erb and his co-workers at Yale and Ken Katori and his co-workers at Tsukuba University have seen one carbon nucleus absorb 14.05 MeV and move to a higher spin state as the other carbon nucleus either remained in the ground state or absorbed 4.43 MeV. In the latter case 18.48 MeV of energy, which is an extremely large amount for nuclear phenomena, was transferred from relative motion to internal excitation through the simple mechanism of rotating both carbon nuclei to higher spin states.

The collisions in which both nuclei are simultaneously promoted to higher rotational states have surprisingly high cross sections; the probability that both nuclei will be excited is comparable to the probability that only one nucleus will be. That is in dramatic contrast to the normal situation in nuclear collisions, and to account for the anomaly we have proposed a "gear wheel" interaction in which the two nuclei are set into equal and opposite rotation through friction at the point of contact in off-center collisions. Experimental proof that the angular momenta in such collisions are oppositely aligned has not yet been obtained but would provide a unique signature for this simple excitation mechanism.

Most of the theoretical work with nuclear molecules has concentrated on macroscopic properties such as their rotational characteristics. Recently it has become possible to also study such microscopic properties as the behavior of individual protons and neutrons within the colliding nuclei. For example, at the Oak Ridge National Laboratory, Joachim Maruhn and Ronald Y. Cusson have calculated how the density of matter in a head-on ^{12}C-^{12}C collision changes in the course of the brief life of the interaction. The phenomena involved are so complicated that Maruhn and Cusson made certain simplifying approximations in their calculations. For example, they restricted themselves to head-on collisions so that they did not have to consider the effects of angular momentum, and they treated each proton and neutron as if it "felt" only the mean force of the remaining 23 protons and neutrons. In particular they ignored all effects that individual collisions between the protons and neutrons would have on orbital configurations within the nuclei involved. It was particularly gratifying that nuclear-molecule configurations emerged even from these crude microscopic calculations; there had been no a priori reason to believe they would.

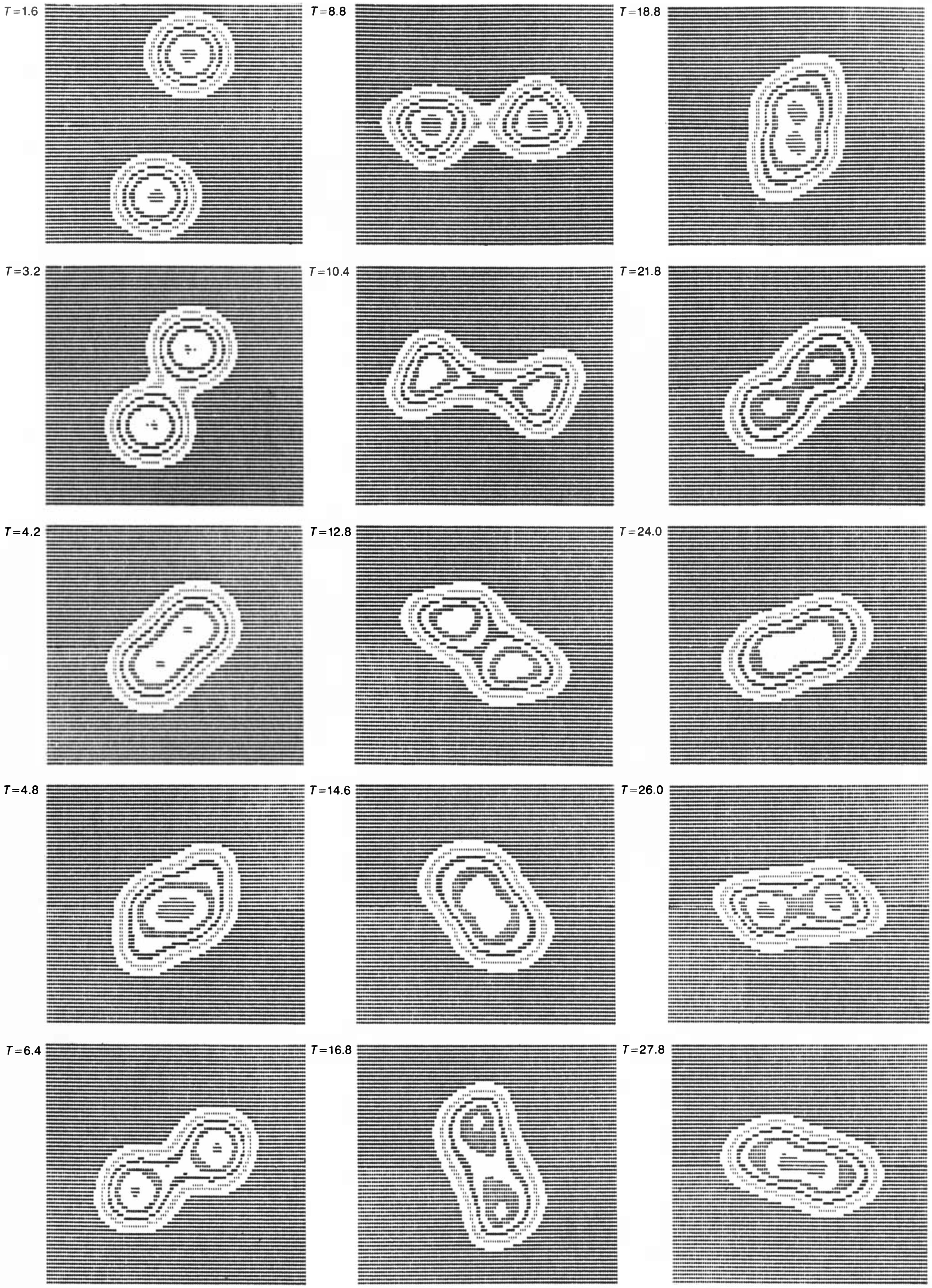
Work is now under way at M.I.T., Yale, Oak Ridge, the University of California at Berkeley and the Lawrence Livermore Laboratory that promises to increase the accuracy of these calculations. The early calculations apply to collisions where the carbon nuclei fuse into a highly excited magnesium-24 nucleus, vibrate collectively and then separate back into two carbon nuclei. Since the collision was assumed to be head on, the calculations reveal nothing about the rotation of the system. After the collision the density of each nucleus varies from point to point in a manner that is irregular compared with the smooth variation in the density prior to the collision. The irregular density is a signature that energy was transferred from relative motion to complex internal excitation. Hubert C. Flocard, Steven Koonin and Morton Weiss at Livermore have made even more ambitious density calculations for a collision between oxygen nuclei that was not head on and hence included rotational effects as well as vibrational ones.

The calculations suggest that at relatively low energies the density of the colliding nuclei never rises much above the value of the density at the center of a single carbon nucleus. At both low and high energies, however, a long neck forms during the collision to bind the carbon nuclei for a relatively long time into a molecular configuration that rotates and vibrates. The calculations have usually been limited to the early stages of the collision by the capacity of existing computers that cut short the calculations long before the collision reaches its final stage.

Ulrich Mosel and his co-workers at Justus Liebig University in Giessen have worked with a shell model of the nucleus, in which the protons and neutrons of the nucleus are assumed to form shells analogous to the electron shells of the atom, to trace the motions of individual neutrons and protons during the collision of carbon nuclei. They have obtained results that are similar to the Livermore ones. Although the techniques for making these microscopic calculations are still in their infancy, they promise to eventually provide a detailed picture of the role individual protons and neutrons play in heavy-ion collisions. Such a picture would constitute a major breakthrough in the understanding of nuclear dynamics and nuclear structure.

From an isolated curiosity in 1960 nuclear molecules have emerged as a common aspect of the nuclear structure and dynamics of those heavy-ion systems that have been studied so far. Nuclear molecules have provided a fresh answer to an old question: What happens to a nucleus as energy is added? A few years ago Peter D. Parker and his collaborators at Yale showed that to a rough approximation the spectra of excited states in light nuclei could be interpreted as though the radius of the nucleus increases by about 10^{-14} centimeter for each million electron volts of added energy. In other words, the nucleus expands when it is heated. If this were the only thing that happens, the nucleus would be a dull object indeed. It has now been found, however, that at certain specific energies, far above those necessary to boil off a neutron, the protons and neutrons in a nucleus form clusters and molecular configurations in which subgroups come together to form well-defined nuclei that move in a simple minuet with respect to each other. This opens up an entire new area of nuclear structure and nuclear dynamics.

CONTOUR LINES indicate the calculated density in the direction perpendicular to the scattering plane for collisions between oxygen-16 nuclei with an energy of 52.5 MeV and with an angular momentum of $13h/2\pi$. The unit of time is 10^{-22} second. These contour plots, calculated by Hubert C. Flocard, Steven Koonin and Morton Weiss at the Lawrence Livermore Laboratory of the University of California, illustrate how oxygen-16 nuclei are expected to come together to form a molecule, which rotates and vibrates after the 3×10^{-21} second shown here.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Fuel-Cell Power Plants

These devices that generate electricity directly from fuel without emitting pollutants are currently being scaled up to determine if they can be economic for electric utilities

by Arnold P. Fickett

Over the next decade electric utilities in the U.S. will require power generators that fulfill certain unusual requirements: high efficiency, low emission of pollutants, quiet operation and quick installation. The generators must be able to supply electricity in urban areas where conventional generators would be unacceptable for environmental reasons. A likely candidate is the fuel cell.

A fuel cell converts the chemical energy of a fuel into electricity directly, with no intermediate combustion cycle. For a device that was invented in 1839 (by Sir William Grove, a British jurist who made noteworthy contributions to science) the fuel cell has taken a long time to come into its own. It did furnish power for the Gemini and Apollo spacecraft, but that was an exotic and expensive application. Now the fuel cell, vastly improved over the spacecraft versions and in assemblies 1,000 times larger than the ones carried by the spacecraft, appears to have reached a stage where it can make a significant contribution to a nation's supply of electricity. Indeed, it is viewed by the electric-utility industry in the U.S. as an important alternative for meeting the load growth expected over the next two decades and for doing so in a way that is environmentally acceptable and conserves fuel.

In the short run the hope is that fuel-cell systems can be deployed in the 1980's for handling peak loads and for what the utility industry calls load following. Peaking generators are started only when the need for additional power is temporarily high. Load-following generators are started daily and run most of the time to cope with daily swings in the load; they may be shut down at night and over the weekend. As dispersed peaking or load-following generators, the fuel-cell power plant will most efficiently use liquid fuels from petroleum or coal, thereby stretching the nation's supply of fossil fuel. In the long run fuel cells integrated with coal gasifiers are seen as a possibility for central-station base-load plants, which operate continuously and use coal directly.

A fuel cell consists of two electrodes—a positive electrode, the cathode, and a negative one, the anode—separated by an electrolyte, which transmits ions but not electrons. A fuel, typically hydrogen, is supplied to the anode and oxygen (in air) is supplied to the cathode. A catalyst on the porous anode causes hydrogen molecules (H_2) to dissociate into hydrogen ions (H^+) and electrons. If the electrolyte is acidic, the hydrogen ions migrate through it to the cathode, where they react with electrons (supplied through the external-circuit load) and oxygen to form water (H_2O). The nature of the migrating ion depends on the electrolyte. Hydrogen ions migrate from the anode to the cathode in an acid electrolyte; hydroxyl ions (OH^-) migrate from the cathode to the anode in an alkaline electrolyte; carbonate ions (CO_3^{--}) migrate from the cathode to the anode in a carbonate-salt electrolyte and oxide ions (O^{--}) migrate from the cathode to the anode in a solid oxide electrolyte. In each instance the reactions yield electrons that, if the electrodes are connected by a conductor, flow from one electrode to the other through the external circuit. Since a flow of electrons is an electric current, the electrons moving in the circuit can be used to light a lamp, drive an electric motor and so on.

The maximum direct-current voltage produced by a fuel cell is a thermodynamic function of the fuel and the oxidant. For a cell operating on hydrogen and oxygen the theoretical voltage at ordinary pressure and temperature is 1.23 volts. The actual voltage will be from .6 to .85 volt because of losses within the cell. The current produced is controlled by the rate at which the electrochemical reactions (the oxidation of hydrogen, which entails the removal of electrons from hydrogen atoms, and the reduction of oxygen, which entails the addition of electrons to oxygen atoms) proceed and also by the surface area available for the reactions.

A simple fuel cell can be made by putting two carbon rods catalyzed with small amounts of platinum into a jar containing sulfuric acid. If hydrogen is bubbled across the surface of one rod and oxygen across the surface of the other, about one volt of direct current will be generated as a result of the electrochemical reaction between the hydrogen and the oxygen. The sulfuric acid functions as the electrolyte. The voltage can be observed by connecting a voltmeter between the carbon rods. If the rods are connected through an external load, electrons will flow through the circuit, generating electric power.

Although this fuel cell will produce a voltage, it is impractical for several reasons. The carbon rods functioning as electrodes do not offer a large surface area for the reactions. Moreover, sulfuric acid is not a stable electrolyte, and jars are not easy to assemble in large multicell groups.

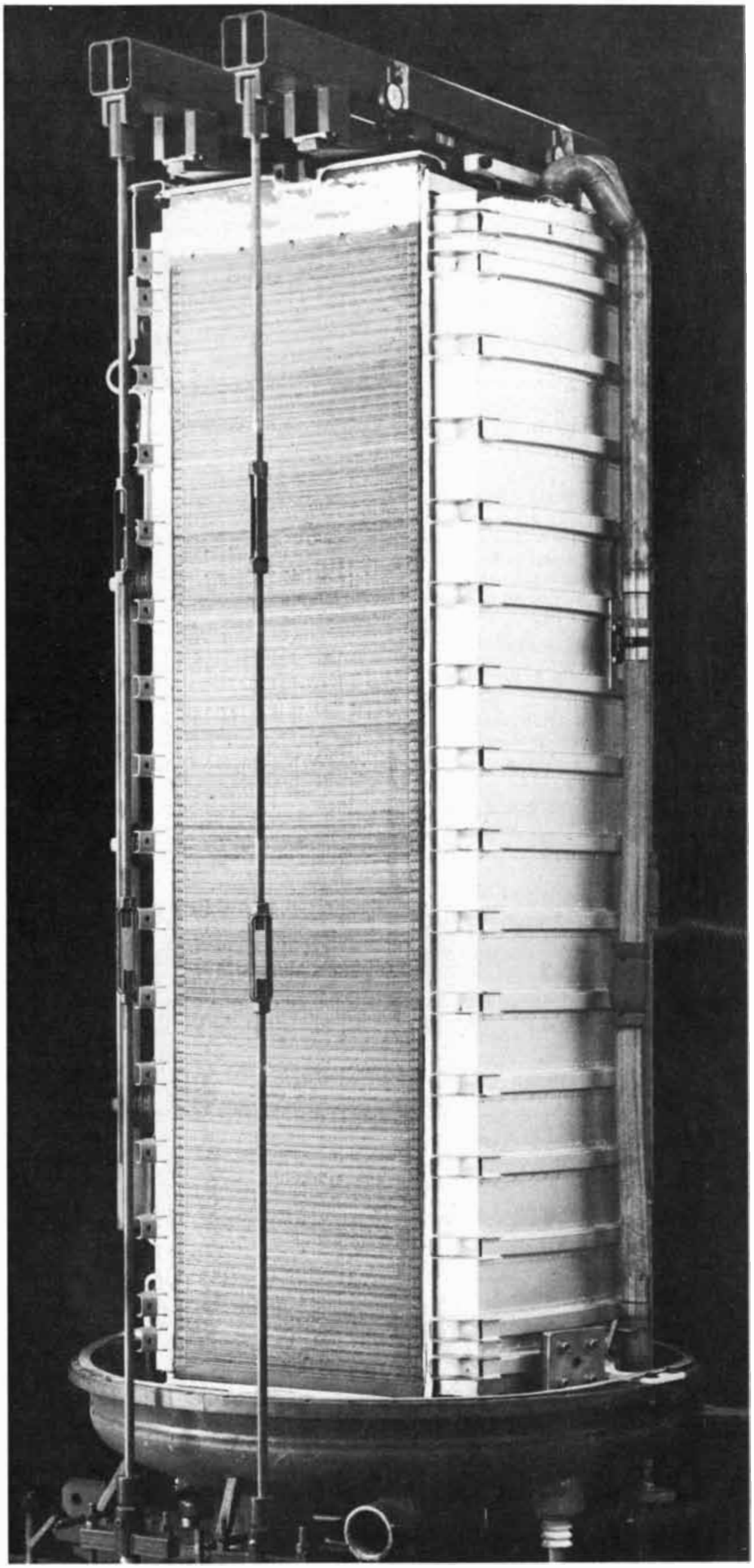
A practical configuration for a fuel cell can be obtained by putting the electrolyte in a thin matrix or blotter sandwiched between two porous electrodes. (The porosity gives the electrodes a large surface area.) Catalysts for the respective electrochemical reactions are incorporated in the electrodes. Individual fuel cells are combined to form a "stack" having a voltage output that is the product of the voltage of one cell and the number of cells. A "power section," an assembly of fuel cells designed to yield a significant amount of power, may consist of one stack or more.

If a power plant made up of fuel cells is to be a useful generator of power for an electric utility, it must use the type of fuel that is economically available to the utility, and it must produce alternating current compatible with the utility's transmission system. Therefore a fuel-cell power plant must include not only fuel cells but also a fuel processor and a power conditioner. The fuel processor converts a utility fuel, such as coal, into a hydrogen-rich gas, and the power conditioner converts direct current into alternating current.

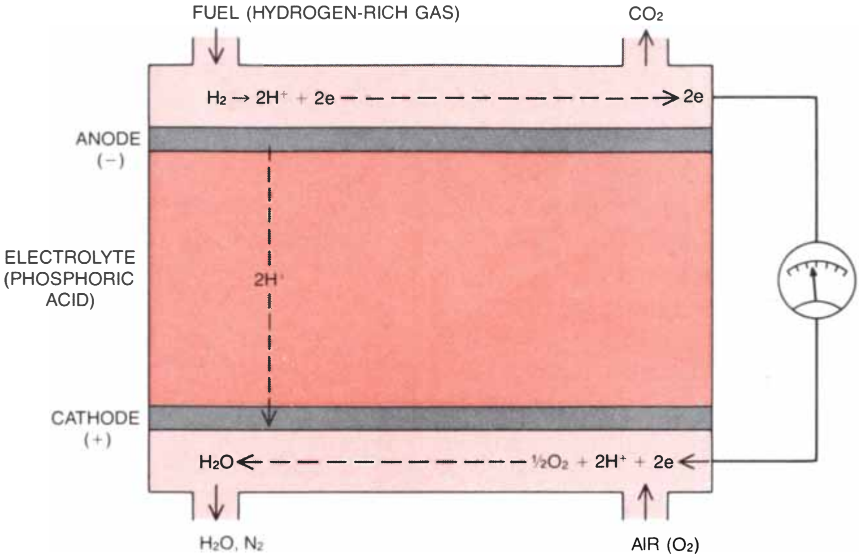
The cost and the efficiency of the total power plant are to a large extent governed by the performance of the individual cell. A rough estimate of the overall efficiency of a power plant, from fuel to alternating-current power, can be made through the equation $N_p = 59V_c$, where N_p is the efficiency of the plant (as a percent) and V_c is the voltage of a single cell. This relation is accurate to within about 5 percent and illustrates the importance of single-cell voltage in establishing the overall efficiency of a plant.

The capital cost of a power section, expressed in terms of dollars per kilowatt of capacity, is inversely proportional to the power density of the single cell. The power rating of the cell therefore in effect establishes the capital cost of the power section. Typically the power section will cost $100 per kilowatt, which represents from 12 to 30 percent of the cost of the power plant, depending on the complexity of the fuel processor. Coal processing is much more complex than oil processing, and so a power plant fueled by coal will have a higher total cost than one fueled by oil. The goals of most fuel-cell programs are to improve the performance of the cell, reduce its cost per unit of area and increase its reliability and endurance.

Fuel cells can be classified by electrolyte, by temperature of operation, by oxidant and by fuel. It might seem that there would be a limitless combination of these factors, but relatively few of the possible combinations are practical. This limitation results from the constraint the electrolyte imposes on the other factors and vice versa. For example, the selection of phosphoric acid as the electrolyte establishes a range of operating temperatures from 150 to 200 degrees Celsius (302 to 392 degrees Fahrenheit). Below 150 degrees C. phosphoric acid has poor conductivity; above 200 degrees the electrode materials become unstable. A fuel cell with a molten-carbonate electrolyte requires an operating temperature of between 600 and 700 degrees and a fuel stream



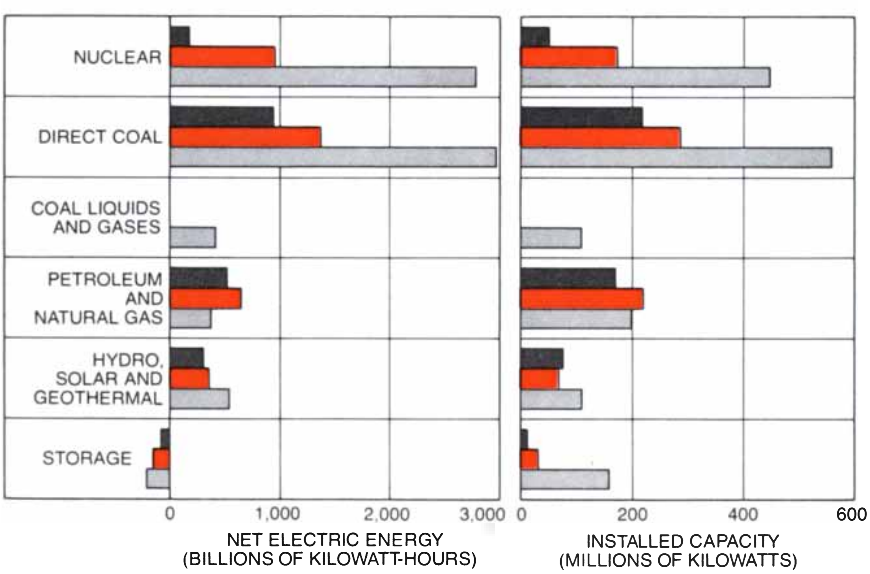
FUEL-CELL "STACK" was photographed at the plant of the manufacturer, the United Technologies Corporation. Each layer in the stack is a fuel cell capable of producing 500 watts of power at .65 volt. The output of the stack is that power (or voltage) times the number of cells in the stack (nearly 500). The stack is one of 20 that will be installed in the 4.5-megawatt plant to be built in New York City for an advanced test of the technology. Cells have phosphoric acid as electrolyte and will use as fuel a hydrogen-rich gas from naphtha.



OPERATION OF A FUEL CELL is based on the electrochemical reactions between a fuel, in this case a hydrogen-rich gas made from coal or oil, and an oxidant, in this case oxygen in air. At the anode of the cell hydrogen molecules are oxidized (an electron is removed from each of the two hydrogen atoms in the molecule) to form hydrogen ions. The ions are transported through the electrolyte to the cathode, and the electrons flow through an external circuit to the cathode, producing power. At the cathode hydrogen ions, electrons and oxygen form water.

that contains carbon oxides as well as hydrogen.

Cells with potassium hydroxide as the electrolyte operate best between 50 and 150 degrees. This electrolyte cannot tolerate oxides of carbon in either the fuel or the oxidant. The reaction of the hydroxide with carbon oxides leads to the formation of potassium carbonate, which drastically diminishes the performance of the cell. Fuel cells with this electrolyte (and pure hydrogen and oxygen as the reactants) have served well on spacecraft, but their nonspace use is limited by the cost of producing reactants that are free of carbon oxides.



ELECTRICITY DEMAND AND CAPACITY are charted as they existed in 1976 (*dark gray*) and as they have been projected by the Electric Power Research Institute for 1985 (*color*) and 2000 (*light gray*). The estimates assume a reduction of 17 percent in the total demand through conservation. Projections are for nuclear and coal plants to supply 82 percent of the electricity produced. Shortfalls in electricity produced by nuclear or coal plants resulting from siting or environmental problems will have to be made up by production from other energy sources such as liquids and gases. Fuel cells offer efficient utilization of those premium fuels.

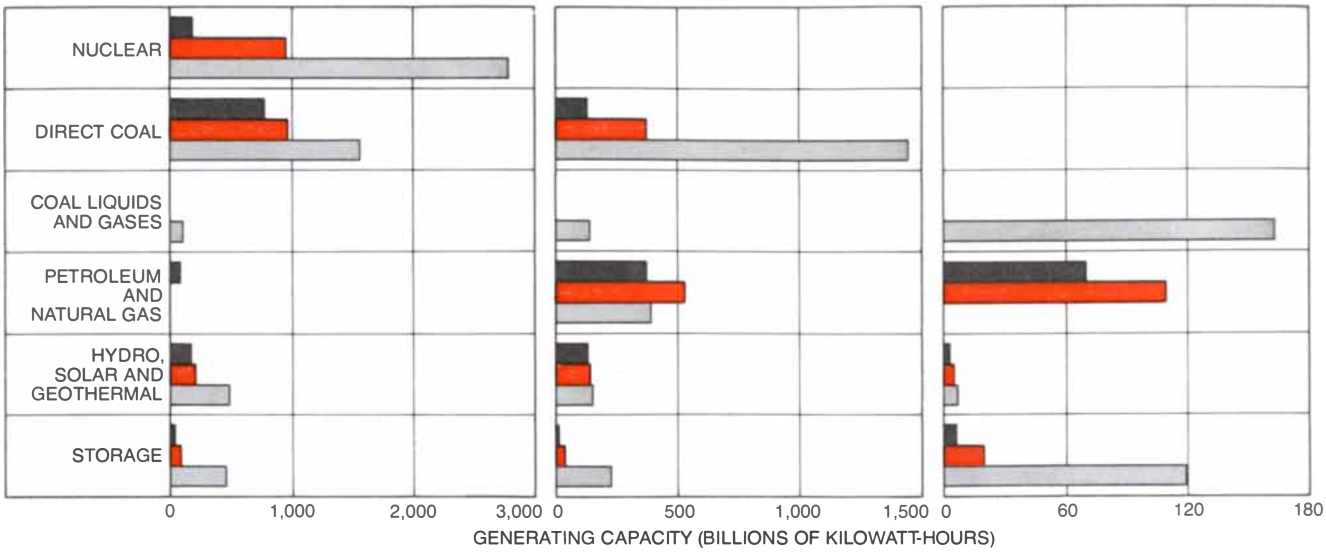
Fuel cells with sulfuric acid, sulfonic acid or solid polymers as the electrolyte are limited by the vapor pressure of the water in the electrolyte. If air is the source of the oxygen, such cells must operate at temperatures below 100 degrees C.; otherwise too much water goes out with the nitrogen (the other major constituent of air) that is vented, and the electrolyte becomes unstable. At temperatures below 100 degrees C., however, the high efficiency desired from fuel-cell power plants serving electric utilities cannot be achieved. These electrolytes are therefore not receiving much attention for nonspace applications.

The electrolytes that are receiving attention are phosphoric acid and molten-carbonate salt. About $48 million has been spent this year by Government agencies and such organizations as the Electric Power Research Institute on nonspace fuel cells. About $39 million of that amount supported work on fuel cells based on phosphoric acid and $7 million work on cells based on molten carbonate.

Research has also been conducted for a number of years on solid electrolytes that conduct ions of oxygen. Such a solid-oxide fuel cell operates at a temperature of about 1,000 degrees C. The technology still has a considerable way to go before it can be employed in practical fuel cells.

Interest in the fuel cell as a utility power plant results from its efficiency, its environmental acceptability and the fact that it is modular. In terms of efficiency the key point is that the fuel cell, not being a heat engine, is not limited by the Carnot cycle, which describes the limits on the efficiency of such engines. The fuel cell therefore offers the potential for higher conversion efficiencies than thermal generators can achieve. Since the efficiency of the fuel cell is determined chiefly by the voltage of the single cell, the efficiency of a fuel-cell power plant is (to a degree) independent of the size of the plant.

Moreover, in contrast to conventional generators the fuel cell is nearly constant in efficiency in the range from 25 to 100 percent of its rated power output. Hence fuel cells providing power for load following offer the potential of conserving fuel. The potential can best be visualized by considering heat rate rather than efficiency. The heat rate is a measure of the quantity (expressed in British thermal units) of fuel required to generate one kilowatt-hour of electricity. At the rated power output an oil-fired power plant operating on a combined cycle (in which waste heat from a primary generator such as a gas turbine is employed to run a secondary generator such as a steam turbine) is the most efficient power generator now available; it requires 8,500 B.t.u.'s of fuel per kilo-



FUEL SOURCES for the generation of electric power are compared for different types of generators in 1976 (*dark gray*), 1985 (*color*) and 2000 (*light gray*). A base-load electric-generating plant (*bars at left*) operates continuously and is best run on coal or nuclear power. A load-following plant (*bars in center*) is typically run during the day, except on weekends, to follow swings in the load, and a peaking plant (*bars at right*) is started up only when the demand for electric power is high. The fuel for load-following and peaking plants is more likely to be fossil-fuel liquids or gases. Fuel-cell plants that were fueled by liquids would be used as either load-following or peaking plants.

watt-hour, compared with the projected requirement of 9,000 B.t.u.'s for a first-generation power plant based on fuel cells. At 40 percent of rated capacity, however, which is realistic in load-following operations, the combined-cycle plant will require 11,250 B.t.u.'s per kilowatt-hour, compared with 9,250 for a fuel-cell plant. Thus the fuel cell offers the greatest potential for fuel conservation when it is used for load following, meanwhile allowing the other generators to operate close to their maximum efficiency.

Since the fuel cell produces power by an electrochemical process rather than by combustion, the only emissions other than air and water are those from the fuel processor. Fuel-cell power plants that work on fuels from petroleum or coal will produce sulfur dioxide and nitrous oxide emissions respectively of less than .0001 and .2 pound per million B.t.u.'s. These emissions and others will be at least 10 times lower than Federal standards.

The sulfur emissions are low because fuel-cell power plants do not tolerate sulfur compounds well, so that such compounds are removed by a special subsystem of the fuel processor. The other emissions are low because of the inherent cleanness of the electrochemical processes. A fuel-cell plant is expected to operate quietly and to require no makeup water at ambient temperatures of 35 degrees C. (95 degrees F.) and below. As a result of its environmental attributes a fuel-cell plant can be located in the area it is to serve. Enabled to disperse fuel-cell plants in this way, the utility company can defer investments in new lines for the transmission and distribution of power and can reduce the losses inherent in transmission lines.

Since the fuel cell is essentially modular in configuration, the components of a plant can be made in a factory by mass-production techniques instead of having to be built at the site. Construction costs will therefore be lower. In addition the availability of small modular generators enables a utility to add relatively small blocks of capacity, matching the growth of demand in an economical way. The existence of small, reliable modular plants could also increase the inherent reliability of a utility system and allow a reduction in the reserve generating capacity the utility maintains.

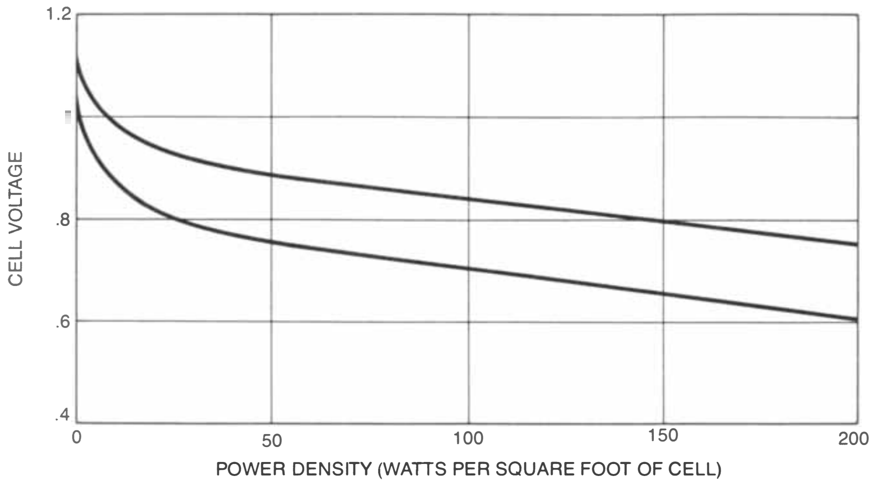
As a result of these characteristics, which are not available in conventional power generators, the fuel cell could serve a utility network in several ways. Relatively small fuel-cell power plants (with a capacity ranging from 25 to 200 kilowatts) could be set up in commercial and residential buildings. Such a plant would use natural gas as a fuel. The plant would provide both electric and thermal energy (the latter from the waste heat of the fuel cells), consuming the same amount of fuel ordinarily required for the thermal demand alone. Efficiencies approaching 100 percent have been projected for fuel-cell power plants of this type. The plants would have the added advantage of stretching the supply of natural gas.

Larger plants, ranging in capacity from five to 25 megawatts, could be dispersed throughout an electric-utility system to perform load-following duty efficiently. If they were equipped to recover waste heat (a matter that is under study), they would represent a highly efficient end use of fossil-fuel resources. Efficiencies of more than 80 percent (based on fuel consumption) are attainable.

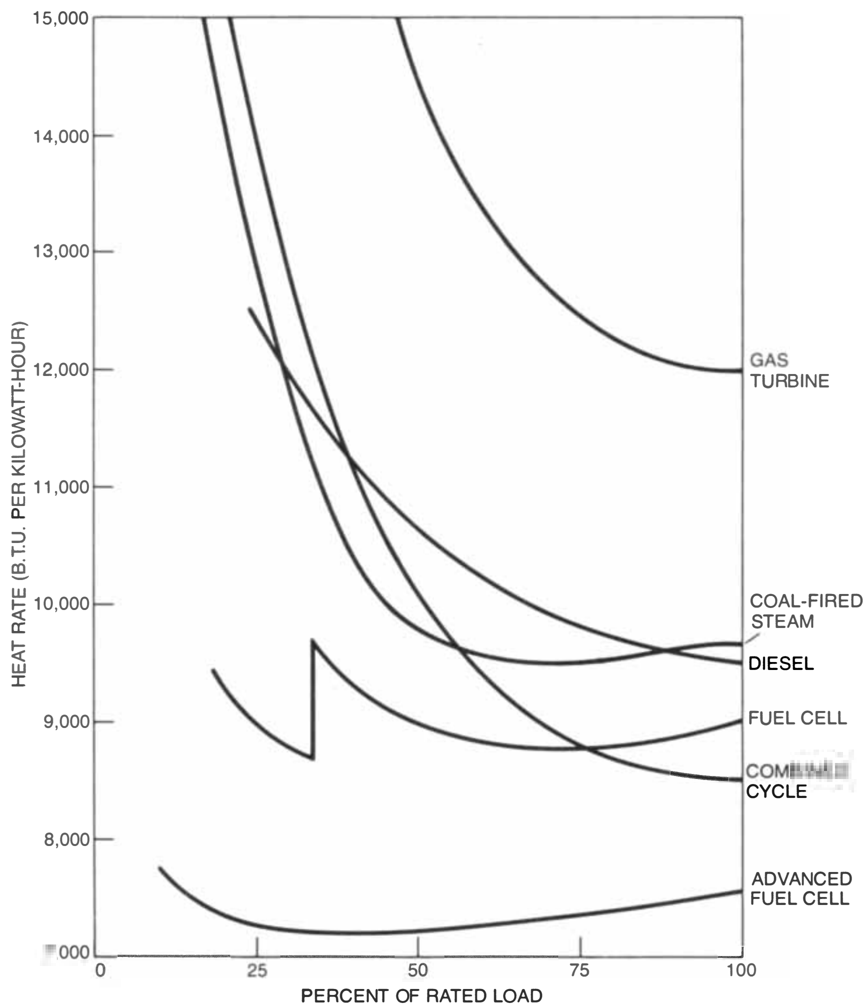
In the more distant future fuel cells could be integrated with coal gasifiers to provide large, central base-load power plants that utilize coal directly. The capacity of such plants would range from 150 to 600 megawatts. A plant of this kind is projected to be more than 45 percent efficient, based on the heating value of the coal consumed.

Three major projects aimed at hastening the development of the fuel cell as a commercial technology are in progress. One is an extension of a project named TARGET (for Team to Advance Research for Gas Energy Transformation). The project was originally sponsored jointly by the United Technologies Corporation and a consortium of gas and gas-electric utilities. Starting in 1967 the group supported the development of phosphoric acid fuel cells for on-site residential and commercial applications.

The TARGET power-plant concept utilizes gas (natural or synthetic) as the fuel, converting it into electricity and into thermal energy for heating and cooling. The efficiency is quite high, since virtually all the waste heat is directed toward the heating and cooling part of the operation. The industry has spent about $100 million on the concept so far. In 1972 and 1973 more than 60 power plants of 12.5-kilowatt capacity



PERFORMANCE CHARACTERISTICS of a fuel cell have a major influence on the design and cost of a power plant. The power density and the voltage are plotted here for a fuel cell with a phosphoric acid electrolyte (*bottom curve*) and as projected for a fuel cell with a molten-carbonate electrolyte (*top curve*). The cost of a "power section" generating power from fuel cells goes down as power density rises, but so does the voltage. Plant design is often a matter of setting voltage at the desired level of efficiency and accepting the resulting power density. Efforts at improving the cell focus on obtaining a higher voltage for a given power density.



CONSERVATION POTENTIAL of the fuel cell can be seen in comparisons of its heat rate (the number of British thermal units of fuel required to produce one kilowatt-hour of electric energy) with that of other types of power plant over a wide range of loads. Fuel cells installed for load-following duty would enable other generators to operate at their most efficient rate.

were tested under field conditions; the tests led to the development and demonstration of a 40-kilowatt plant in 1975. Now, in an extension of the program with the support of the Department of Energy and the Gas Research Institute, the objective is the testing of 50 plants of 40-kilowatt capacity between 1979 and 1981 and the attainment of commercial availability of the technology in 1982.

The second project originated with the electric-utility industry in 1971, when a group of utility companies joined the Edison Electric Institute and United Technologies in an assessment of the potential benefit of fuel cells to the industry. The venture led in 1972 to the FCG-1 (for fuel-cell generator) program, an effort sponsored by United Technologies and nine utility companies to develop a 26-megawatt phosphoric acid power plant for commercial service by 1980.

The FCG-1 program developed and demonstrated (in 1976 and 1977) a one-megawatt pilot plant. The demonstration showed that a power plant fueled by naphtha could provide large amounts of energy to a utility system while satisfactorily meeting the industry's operational requirements for heat rate, emissions and load-following capability.

In 1976, seeking to expedite the commercial application of fuel cells, the Electric Power Research Institute and the Energy Research and Development Administration (now the Department of Energy) became involved in the FCG-1 program. One result was a project to design, build and test a 4.5-megawatt module of the FCG-1 power plant in a utility system by 1980. The Consolidated Edison Company of New York was chosen as the host utility for the demonstration. The project will cost about $60 million, of which about 55 percent will be provided by the Department of Energy, 20 percent by the Electric Power Research Institute, 20 percent by United Technologies and the remainder by a group headed by Consolidated Edison.

The plant will provide not only an important technical demonstration but also an opportunity to validate the claims of fuel-cell advocates about the advantages of the technology in terms of versatility and ease of siting. The plant will be in downtown New York City, where a conventional fossil-fuel generator would be out of the question because of its emissions. Clean, dispersed fuel-cell power plants located in urban areas offer one of the two options for increasing electric-generating capacity to meet rising demands. (The other option is to build conventional plants in remote locations and transmit the electricity into the city. The cost of obtaining rights-of-way and building new transmission lines has become almost prohibitive.)

The third major project grew out of efforts undertaken by the gas- and electric-utility industries to advance the technology of the fuel cell. The focus of the program, which has now been joined by the Department of Energy and the Electric Power Research Institute, is a molten-carbonate fuel-cell power plant that will be integrated with fuels derived from coal and will be available for commercial service in about a decade. The organizations involved in the program are the Argonne National Laboratory, the Energy Research Corporation, the General Electric Company, the Institute of Gas Technology and the Oak Ridge National Laboratory.

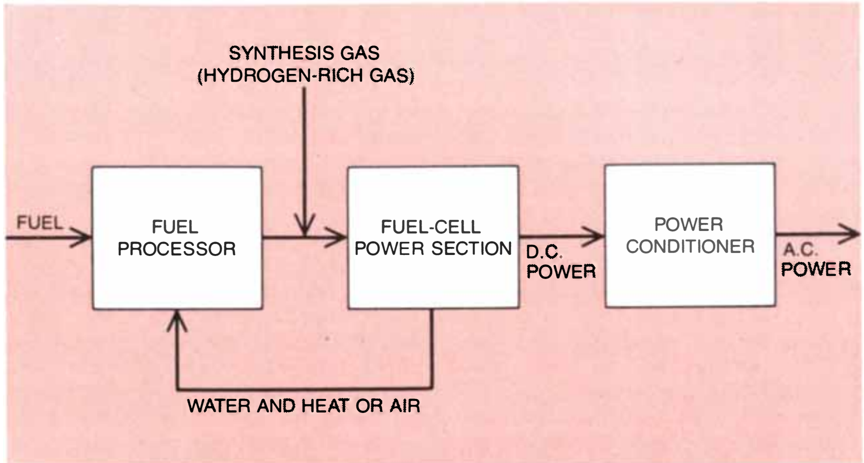
The technology of the phosphoric acid fuel cell is highly developed. A single cell consists of a thin porous matrix containing concentrated phosphoric acid. This electrolyte matrix is sandwiched between porous carbon electrodes catalyzed with small amounts of platinum, typically from .25 to .75 gram per square foot of cell area. Cells operate at temperatures of from 150 to 190 degrees C. and produce from 100 to 200 watts of power per square foot at .64 volt of direct current (assuming the efficiency of the plant to be 38 percent).

The present phosphoric acid cell is nearly adequate for utility applications. Its efficiency has been demonstrated at power densities that are consistent with reasonable stack costs, provided the stacks are made by mass-production techniques. The capital cost is no longer controlled by the inherent cost of the materials; the governing factor now is the level of production. The Electric Power Research Institute estimates that a complete phosphoric acid power plant could be mass-produced for $350 per kilowatt (in 1980 dollars) if the rate of production were 500 megawatts per year. This would be consistent with the cost of other generators designed for load-following operation.

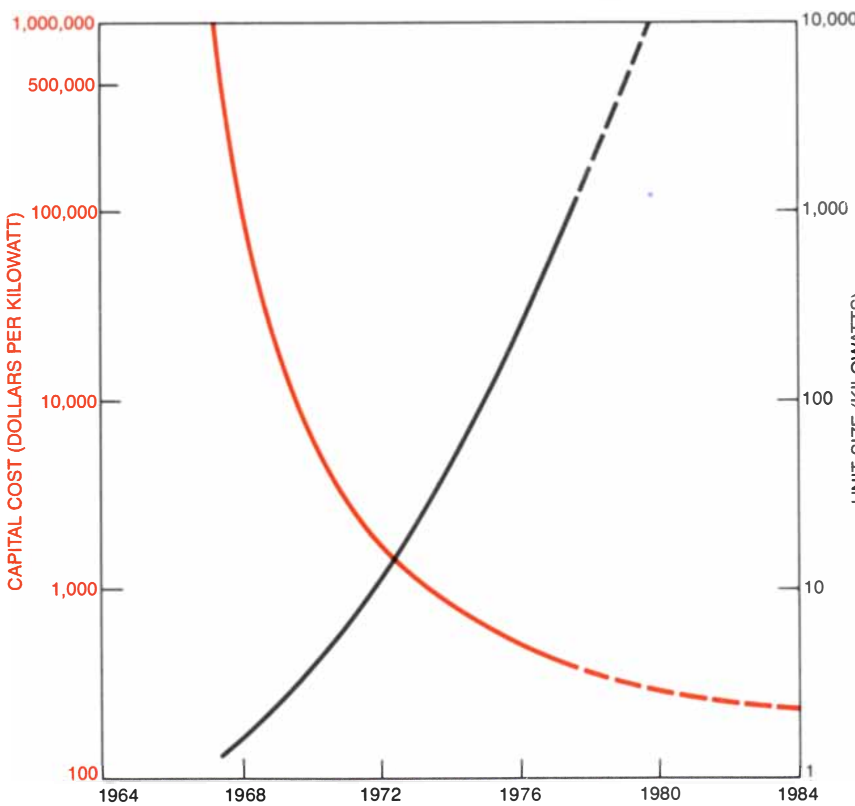
Although small phosphoric acid stacks have operated for many thousands of hours, the desired 40,000 hours (four and a half years) of endurance by a large stack has yet to be demonstrated. The 4.5-megawatt demonstration plant to be built in New York City is scheduled to be operated for 6,700 hours. Improvements beyond the technology incorporated in the New York demonstration promise cell stacks that will achieve the necessary 40,000 hours. The ultimate life and reliability of phosphoric acid plants will be established only after significantly more experience has been gained with large plants. Beyond this first-generation phosphoric acid fuel cell, prospects are excellent for evolutionary advances that project even better efficiencies and lower costs.

The molten-carbonate technology is at least five years behind the phosphoric acid technology. The electrolyte is a thin layer composed of molten-carbonate salt and an inert filler; it is sandwiched between two electrodes made of porous nickel. At the operating temperature of 650 degrees C. the reaction rate at the electrodes is so high that no special catalyst is needed. Under operating conditions nickel oxide forms on the oxygen electrode (the cathode) and becomes the active electrode material; nickel remains the active anode material.

Molten-carbonate cells have demon-



POWER PLANT based on fuel cells is represented schematically. A fuel, which could be coal or gas or a petroleum distillate, is converted by a fuel processor into a hydrogen-rich gas, which is what goes into the fuel cells. Power generated by a fuel-cell power section is direct current, which must be converted by the power conditioner into alternating current for distribution.



CAPITAL COST AND PLANT SIZE of existing and projected fuel-cell power plants are compared. The progression in unit size (*black*) and capital cost (*color*) is from a 1.5-kilowatt unit that was built for the Army in the late 1960's at a cost exceeding $100,000 per kilowatt to the 4.5-megawatt unit that will be tested in New York starting in 1980. The solid lines reflect actual figures, broken lines projected figures. Costs are projections for production quantities.

strated a power density of from 100 to 120 watts per square foot of cell area at .785 volt (45 percent power-plant efficiency). This higher voltage and a tolerance to carbon oxides are the advantages of the molten-carbonate technology. A small cell has operated for 14,000 hours, and a stack consisting of 19 one-square-foot cells has operated for 1,400.

Notwithstanding these promising results, significant problems remain. They involve mostly structural changes that take place in the electrolyte and the gradual loss of electrolyte over long periods of operation. At present these problems limit the endurance and reliability of the cells, but there is reason to expect that they will be solved. The best estimate of the capital cost of a molten-carbonate power plant in mass production is $350 per kilowatt-hour (in 1980 dollars), the same as the cost of a phosphoric acid plant.

The other subsystems—the fuel processor and the power conditioner—are virtually in hand for a first-generation power plant. In other words, fuel processors capable of re-forming natural gas and naphtha so that they can function in a fuel-cell plant are available. Further efforts will be required to expand the fuel-processing capability beyond naphtha to heavier petroleum liquids and to liquids made from coal. The power conditioners now available appear to be satisfactory for both first-generation fuel-cell plants and for the more advanced ones that will come later.

The long-range objective of integrating a fuel-cell system and gas made from coal will require the development of economically attractive gasifiers. Many major gasification projects are under way. Indeed, the effort directed to coal gasification in the U.S. is considerably larger than the fuel-cell effort.

The benefits the fuel cell offers the utility industry and society at large will be realized only after the fuel cell has attained commercial scale. Commercialization is the major obstacle the fuel cell now faces. One problem is the large degree of uncertainty over energy policy in the U.S. A more important problem is the price of the fuel cell, which will not reach a level that is acceptable to potential users until a manufacturing facility of appropriate size is in place and a large number of power plants have been produced.

The value of multimegawatt fuel cells to the electric utility will range from $330 to perhaps $600 per kilowatt, depending on the utility's other constraints and its evaluation of such indirect benefits of the fuel cell as the deferral of investment in new transmission and distribution lines and the reduction of reserve generating margins. It is likely that between 500 and 1,500 megawatts of fuel cells will have to be produced before the "learned out" price reaches the target level of $350 per kilowatt. For a spontaneous market of commercial scale to develop it is apparent that there must be some combination of three factors: (1) the manufacturer must assume the risk of underwriting the learning curve from the level of $1,500 per kilowatt, which is what the first production unit may cost, to the target level of $350, (2) users must buy the first units at their actual cost ($1,500 per kilowatt, with subsequent units decreasing in cost toward the ultimate level of $350) and (3) the Government must assist the private sector by reducing the risks or helping to underwrite the cost of the initial units.

Uncertainties about the national policy on energy, the supply of fuel, the future demand for electric energy and the rate structure for electric utilities, coupled with the uncertainties inherent in any new and immature technology, will probably prevent the manufacturers and the utility industry from undertaking the risk that would lead the fuel-cell program to the commercial level. Since the benefits of the fuel cell extend beyond the private sector to society at large, it is appropriate for the Government to assist the private sector in its development. The fuel cell is perhaps the first new energy technology to emerge in the past two decades and may therefore bear the burden of exploring mechanisms of commercialization. It is not at all impossible that the fuel cell will fall by the wayside because of the inability of the public and private sectors to deal with this complex issue in a timely way.

PROJECT	FUNCTION	DUTY	SIZE	FUEL	COST	EFFICIENCY	AVAILABLE	ELECTROLYTE
TARGET	ON-SITE POWER PLANTS	LOAD FOLLOWING (CONTINUOUS)	25 TO 200 KILOWATTS	NATURAL GAS	500	35 TO 40 OR 100	EARLY 1980'S	PHOSPHORIC ACID
FCG-1	DISPERSED POWER PLANTS	LOAD FOLLOWING (INTERMEDIATE)	10 TO 25 MEGAWATTS	NAPHTHA	350	37 TO 39 OR 75 TO 80	EARLY 1980'S	PHOSPHORIC ACID
UTILITY	DISPERSED POWER PLANTS	LOAD FOLLOWING (INTERMEDIATE)	10 TO 25 MEGAWATTS	PETROLEUM OR COAL-DERIVED LIQUIDS	350	45 TO 47 OR 75 TO 80	LATE 1980'S	MOLTEN CARBONATE OR PHOSPHORIC ACID
UTILITY	CENTRAL POWER PLANTS	BASE LOAD	150 TO 600 MEGAWATTS	COAL	800	45 TO 47	1990'S	MOLTEN CARBONATE OR PHOSPHORIC ACID

MAJOR FUEL-CELL PROJECTS are shown here. The TARGET program (for Team to Advance Research for Gas Energy Transformation) was originated by the gas-utility industry, the FCG (for fuel-cell generator) program by the electric-utility industry. The projects labeled "Utility" represent long-range plans by the electric-utility industry. The figures under "Cost" are hundreds of dollars (1980 value) per kilowatt of installed capacity. Efficiency is in percent; where alternative figures are given the ones on the upper line represent plants operated without recovery of waste heat and the ones on the lower line are for plants that do incorporate equipment for recovering heat.

SCIENCE AND THE CITIZEN

Off the Beam

Efforts to revive the U.S. anti-ballistic-missile program, which was severely limited under the terms of the 1972 ABM treaty with the U.S.S.R., have gained momentum in some circles over the past year or two, energized in part by recurrent public assertions that the Russians are engaged in a secret multibillion-ruble program of their own to develop a new kind of ABM system, based this time not on nuclear-armed interceptor missiles but on intense beams of charged particles. In spite of the generally accepted view that the initial alarms about the Russians' intentions were exaggerated, the Carter Administration has responded to the persistent controversy by appointing a committee of technical experts to review the engineering aspects of developing particle-beam weapons as a defense against ballistic missiles.

The real problem, however, may lie elsewhere. According to Richard L. Garwin, a physicist and long-time student of the comparative cost-effectiveness of strategic weaponry, the feasibility and utility of any ABM system based on particle beams "can be assessed apart from the question of whether the Soviet Union has or has not made certain technical demonstrations, or possesses the facilities implied by recent publications." His own assessment of the situation, given in a recent article in *The Bulletin of the Atomic Scientists,* is that "regardless of the status of charged-particle-beam generation, propagation, pointing and the like, a charged-particle-beam ABM system has problems such that its effectiveness against a ballistic-missile force is highly questionable." Therefore, he concludes, "even if it were true, the 'evidence' used to demonstrate that the Soviet Union is close to deploying an effective charged-particle-beam ABM system is completely irrelevant."

In many respects, Garwin points out, the requirements for a charged-particle-beam (CPB) weapon are analogous to those of an interceptor-missile ABM system. For example, both systems would require long-range radars to detect and track the ballistic-missile reentry vehicles. In addition an ABM system of the CPB type would need to be able to "discriminate against decoys outside the atmosphere, generate the charged-particle beam, point and track that beam, propagate that beam through the atmosphere, determine how far and in what direction the beam missed the target, correct the aiming of the beam, measure once more the miss, determine whether the target has in fact been killed and attack all other objects that might be threatening. Furthermore, the system must be able to defend itself—its radars, accelerator and the like—against nuclear attack."

Even if any of the earlier versions of the U.S. ABM system (Nike-Zeus, Nike X, Sentinel or Safeguard) had been built, Garwin writes, "they would have been ineffective because the effectiveness of ABM systems depends on more than just an interceptor (which is all that would be replaced by a new weapon such as a charged-particle beam)."

Nevertheless, the *Bulletin* article continues, there are some important differences between an ABM system based on a charged-particle beam and one based on a nuclear-armed interceptor. "One great difference... is that the nuclear weapon has a kill radius of some kilometers, while the particle beam must actually strike the reentry vehicle to injure it. Thus, at a range of 100 to 1,000 kilometers, the radar and the beam-pointing accuracy of a charged-particle-beam weapon must be 1,000 or more times better than that of an ABM interceptor. Furthermore, because a charged-particle beam is bent substantially by the earth's magnetic field, the beam cannot be pointed directly at the target. Finally, an attacker could help ensure the survival of his reentry vehicles by exploding nuclear devices outside the atmosphere that would readily disturb the earth's magnetic field and so bend the particle beam by a variable and unknown amount."

The problems involved in penetrating the atmosphere could be avoided by mounting charged-particle-beam weapons on satellites. Even if such an approach were technically feasible (and Garwin cites a number of reasons for believing it is not), the deployment of CPB weapons on satellites is "doubtful" because of the availability of cheap, effective countermeasures. For example, CPB-bearing satellites would presumably be much more expensive than "little satellites which (by following the former in a similar orbit and carrying a few pounds of high explosives) could be used to destroy the CPB satellites on command."

In short, Garwin writes, his analysis "provides good reason to doubt the supposed progress of the development of a weapon utilizing charged-particle or hydrogen-atom beams for defense against ballistic missiles. It also provides good reason to doubt the depth of understanding of those who emphasize such a threat or the good sense of any government officials—either in the United States or in the Soviet Union—who would authorize large amounts of funds to develop such weapons. Long years of 'head in the sand' behavior by system proponents and defense leaders brought us to the Safeguard ABM system fiasco. We should learn from that experience."

The Nobel Prizes

The Nobel prizes in science for 1978 were awarded to three microbiologists for the discovery and application of enzymes that cut DNA at specific sites; to two physicists for discovering the faint cosmic radiation left from the "big bang" in which the universe was created and to a third for his pioneering work with liquid helium; to a biochemist for his theory of how cells transform energy, and to an economist for exploring how large organizations make economic decisions.

The prize in physiology or medicine was awarded jointly to Werner Arber of the University of Basel and to Hamilton O. Smith and Daniel Nathans of the Johns Hopkins University School of Medicine. The Nobel committee credited Arber with discovering "restriction" enzymes, bacterial enzymes whose function is evidently to destroy invading viruses by cutting up their DNA before it can give rise to new virus particles in the host. He postulated that the enzymes bind to the DNA at specific sites where the double-strand molecule is cross-linked by specific sequences of nucleotide bases. (The genetic code is written in triplet sequences of four different bases: adenine, thymine, guanine and cytosine.) Smith verified Arber's hypothesis with an enzyme extracted from the bacterium *Hemophilus influenzae.* He showed that the enzyme cuts DNA in the middle of a specific symmetrical sequence of bases. More than 100 restriction enzymes with different cutting properties have now been discovered. Nathans pioneered the application of restriction enzymes to genetic problems by showing how they could be used to map the genes of the monkey tumor virus SV-40. The enzymes have given microbiologists sharp tools for determining the order of genes in chromosomes, for establishing the base sequence of genes and for splicing together genes from different organisms, now best known as the recombinant-DNA technique.

Half of the Nobel prize in physics was awarded to Pyotr Leonovitch Kapitsa "for his basic inventions and discoveries in the area of low-temperature physics." Now 84, Kapitsa was for many years head of the Institute of Physical Problems of the U.S.S.R. Academy of Sciences. In 1934 he built the first machine capable of producing liquid helium in large quantities. A few years later he showed that a form of liquid helium, helium II, exhibits a vanishingly low vis-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cosity and so acts as a "superfluid." Kapitsa's experiments indicated that helium II is in a macroscopic quantum state, exhibiting perfect atomic order. "Kapitsa's discoveries, ideas and new techniques," according to the Nobel prize announcement, "have been basic to expansion of the science of low-temperature physics."

The other half of the award in physics went to Arno A. Penzias and Robert W. Wilson of Bell Laboratories "for the discovery of cosmic microwave background radiation." In the late 1940's George Gamow proposed that if the universe had been created in a big bang, the resulting "fireball" would still not have cooled to absolute zero. In 1948 he and his collaborators Ralph A. Alpher and Robert Herman predicted that the radiation emitted by the big bang would fill the present universe with a microwave background radiation having a spectrum corresponding to that of the radiation emitted by a black body at a temperature of five degrees Kelvin (degrees Celsius above absolute zero).

In 1964, unaware of this prediction, Penzias and Wilson undertook to measure the background radio emission of the galaxy with an extremely sensitive 20-foot horn detector that had been designed to receive signals bounced off the balloonlike Echo satellite. To their surprise Penzias and Wilson detected a substantial amount of microwave noise at a wavelength of 7.35 centimeters (4,080 megacycles per second), corresponding to radiation from a black body with a temperature of three degrees K. At the level of sensitivity of their measurements the emission was independent of direction in space. Clearly it was coming from outside our galaxy and evidently from the universe at large. The implication of their discovery was clarified when word of it reached Robert H. Dicke and his colleagues at Princeton University, who were preparing to search for the remnant big-bang radiation with a receiver of their own.

The discovery was announced in two letters to *The Astrophysical Journal,* one from Penzias and Wilson describing "a measurement of excess antenna temperature at 4,080 megacycles per second" and the other from Dicke, P. G. Roll, David T. Wilkinson and P. James E. Peebles providing the cosmological, or big-bang, explanation for the excess. The near but not quite perfect isotropy of the cosmic background radiation has recently been used to establish the absolute motion of the earth, and hence of our galaxy, in space (see "The Cosmic Background Radiation and the New Aether Drift," by Richard A. Muller; SCIENTIFIC AMERICAN, May).

The award in chemistry went to Peter Mitchell of the Glynn Research Laboratories in Cornwall "for his contributions to the understanding of biological energy transfer through the formulation of the chemiosmotic theory." It was the first Nobel prize in recent memory awarded to an investigator who was not affiliated with a major institution. Formerly on the faculty of the University of Edinburgh, Mitchell has operated his own private laboratory in a large manor house that he bought and renovated in the early 1960's. There he works with one principal colleague, Jennifer M. Moyle, and visiting investigators.

Mitchell's concern has been with the mechanism by which the living cell obtains, transforms and utilizes the energy needed for its manifold activities. The primary energy-carrying molecule is adenosine triphosphate (ATP). A key puzzle is the mechanism by which an inorganic phosphate group is coupled to adenosine diphosphate (ADP) in the process of oxidative phosphorylation. Before Mitchell's work the prevailing hypotheses postulated that the linkage was achieved directly by enzyme intermediates. In spite of intensive research in many laboratories, however, these hypotheses had found no support.

In 1961 Mitchell proposed a radically different idea. He suggested that a flow of electrons through a system of carrier molecules drives hydrogen ions (protons) across the outer membrane of bacterial cells, or the similar membranes that enclose such subcellular organelles as mitochondria or chloroplasts. As a result an electrochemical gradient is created across the membrane. The gradient consists of two components: a difference in *p*H, or hydrogen-ion concentration, and a difference in electric potential. Together they provide what Mitchell calls a "proton motive" force capable of driving the synthesis of ATP. Long viewed skeptically, Mitchell's "chemiosmotic theory" is now generally accepted (see "How Cells Make ATP," by Peter C. Hinkle and Richard E. McCarty; SCIENTIFIC AMERICAN, March).

The award in economics was given to Herbert A. Simon of Carnegie-Mellon University "for his pioneering research into the decision-making process within economic organizations." In classical economic thought the entrepreneur was regarded as an omniscient, rational decision maker, concerned only with maximizing profit. In Simon's 1947 book *Administrative Behavior* and in subsequent works he replaced this mythical figure with a number of cooperating decision makers whose capacities for rational action are limited both by lack of knowledge about the total consequences of their decisions and by personal and social ties. The best they can hope to do is to find acceptable solutions to acute problems, often reconciling contradictory goals. According to the Nobel announcement, "Simon's theories are less elegant and less suited to overall analysis than is the classic profit-maximizing theory. But they ... apply very well to the systems and techniques of planning,

The new Parker 50 in brushed stainless steel. The set, $37.50; fountain pen, $25; ball pen, $12.50.

budgeting and control that are used in modern business and public administration."

Organic Conductors

A metal conducts electricity because some of the electrons in a metallic solid are free to move from atom to atom over long distances. In the past few years several organic materials have been found that mimic this property; they can be regarded as synthetic metals. One of the latest to be recognized is a polymer whose chemical structure is much like that of some common plastics. It can be made to serve not only as a conductor but also as a semiconductor.

A distinctive feature of all the organic conductors is that they are asymmetrical in microscopic structure; they are quasi-one-dimensional solids, composed of linear strings of atoms or molecules. Along the axis of the strings conductivity is high, but in other directions it is low. One kind of organic conductor, called a charge-transfer salt, consists of electron-donor and electron-acceptor molecules arranged in parallel stacks. The two kinds of molecule are not chemically bonded but are merely held together in a crystal lattice. In that configuration electron orbitals of the donor and the acceptor overlap, allowing electricity to be conducted along the stacks. Conduction perpendicular to the stacks is negligible.

A fundamental limitation of the charge-transfer salts is that the donor and acceptor molecules are rather far apart and their orbitals overlap only slightly. A straightforward strategy for improving the performance of the conductor is to form a long-chain polymer, which has a natural quasi-one-dimensional structure. In a polymer the atoms are only about half as far apart, so that in principle the orbitals could overlap extensively. It would seem, then, that polymers should be excellent conductors. Most of them are not, and are in fact good insulators, because there are no free electrons available to serve as charge carriers. All the electrons are confined to the bonds between atoms.

A conducting polymer has been developed during the past year by Alan J. Heeger, Alan G. MacDiarmid and their colleagues at the University of Pennsylvania. Contributions have also been made by investigators at other laboratories in the U.S., Austria and Japan. The material is a polymeric form of acetylene (the welding gas), which has the formula $HC \equiv CH$, the three lines denoting a triple bond between the carbon atoms. Polyacetylene, which is formed from the gas by a catalytic process, consists of long chains of CH units connected by alternating single and double bonds. The orbitals of adjacent carbon atoms overlap, and under appropriate circumstances they can carry a current of electrons.

Following techniques developed by H. Shirakawa and S. Ikeda of the Tokyo Institute of Technology, Heeger and MacDiarmid synthesized polyacetylene as a thin film. It has a bright metallic luster, like polished nickel, but in other properties, such as density and texture, it is more like plastic food wrapping. The microscopic structure is not that of a crystal but is a tangled net of fibers, each fiber probably made up of many polymer strands. The conductivity can be adjusted over a range of some 12 orders of magnitude (a factor of one trillion), from the conductivity of a fair insulator to that of a metal.

The conductivity is controlled by doping the film with impurities, the same procedure employed in the manufacture of silicon semiconductors. Doping with an electron donor, such as sodium or lithium, creates an *n*-type semiconductor, in which the electric charge is carried by mobile electrons. Doping with iodine or bromine, which are electron acceptors, yields a *p*-type semiconductor, where the charge carriers are "holes" representing the absence of an electron. The conductivity increases along with the concentration of the dopant, up to concentrations of from 10 to 15 percent. The maximum conductivity observed so far was obtained by doping with arsenic pentafluoride (AsF_5) and stretching the film to orient the fibers along the axis of conduction. The maximum conductivity is somewhat greater than 2,000 reciprocal ohms per centimeter (equivalent to a resistivity of less than .0005 ohm per centimeter). That is still far short of the conductivity of copper, but it exceeds the conductivity of polycrystalline specimens of any other organic conductor.

It is conceivable that a polyacetylene film could replace ordinary metal conductors in some special circumstances, such as where weight or resistance to corrosion is important. It might also be employed as a semiconductor. Heeger and MacDiarmid have shown that a diode (a *p-n* junction) can be constructed simply by clamping two films together or by oppositely doping two regions of a single film. Polyacetylene could not replace silicon in the fabrication of integrated circuits, but it might be suitable for photovoltaic solar cells, where low cost is the most important consideration. Heeger points out that polyacetylene is essentially a "junk material"; similar plastics are made in commercial quantities for about 30 cents per pound. For now all such applications are speculative. On the other hand, any attempt to employ polyacetylene conductors or semiconductors could profit from the well-developed technology for the fabrication of polymer materials.

In 1965 W. A. Little of Stanford Uni-

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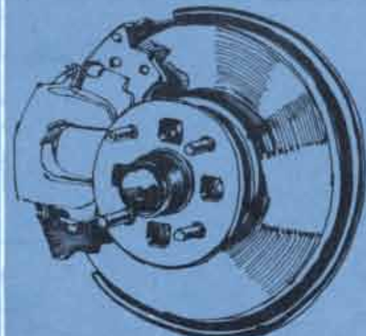
There's good news and *good* news. First, the good news. The new 1979 Toyota Corona has been redesigned to deliver even more style, comfort and value than you've come to expect of this class car. Now, the *good* news. There's a new sportier Corona with a large rear opening hatch. As you can see by the illustration, this opens up a whole new world of convenience and versatility. The Corona Liftback is the newest of the new. A grand addition to a great car.

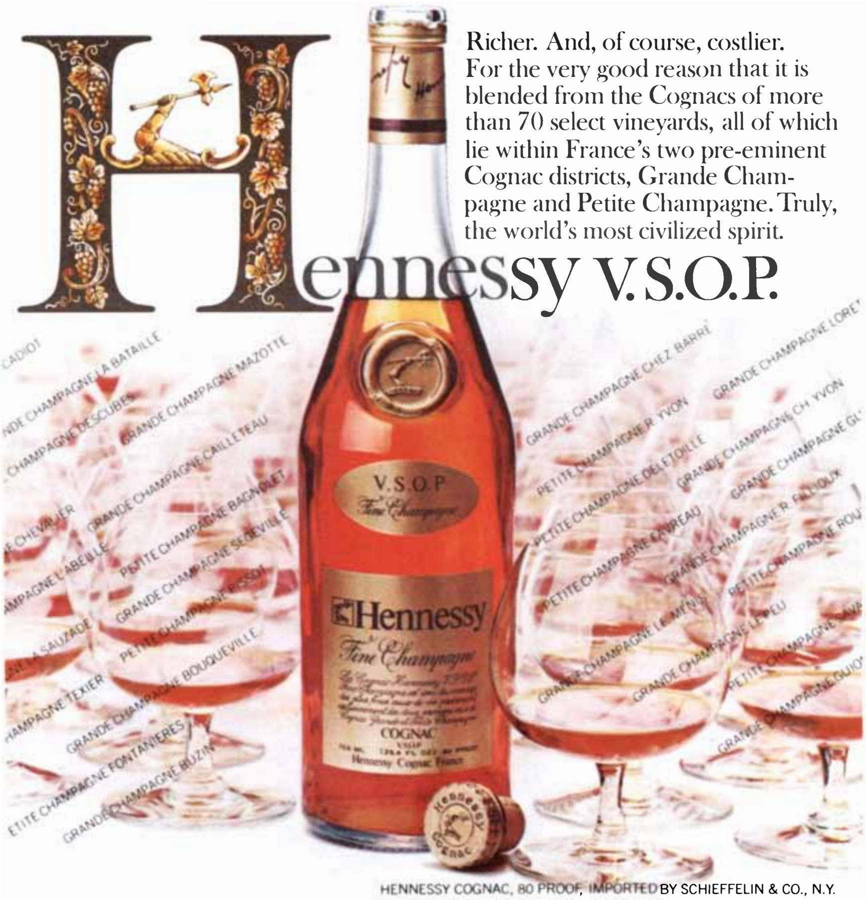


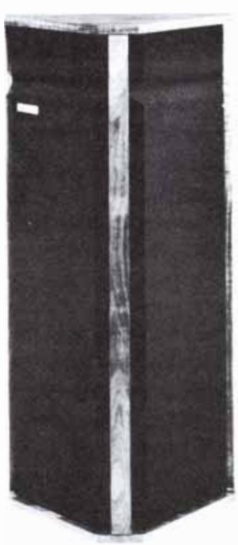
The news gets better. The European influenced styling you can see, but wait until you experience the comfort, convenience and Toyota quality. Fully adjustable/reclining bucket seats, tinted glass, and plush pile carpeting. It's all there. What you may not see is the newly redesigned front suspension which gives the '79 Corona a really smooth ride. It's beauty. It's comfort. It's Toyota.

The best news isn't news. The new Corona is a Toyota. Built in a tradition of toughness. Welded unitized body construction helps eliminate rattles and squeaks. Power assisted front disc brakes instill a feeling of confidence. Extensive rust preventative measures help ensure a car that will last. All in all, the new Corona does a lot to further the premise, "If you can find a better built small car than a Toyota...buy it." The new Toyota Corona.

YOU GOT IT.

THE NEW 5-DOOR CORONA **TOYOTA**





versity proposed that a quasi-one-dimensional polymer might be designed in which a novel form of superconductivity could be observed. Much of the subsequent investigation of organic conductors was inspired by that speculation. The organic superconductor has not been found, but the search has turned up a number of other materials whose properties are almost as interesting.

Cell-Receptor Disorders

What may turn out to be a significant category of diseases characterized by a broad commonality of causative mechanisms has been officially recognized by a workshop on cell-receptor disorders held at the Western Behavioral Sciences Institute (WBSI) in La Jolla, Calif. Receptors are molecules, in the outer membrane of a cell or within the cell's cytoplasm, that recognize and bind specific messengers—either neurotransmitters or hormones—and pass their message on to other molecules that respond to it in a specific way. When there are too many or too few receptors, when they are blocked or for some other reason do not bind a messenger or when they fail to properly activate an effector molecule, there may be an undesirable increase or decrease in responsiveness to the original message. A report on the WBSI workshop by Theodore Melnechuk summarizes discussions covering some 20 disorders that involve—or may involve—abnormalities in cell-receptor function.

One of the disorders is myasthenia gravis, in which impaired transmission of the nerve impulse at neuromuscular junctions results in muscular weakness. Molecules of the neurotransmitter acetylcholine released at a motor-nerve ending are bound by acetylcholine receptors: glycoprotein molecules in the membrane of muscle-fiber cells. The binding evokes an action potential along the muscle fiber, triggering muscle contraction. Jon M. Lindstrom of the Salk Institute described how he and his colleagues developed an animal model of myasthenia gravis by immunizing animals with acetylcholine-receptor material from the electric organ of the eel; the immunized animals manufacture antibodies to the receptor that impair their own neuromuscular activity. Myasthenia gravis is apparently an autoimmune disease in which antibody to the acetylcholine receptors is produced, possibly as the result of a virus infection that alters cell-membrane components of muscle cells or their precursors; the antibody blocks the receptors and may also interfere with their activity in other ways. Various methods of treatment are being developed based on this understanding of the disorder.

Faulty nerve-impulse transmission

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mediated by the neurotransmitter dopamine has been implicated in schizophrenia. Several lines of evidence assembled in the laboratory of Solomon H. Snyder of the Johns Hopkins University School of Medicine were presented by Ian Creese. For example, amphetamine, which releases dopamine in the brain, exacerbates schizophrenic symptoms, and addiction to amphetamine can produce a psychosis that mimics paranoid schizophrenia. Moreover, symptoms of schizophrenia have been relieved by drugs that appear to act by blocking receptors for dopamine. Taken together, the data suggest that overactivity of the dopamine system is involved in the disease. The overactivity could result from the excessive release of dopamine, from an oversupply of dopamine receptors or from their hypersensitivity. Several studies to determine the actual changes in brain samples taken at autopsy from schizophrenic patients are under way, but so far results are not conclusive.

The Search Goes On

In 1969 Joseph Weber of the University of Maryland reported that he had detected bursts of gravitational radiation emanating from the center of the galaxy. Since that time at least 14 groups of investigators have tried to confirm his observations of gravity waves, and all have failed, even those who have built detectors several times more sensitive than Weber's original apparatus. In spite of these negative results investigators have continued to search for gravity waves because their existence is predicted by the general theory of relativity. Just as an accelerated charge radiates electromagnetic waves, so should an accelerated mass radiate gravity waves. Such waves would resemble electromagnetic waves in that they would carry energy, momentum and information at the speed of light. Unlike electromagnetic waves, however, gravitational waves would interact with all forms of matter and energy, not just with electric charges and currents.

What apparently prevents physicists from detecting gravitational radiation is their inability so far to construct a detector capable of distinguishing the effects of gravity waves from those of other phenomena. Weber's pioneering apparatus was an aluminum cylinder measuring five feet in length and three feet in diameter and weighing about three and a half tons. If gravity waves traveled past the cylinder, they were expected to set its ends into oscillation. The oscillations would be picked up by piezoelectric transducers, crystals that respond electrically to mechanical stress.

Since 1969 Weber's apparatus has served as the prototype for gravity-wave detection systems that rely on oscillatory antennas. These sophisticated systems, however, suffer from the same difficulties that plagued Weber's original apparatus. Thermal fluctuations will also set the ends of the cylinder into oscillation, and such oscillations could obscure those that are caused by gravity waves. To reduce the thermal fluctuations three teams of investigators cooled the antennas down to temperatures of between four and five degrees Kelvin, but they failed to detect gravity waves. Soon the thermal noise will be reduced further when detectors start operating at temperatures as low as 1.5 degrees K. Plans are also under way for the building of antennas out of materials such as silicon and sapphire, which will be less affected by thermal fluctuations. Such antennas, however, will be much lighter than aluminum ones, and so there is a greater chance that meteorological and seismic phenomena will disturb them. Nevertheless, the freedom from thermal noise should more than outweigh the adverse effects of these disturbances.

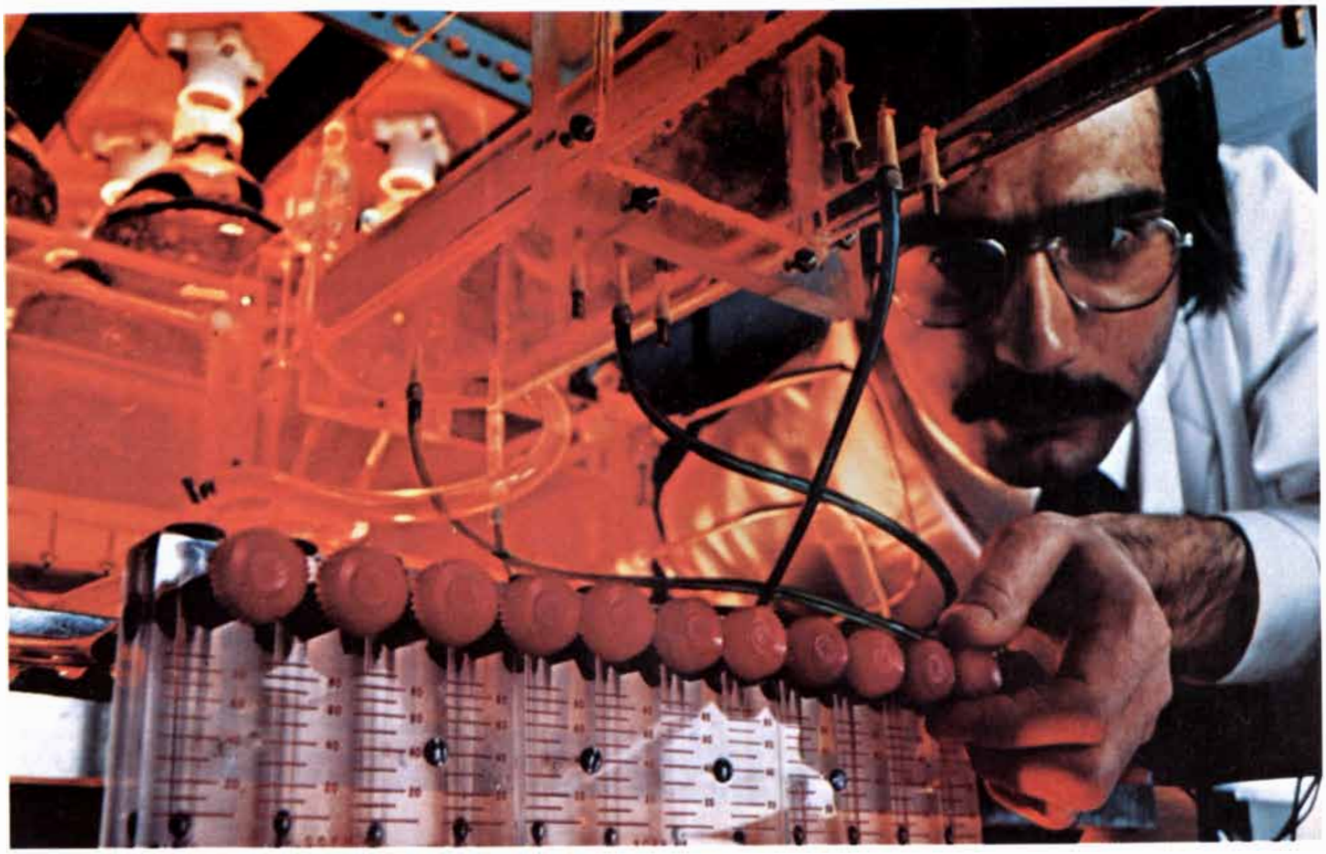
Even if thermal noise could be eliminated completely, quantum-mechanical limitations might prevent the Weber type of antenna from ever detecting gravity waves. The basic problem is that quantum mechanics seems to require that a transducer disturb the vibrating antenna. Theoretical calculations indicate that the oscillations resulting from gravitational waves would be much smaller than those resulting from the presence of the transducer. As a result the gravity-induced oscillations might be smeared out beyond recognition. Several theorists are currently exploring ingenious ways of circumventing these apparent quantum-mechanical limitations.

In recent years three teams of investigators have turned from Weber-type antennas to laser interferometers as their gravity-wave detectors. These interferometers, which are not yet in operation, are based on the original Michelson-Morley design, in which a shift in the interference pattern between light beams traveling in horizontal and in vertical directions would indicate that there had been a change in the geometry of space-time. Such a change would constitute the signature of a gravity wave. Although interferometers are free of quantum-mechanical limitations, formidable difficulties stand in the way of their successful operation. For example, the interferometer must be shielded from any kind of natural phenomenon that might disturb it and shift the interference pattern. Such disturbances would be reduced if the interferometers could be set up in space.

Workers at the Jet Propulsion Laboratory of the California Institute of Technology have in mind still a third way of detecting gravitational radiation. They want to send an electromagnetic wave between the earth and a spacecraft

DP Dialogue

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



Owens-Corning's Dr. Gary Ganzala tests a computer-model design of a glass-making furnace by analyzing the operation of this working scale model.

Modeling New Processes at Owens-Corning

Engineers at the Technical Center of Owens-Corning Fiberglas Corporation, in Granville, Ohio, are modeling manufacturing processes using a computer in the search for better ways to make products of glass fiber.

"To verify the design of a new or modified glass-making furnace," says Dr. Gary Ganzala, senior engineer, "we can build a physical scale model in six to eight months – and begin evaluating it. On the other hand, we can build and evaluate a computer model of the design in two weeks and, in some cases, two hours. This lets us try many more designs before we build a physical scale model."

Recently, for example, the Technical Center modified a furnace for use in a new process with potentially double the productivity of the old one. "When we started it up, however," explains Ganzala, "it didn't meet expectations. A computer simulation identified some fluid flow effects that weren't understood before. We moved one part two feet – and cured the problem. Without the computer model, we might well have abandoned the new process."

The Technical Center's System/370 Model 158 allows new statistical analysis methods. Recently, Craig Thom, laboratory director of process and materials technology, and Darryl Costin, manager of process technology, identified improvements in manufacturing insulating material for commercial buildings.

"The material has properties such as compressive strength and thermal conductivity, which change when we alter temperature, pressure or other process variables," Thom explains. "With eight properties plus one cost variable, the graph of the process equation is a surface in a nine-dimensional 'hyperspace.'

"With just one trial, a regression analysis can find the sensitivity of these properties to changes in process variables. This lets us interactively search the hyperspace for peaks in the nine-dimensional surface. We tested these apparent optimum settings and found a better process operating point than we could have any other way."

Wichita Fire Fighters Plan by Computer

Old fire houses such as this Wichita, Kansas, station of the early 1900's were located so the horses would not have to run more than ten city blocks. Today an IBM computer helps Wichita account for many factors in site selection of new stations.

Horses pulling a fire wagon, it was once decided, can run no farther than ten city blocks. For that reason, fire stations in many American cities were located 20 blocks apart.

Today Wichita, Kansas, is saving nearly $3 million in construction and operating costs by using an IBM computer to help plan the locations, manning and equipping of its fire stations.

For example, the city had planned to construct five new stations during the 1970's. But, after a computer analysis, the Fire Department decided to relocate two stations, construct only two new stations and transfer three existing companies to man them.

Meeting Requirements

A prime requirement is that it take less than four minutes to reach the scene of a fire, at no more than ten miles an hour over the speed limit. Also factored into the study, which used the city's IBM System/370, were such data as Wichita's projected growth to 1980 and 1990 and fire records of years past.

Explains Fire Captain Ellis Ingle, who helped develop the site location plan: "Planners use the computer to study growth patterns, existing and planned roads, and how fast any three stations could respond to fires. They evaluate traffic conditions, alternate routes to fires, natural barriers, such as rivers, and man-made ones like railroad crossings."

Data from the system contributed to decisions on the personnel and equipment assigned to stations. In such places as industrial plants and hospitals, the computer notes potential hazards, and equipment designed to combat specific types of fire is placed in the appropriate stations. Using the geographical location of all water hydrants, stored with the type, main size, and flow of each, the system schedules inspections twice a year.

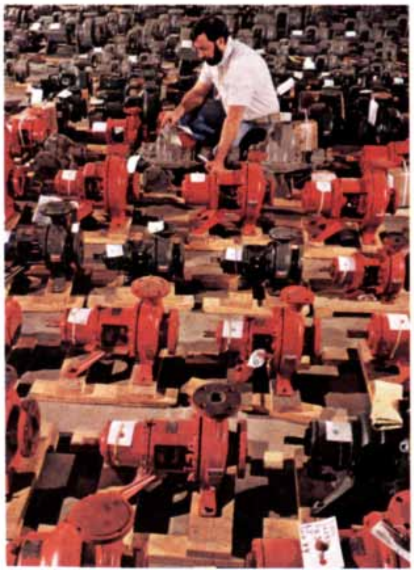
"The computer also helps pinpoint where 70 percent of all fires occur. We have inspectors and fire fighters educating property owners on fire prevention, and we concentrated them in those high-risk areas. This enabled us to reduce inspection teams from 29 to 11, and since this allowed us to cut the miles driven on inspection tours by more than half, it meant a saving in gasoline as well.

Protecting Invalids

"We also use the system to maintain a list of some 400 invalids. A dispatcher checks the location of an alarm and notifies the fire fighters en route if the system indicates that an invalid lives at that address.

"If our stations are properly located," Ingle adds, "we can do a better job of saving lives and property. With the help of the computer, that is just what we are achieving."

Worthington Keeps Centrifugal Pump Specifications Flowing



To specify these centrifugal pumps, Worthington engineers key application data into a computer terminal and receive a complete data sheet, bill of materials and price.

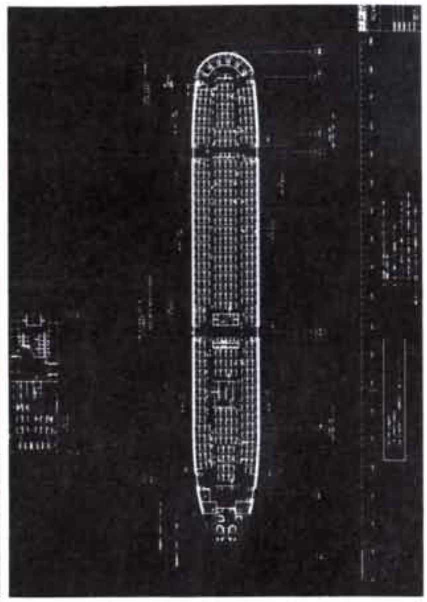
Selection of an industrial centrifugal pump can involve as many as 40 conditions of service. Once these are specified, it takes an hour or more of manual calculations to determine the characteristics of a suitable pump.

At Worthington Pump, this work is done in moments by a computer. A sales engineer takes the details of an application over the phone and enters the conditions of service through a terminal. The IBM System/370 displays a selection of three pumps: the lowest in price, the most energy-efficient, and the one requiring the lowest net positive suction head (NPSH).

Robert Glacken, senior programmer-analyst at the Mountainside, New Jersey headquarters of the Studebaker-Worthington, Incorporated subsidiary, created two programs: the Centrifugal Pump Selection (CPS) and Vertical Pump Selection (VPS) systems. "Either program," he explains; "accepts such operating data as specific gravity, viscosity of the fluid, temperature, and head pressure. For each selected pump, the program specifies shaft horsepower, type and size of impeller, construction materials, working pressure and other characteristics.

"The system is interactive – the terminal prompts the user with questions at every step."

Often, Glacken points out, a vertical pump application can use either one large pump or two smaller ones, staged. The computer models both alternatives, calculating efficiency and identifying the minimum-price selection. It determines the drive torque, required shaft weight and number of bearings. And it finds any critical speeds at which harmonics will generate harmful vibrations. Once a



The CADAM system aids in the design of seating for jumbo jets like this Lockheed L1011 TriStar aircraft. An engineer at a graphics terminal uses a light pen to move outlines of standard seat assemblies around an image of the aircraft floor plan, often saving weeks of tedious work.

Taking TriStar from First Sketch to Last Detail

At Lockheed-California Company, engineers use the power of the CADAM® (Computer-Graphics Augmented Design and Manufacturing) system through the life of a project. Its power is suggested by C.J. Benjamin, computer graphics manager, production design. "A designer and a CADAM system operator, working together, can do six or seven times as much area of a typical drawing per hour as a person at a drafting board," he says.

Engineers start to use the CADAM system as soon as the first rough concepts of a new airplane begin to emerge. Using an IBM graphic display as if it were a drafting board, the designer interacts with the computer to create his design.

For detailed design work, repetitive elements can be generated rapidly, once they are defined to the CADAM system. These can be cutouts, brackets, or entire structural sections. For example, a typical floor beam design was prepared and copies made for all similar beams. Then the detailed changes peculiar to each beam were made to accommodate the hydraulic plumbing and electrical wiring. The finished beams and floor boards were then overlaid on the screen to check for incompatibilities.

Variations are introduced into the design of an aircraft as successive planes are produced, to accommodate the needs of individual customers. T.A. Barker, group engineer of L1011 TriStar wiring diagrams, says: "We issue up to 6,000 new drawings each quarter for the L1011 fleet. With the CADAM system, four people at two terminals keep the entire set of 250,000 L1011 TriStar aircraft wiring drawings up to date."

When an airline needs a seating change, Lockheed engineers use outlines of floor panels and a standard library of over 70 various seat assemblies stored in the data base. They analyze the layout by moving these shapes around in the display. "Working at the terminal with the airline representative, we achieve new plans in as little as two or three hours, instead of several weeks," Benjamin says.

"The CADAM system is often at its best when a problem crops up late in the design cycle," Benjamin adds. "Engineering was 70 percent complete on one aircraft we were building when we found we had to rework some air ducts. Without it, there would have been 750 hours of drafting; we finished in 40 hours at the terminal."

"We've used the CADAM system to design everything from a simple mill fixture to an experimental windmill," notes Harmon A. Thompson, manager, interactive graphics, manufacturing. "The work was done in a fifth to a twenty-fifth of the estimated manual drafting time. And when the time comes to put a complex assembly together, the attachment holes line up on the first try."

®CADAM is a registered trademark of the Lockheed Corporation.

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pump is selected, the system produces a bill of materials, computes a total price, and prints a data sheet which gives the customer about 120 specification items.

One user of CPS and VPS is Dan Gromko, office engineer in Worthington's Springfield, New Jersey office. "They are invaluable tools," he says. "Accurate, complete, and neat. Recently a customer asked on a Tuesday for 210 pump selections by Friday. It would have taken nearly two work weeks manually, but with CPS we submitted detailed bids and prices on time."

The curves for each pump are based on the viscosity of water, and the relationships are not linear. CPS makes this correction much more accurately than the best manual method.

Says Gromko: "I can key the variables into the terminal and see a selection on the screen in seconds, or come back later and pick up a printed data sheet. I use the computer for every selection it can run, one pump or 200. No job is too big or too small."

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and then back to the earth. Theoretical considerations suggest that if a gravity wave traveled past the electromagnetic wave, it would change the properties of the electromagnetic wave in a characteristic way. In principle such a change could be detected and would indicate that a gravity wave had passed by. Once again formidable difficulties must be overcome before such a detection system can be implemented. For example, the charged particles that spew out of the sun also affect electromagnetic waves, and ways must be found to eliminate such effects or to distinguish them from those of gravity waves.

In spite of all these ambitious detection efforts, some physicists think gravity waves may not be found because the waves are too weak and the competing phenomena are too strong. Interestingly enough, it was the man who predicted the existence of gravity waves who first perceived the difficulties in detecting them. In 1916, when Albert Einstein predicted their existence in his general theory of relativity, he pointed out that his calculations showed that gravitational irradiated power "in all thinkable cases must have a practically vanishing power."

Knight Arrant

Sir Cyril Burt, an eminent British psychologist who died in 1971 at 88, was the first of his profession to be knighted. He may also have been the first to introduce laborsaving practices on his own behalf. Data he published in 1961, purportedly summarizing "surveys and subsequent inquiries . . . carried out at intervals over a period of nearly 50 years, namely from 1913 onward," have recently been reexamined. Far from being the product of half a century's work, the 1961 data were cooked up exclusively from figures Burt and a colleague published in 1926. Most of these earlier data in turn were derived not from interviews, as was asserted in 1926, but from figures contained in a 17-volume study, *Life and Labour of the People in London,* published between 1892 and 1903 by Charles Booth, an English shipping magnate and amateur sociologist. Because Burt's data in general provide much of the evidence cited by those who maintain that nature dominates nurture in the realm of human intelligence, discovery of the ultimate source of this particular set of data is of considerable interest.

Writing in *Science,* Donald D. Dorfman of the University of Iowa reports that recent controversy over the quality of Burt's data led him to analyze the 1961 paper, "Intelligence and Social Mobility" (*British Journal of Statistical Psychology,* Vol. 14). Burt's paper presented six occupational classes, with unskilled workers at the bottom and higher professional workers at the top. In two numerical tables Burt then compared the I.Q. distribution among adult males in each of the six classes, over a range from an I.Q. of between 50 and 60 to one of 140 and higher, with the same range of I.Q. distribution among their offspring. In the accompanying text Burt described the work as a "pilot inquiry" and as "crude and limited." He did not specify what I.Q. tests the children were given but went on to say that for "obvious reasons the assessments of adult intelligence were less thorough and less reliable" than the assessments of child intelligence.

In view of these caveats, Dorfman was surprised to find, as he plotted Burt's figures for adults and children graphically, that the "less reliable" adult data points exactly superposed the offspring data points. Even more surprising, both sets formed a symmetrical bell curve, stepping upward to a plateau (between an I.Q. of 95 and one of 105) that embraced nearly 50 percent of the sample and bottoming out at equidistant abscissal extremes.

As has long been recognized, measurable human attributes such as height and weight show distributions that are skewed, or asymmetrical. A theoretically normal, symmetrical bell-curve distribution is in fact abnormal and a cause for suspicion. "Beyond a reasonable doubt," Dorfman writes, "the frequency distributions of Burt's tables I and II were carefully constructed" to be in agreement with a theoretically normal bell curve and could not have been, as Burt stated, "obtained from the surveys carried out from time to time in a London borough selected as typical of the whole country."

Had Burt gone to the effort of fabricating data for his 1961 paper? Evidently not. Dorfman found an "extraordinary resemblance" between the 1961 figures and similar data published by Burt and W. Spielman in a 1926 paper, *A Study in Vocational Guidance, Report No. 33* (H.M. Stationery Office). Indeed, Dorfman calculates the odds against the resemblance being coincidental as one in 97 million. The two authors attributed their 1926 data to a still earlier publication by Burt, "Some Principles of Vocational Guidance" (*British Journal of Psychology,* 1924). In that paper Burt described his data as being "a rough calculation (based mainly upon Charles Booth's survey, corrected by later census figures)." Thus it appears that Burt never actually had to go to the effort of conducting surveys in his anonymous "London borough" but had instead constructed his idealized data at leisure from the publications of others. In this Sir Cyril may have been following a dictum he included in the 1926 report: "A rough numerical guide is better than no guide at all."

HP measurement and computer advances

The HP 300. An innovation that puts high-powered, flexible computing into a small, compact console.

No larger than a free-standing terminal, the HP 300 is a new, low-cost business system that achieves a new level of computing concentration. Once programmed, it is friendly enough for people with no computer experience to use, yet packs a breadth of capabilities that will surpass normal expectations of a sophisticated applications designer.

The HP 300 computer is designed to simplify the development and control of dedicated on-line business applications. It incorporates HP's proprietary silicon-on-sapphire (SOS) integrated circuit technology: Exhaustively tested and refined, SOS semiconductor chips give the HP 300 the related benefits of smaller size, greater performance, and lower cost than computers using traditional technologies. The HP 300 is designed for office environments and plugs into a standard electrical outlet.

The HP 300 can handle up to 16 terminals in transaction processing environments, and its "virtual memory" allows the use of extremely large programs and data sets without being confined to physical memory size. A powerful new operating system, Amigo/300, in conjunction with an integrated display system (IDS), greatly simplifies user interface, and enables the HP 300 to perform both as a multiprogramming and multi tasking system. For example, the HP 300 can print reports at the same time that higher-priority data entry or data base management inquiry operations are taking place at the system's terminals.

Eight programmable soft keys on the side of the video display screen can be captioned to give the operator a series of choices in performing a job. The display itself can be divided into multiple "windows" to view and control different parts of an application. These windows can even be scrolled individually, both vertically and horizontally, to a width of 160 columns and a length of several thousand lines.

Two widely used business languages, RPG II and Business BASIC, are available, as are IMAGE/300 data base management with an English-like inquiry capability and TYPIST/300 text editing. There's even a HELP key that gives the user direct access to an on-line reference manual for the system. Full control of all job priorities and applications is maintained at the HP 300's central console.

The price of the system is $36,500 with 256k bytes of main memory, 1 megabyte of mass storage on one flexible disc drive, and one 12-megabyte fixed disc. This can be expanded to 1 megabyte of main memory and 240 megabytes of disc storage. In brief, the HP 300 offers the capabilities, flexibility, and growth potential of computers costing two or three times its price.

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This informative management booklet outlines HP's approach to doing business. It summarizes the expertise, resources, support, and computer products we bring to customers. For a free copy write to A.P. Oliverio, Vice President, Marketing, Hewlett-Packard Co., 1501 Page Mill Rd., Palo Alto, CA 94304.

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HP's new fiber optic link: signal advantages in digital data transmission.

Hewlett-Packard's HFBR series fiber optic system can simplify error-free data communications between computers or within systems, especially in environments where electromagnetic interference is generated.

In environments where high-voltage equipment, heavy electrical machinery, transformers, or other devices generate electromagnetic interference, reliable data transmission between computers or within computer-instrument systems can be a problem. The usual data links of twisted wire or coaxial cable may necessitate the use of expensive shielding, conduit, isolation transformers, or data error checking and retransmission circuitry.

However, by converting the electrical signals to light pulses with no electrical charge, data can be transmitted over a single, hair-thin optical fiber without error or disruption. It is precisely such a system that HP has developed. Using standard TTL electrical interfaces and requiring only a single 5-volt power supply, small optical transmitters and receivers translate the coded electrical transmission into light pulses at one end of the fiber, and back to electrical signals at the other. The fiber, reinforced and jacketed in polyurethane, can span distances of up to 100 metres.

The system offers other advantages compared to electrical connections: broad bandwidth over long distances; light-weight, small-diameter, flexible cables; electrical isolation between connected units; and no externally radiated signal.

Typical applications include distributed system networks, process control systems, secure communications, aircraft or shipboard data links, high-voltage or electromagnetic field research, remote instrumentation systems, and factory data collection.

Prices start at $570* for a 10-metre system. The HFBR-1001 Transmitter and HFBR-2001 Receiver are available separately at $225* each, and various fixed-length connector-cable assemblies are available.

Fiber optic transmitter and receiver are connected to modulation/demodulation circuitry on a PC board for insertion in a computer.

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00940

Hemoglobin Structure and Respiratory Transport

Hemoglobin carries oxygen from the lungs to the tissues and helps to transport carbon dioxide back to the lungs. It fulfills this dual role by clicking back and forth between two alternative structures

by M. F. Perutz

Why grasse is greene, or why our blood is red,
Are mysteries which none have reach'd unto.
In this low forme, poore soule, what wilt thou doe?

—JOHN DONNE,
"Of the Progresse of the Soule"

When I was a student, I wanted to solve a great problem in biochemistry. One day I set out from Vienna, my home town, to find the Great Sage at Cambridge. He taught me that the riddle of life was hidden in the structure of proteins, and that X-ray crystallography was the only method capable of solving it. The Sage was John Desmond Bernal, who had just discovered the rich X-ray-diffraction patterns given by crystalline proteins. We really did call him Sage, because he knew everything, and I became his disciple.

In 1937 I chose hemoglobin as the protein whose structure I wanted to solve, but the structure proved so much more complex than any solved before that it eluded me for more than 20 years. First fulfillment of the Sage's promise came in 1959, when Ann F. Cullis, Hilary Muirhead, Michael G. Rossmann, Tony C. T. North and I first unraveled the architecture of the hemoglobin molecule in outline [see "The Hemoglobin Molecule," by M. F. Perutz; SCIENTIFIC AMERICAN, November, 1964]. We felt like explorers who have discovered a new continent, but it was not the end of the voyage, because our much-admired model did not reveal its inner workings: it provided no hint about the molecular mechanism of respiratory transport. Why not? Well-intentioned colleagues were quick to suggest that our hard-won structure was merely an artifact of crystallization and might be quite different from the structure of hemoglobin in its living environment, which is the red blood cell.

Hemoglobin is the vital protein that conveys oxygen from the lungs to the tissues and facilitates the return of carbon dioxide from the tissues back to the lungs. These functions and their subtle interplay also make hemoglobin one of the most interesting proteins to study. Like all proteins, it is made of the small organic molecules called amino acids, strung together in a linear sequence called a polypeptide chain. The amino acids are of 20 different kinds and their sequence in the chain is genetically determined. A hemoglobin molecule is made up of four polypeptide chains, two alpha chains of 141 amino acid residues each and two beta chains of 146 residues each. The alpha and beta chains have different sequences of amino acids but fold up to form similar three-dimensional structures. Each chain harbors one heme, which gives blood its red color. The heme consists of a ring of carbon, nitrogen and hydrogen atoms called porphyrin, with an atom of iron, like a jewel, at its center. A single polypeptide chain combined with a single heme is called a subunit of hemoglobin or a monomer of the molecule. In the complete molecule four subunits are closely joined, as in a three-dimensional jigsaw puzzle, to form a tetramer.

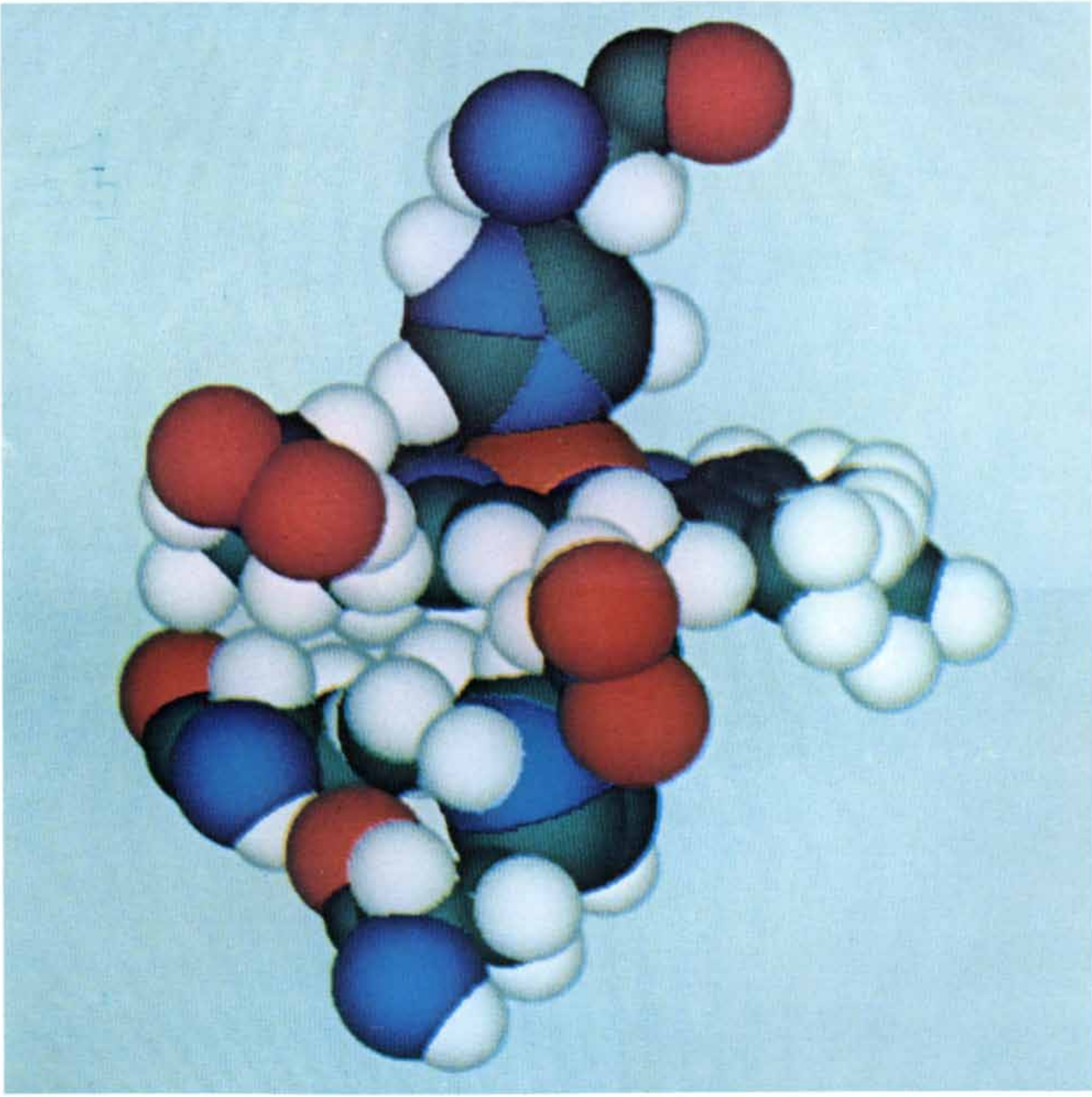
Hemoglobin Function

In red muscle there is another protein, called myoglobin, similar in constitution and structure to a beta subunit of hemoglobin but made up of only one polypeptide chain and one heme. Myoglobin combines with the oxygen released by red cells, stores it and transports it to the subcellular organelles called mitochondria, where the oxygen generates chemical energy by the combustion of glucose to carbon dioxide and water. Myoglobin was the first protein whose three-dimensional structure was determined; the structure was solved by my colleague John C. Kendrew and his collaborators.

Myoglobin is the simpler of the two molecules. This protein, with its 2,500 atoms of carbon, nitrogen, oxygen, hydrogen and sulfur, exists for the sole purpose of allowing its single atom of iron to form a loose chemical bond with a molecule of oxygen (O_2). Why does nature go to so much trouble to accomplish what is apparently such a simple task? Like most compounds of iron, heme by itself combines with oxygen so firmly that the bond, once formed, is hard to break. This happens because an iron atom can exist in two states of valency: ferrous iron, carrying two positive charges, as in iron sulfate, which anemic people are told to eat, and ferric iron, carrying three positive charges, as in iron oxide, or rust. Normally, ferrous heme reacts with oxygen irreversibly to yield ferric heme, but when ferrous heme is embedded in the folds of the globin chain, it is protected so that its reaction with oxygen is reversible. The effect of the globin on the chemistry of the heme has been explained only recently with the discovery that the irreversible oxidation of heme proceeds by way of an intermediate compound in which an oxygen molecule forms a bridge between the iron atoms of two hemes. In myoglobin and hemoglobin the folds of the polypeptide chain prevent the formation of such a bridge by isolating each heme in a separate pocket. Moreover, in the protein the iron is linked to a nitrogen atom of the amino acid histidine, which donates negative charge that enables the iron to form a loose bond with oxygen.

An oxygen-free solution of myoglobin or hemoglobin is purple like venous blood; when oxygen is bubbled through such a solution, it turns scarlet like arterial blood. If these proteins are to act as oxygen carriers, then hemoglobin must be capable of taking up oxygen in the lungs, where it is plentiful, and giving it up to myoglobin in the capillaries of muscle, where it is less plentiful; myoglobin in turn must pass the oxygen on to the mitochondria, where it is still scarcer.

A simple experiment shows that myoglobin and hemoglobin can accomplish this exchange because there is an equilibrium between free oxygen and oxygen bound to heme iron. Suppose a solution of myoglobin is placed in a vessel constructed so that a large volume of gas can be mixed with it and so that its color can also be measured through a spectroscope. Without oxygen only the purple color of deoxymyoglobin is observed. If a little oxygen is injected, some of the oxygen combines with some of the deoxymyoglobin to form oxymyoglobin, which is scarlet. The spectroscope measures the proportion of oxymyoglobin in the solution. The injection of oxygen and the spectroscopic measurements are repeated until all the myoglobin has turned scarlet. The results are plotted on a graph with the partial pressure of oxygen on the horizontal axis and the percentage of oxymyoglobin on the vertical axis. The graph has



HEME GROUP is the active center of the hemoglobin molecule, the binding site for oxygen. The heme is a flat ring, called a porphyrin, with an iron atom at its center; it is seen here edge on and extending horizontally across the middle of the illustration. Three of the 16 amino acid residues of the globin that are in contact with the heme are also shown. In this computer-generated image each atom is represented by a sphere into which no other atom can penetrate unless the atoms are chemically bonded; where two atoms are bonded the spheres overlap. Carbon atoms are black, nitrogen atoms blue, oxygen atoms red, hydrogen atoms white and the iron atom is rust-colored. The model shows the deoxygenated heme; oxygen binds to the lower side of the iron atom. The picture was generated by Richard J. Feldmann and Thomas K. Porter of the National Institutes of Health from atomic coordinates determined by Giulio Fermi of the Medical Research Council Laboratory of Molecular Biology at Cambridge in England. A key to the structure is provided on page 95.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the shape of a rectangular hyperbola: it is steep at the start, when all the myoglobin molecules are free, and it flattens out at the end, when free myoglobin molecules have become so scarce that only a high pressure of oxygen can saturate them.

To understand this equilibrium one must visualize its dynamics. Under the influence of heat the molecules in the solution and in the gas are whizzing around erratically and are constantly colliding. Oxygen molecules are entering and leaving the solution, forming bonds with myoglobin molecules and breaking away from them. The number of iron-oxygen bonds that break in one second is proportional to the number of oxymyoglobin molecules. The number of bonds that form in one second is proportional to the frequency of collisions between myoglobin and oxygen, which is determined in turn by the product of their concentrations. When more oxygen is added to the gas, more oxygen molecules dissolve, collide with and bind to myoglobin; this raises the number of oxymyoglobin molecules present and therefore also the number of iron-oxygen bonds liable to break, until the number of myoglobin molecules combining with oxygen in one second becomes equal to the number that lose their oxygen in one second. When that happens, a chemical equilibrium has been established.

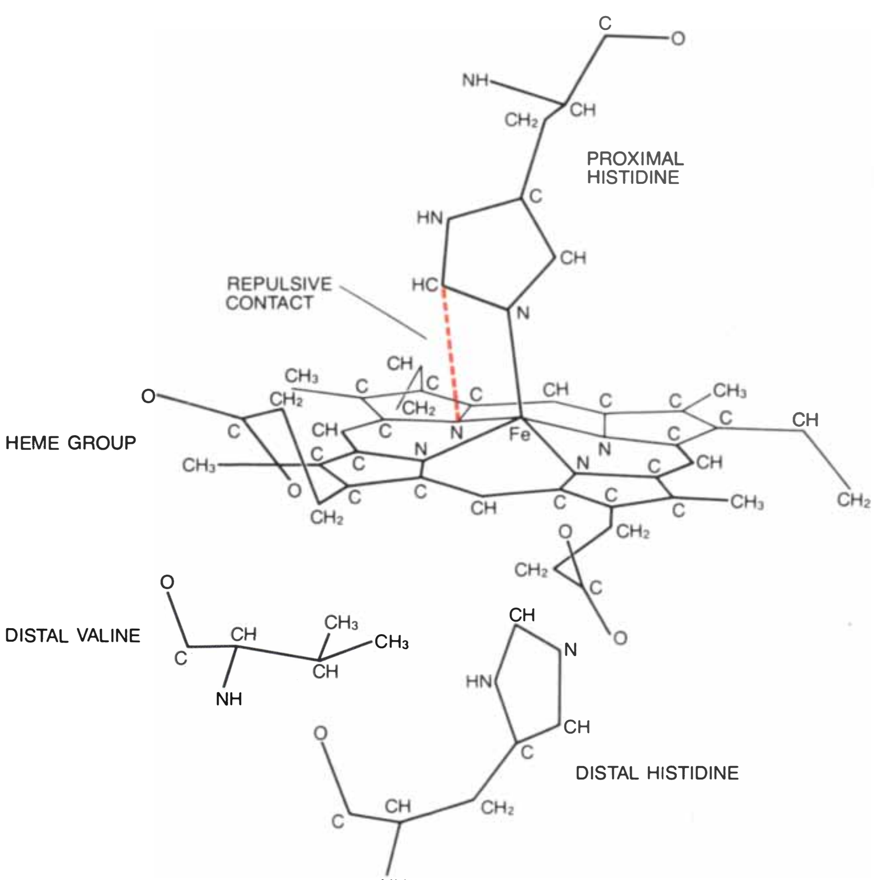
The equilibrium is best represented by a graph in which the logarithm of the ratio of oxymyoglobin molecules (Y) to deoxymyoglobin molecules ($1 - Y$) is plotted against the logarithm of the partial pressure of oxygen. The hyperbola now becomes a straight line at 45 degrees to the axes. The intercept of the line with the horizontal axis drawn at $Y/(1 - Y) = 1$ gives the equilibrium constant K. This is the partial pressure of oxygen at which exactly half of the myoglobin molecules have taken up oxygen. The greater the affinity of the protein for oxygen, the lower the pressure needed to achieve half-saturation and the smaller the equilibrium constant. The 45-degree slope remains unchanged, but lower oxygen affinity shifts the line to the right and higher affinity shifts it to the left.

If the same experiment is done with blood or with a solution of hemoglobin, an entirely different result is obtained. The curve rises gently at first, then steepens and finally flattens out as it approaches the myoglobin curve. This strange sigmoid shape signifies that oxygen-free molecules (deoxyhemoglobin) are reluctant to take up the first oxygen molecule but that their appetite for oxygen grows with the eating. Conversely, the loss of oxygen by some of the hemes lowers the oxygen affinity of the remainder. The distribution of oxygen among the hemoglobin molecules in a solution therefore follows the biblical parable of the rich and the poor: "For unto every one that hath shall be given, and he shall have abundance: but from him that hath not shall be taken away even that which he hath." This phenomenon suggests there is some kind of communication between the hemes in each molecule, and physiologists have therefore called it heme-heme interaction.

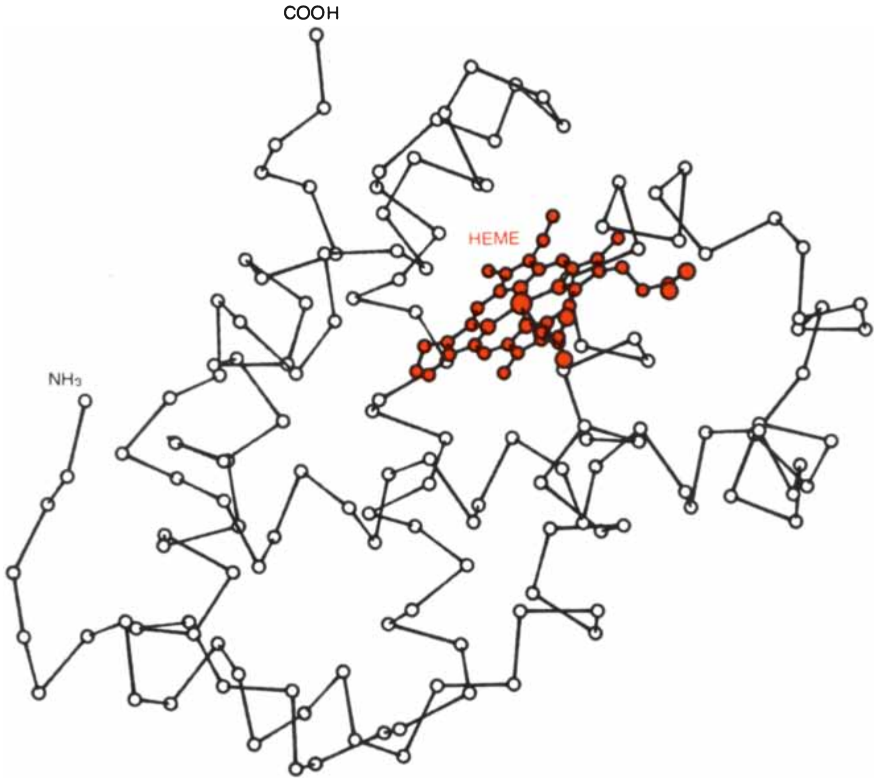
A better picture of the underlying mechanism of heme-heme interaction is obtained in a logarithmic graph. The equilibrium curve then begins with a straight line at 45 degrees to the axes, because at first oxygen molecules are so scarce that only one heme in each hemoglobin molecule has a chance of catching one of them, and all the hemes therefore react independently, as in myoglobin. As more oxygen flows in, the four hemes in each molecule begin to interact and the curve steepens. The tangent to its maximum slope is known as Hill's coefficient (n), after the physiologist A. V. Hill, who first attempted a mathematical analysis of the oxygen equilibrium. The normal value of Hill's coefficient is about 3; without heme-heme interaction it becomes unity. The curve ends with another line at 45 degrees to the axes because oxygen has now become so abundant that only the last heme in each molecule is likely to be free, and all the hemes in the solution react independently once more.

Cooperative Effects

Hill's coefficient and the oxygen affinity of hemoglobin depend on the concentration of several chemical factors in the red blood cell: protons (hydrogen atoms without electrons, whose concentration can be measured as pH), carbon dioxide (CO_2), chloride ions (Cl^-) and a compound of glyceric acid and phosphate called 2,3-diphosphoglycerate (DPG). Increasing the concentration of any of these factors shifts the oxygen equilibrium curve to the right, toward lower oxy-



CHEMICAL STRUCTURE of the heme group and surrounding amino acids is shown by a skeleton of lines connecting the centers of atoms. The only chemical bond between the heme and the protein that engulfs it is the link between the iron atom and the amino acid at the top, called the proximal histidine; the two amino acids at the bottom (the distal histidine and the distal valine) touch the heme but are not bonded to it. The proximal histidine is the principal path for communication between the heme and the rest of the molecule. In the deoxy state shown the iron protrudes above the porphyrin and may be hindered from returning to a centered position by repulsion between one corner of the proximal histidine and one of the porphyrin nitrogen atoms. Key was constructed with aid of a computer by R. Diamond of Cambridge.



SUBUNIT OF HEMOGLOBIN consists of a heme group (*color*) enfolded in a polypeptide chain. The polypeptide is a linear sequence of amino acid residues, each of which is represented here by a single dot, marking the position of the central (alpha) carbon atom. The chain begins with an amino group (NH_3) and ends with a carboxyl group (COOH). Most of the polypeptide is coiled up to form helical segments but there are also nonhelical regions. The computer-generated diagram of a horse-hemoglobin subunit was prepared by Feldmann and Porter.

gen affinity, and makes it more sigmoid. Increased temperature also shifts the curve to the right, but it makes it less sigmoid. Strangely, none of these factors, with the exception of temperature, influences the oxygen equilibrium curve of myoglobin, even though the chemistry and structure of myoglobin are related closely to those of the individual chains of hemoglobin.

What is the purpose of these extraordinary effects? Why is it not good enough for the red cell to contain a simple oxygen carrier such as myoglobin? Such a carrier would not allow enough of the oxygen in the red cell to be unloaded to the tissues, nor would it allow enough carbon dioxide to be carried to the lungs by the blood plasma. The partial pressure of oxygen in the lungs is about 100 millimeters of mercury, which is sufficient to saturate hemoglobin with oxygen whether the equilibrium curve is sigmoid or hyperbolic. In venous blood the pressure is about 35 millimeters of mercury; if the curve were hyperbolic, less than 10 percent of the oxygen carried would be released at that pressure, so that a man would asphyxiate even if he breathed normally.

The more pronounced the sigmoid shape of the equilibrium curve is, the greater the fraction of oxygen that can be released. Several factors conspire to that purpose. Oxidation of nutrients by the tissues liberates lactic acid and carbonic acid; these acids in turn liberate protons, which shift the curve to the right, toward lower oxygen affinity, and make it more sigmoid. Another important regulator of the oxygen affinity is DPG. The number of DPG molecules in the red cell is about the same as the number of hemoglobin molecules, 280 million, and probably remains fairly constant during circulation; a shortage of oxygen, however, causes more DPG to be made, which helps to release more oxygen. With a typical sigmoid curve nearly half of the oxygen carried can be released to the tissues. The human fetus has a hemoglobin with the same alpha chains as the hemoglobin of the human adult but different beta chains, resulting in a lower affinity for DPG. This gives fetal hemoglobin a higher oxygen affinity and facilitates the transfer of oxygen from the maternal circulation to the fetal circulation.

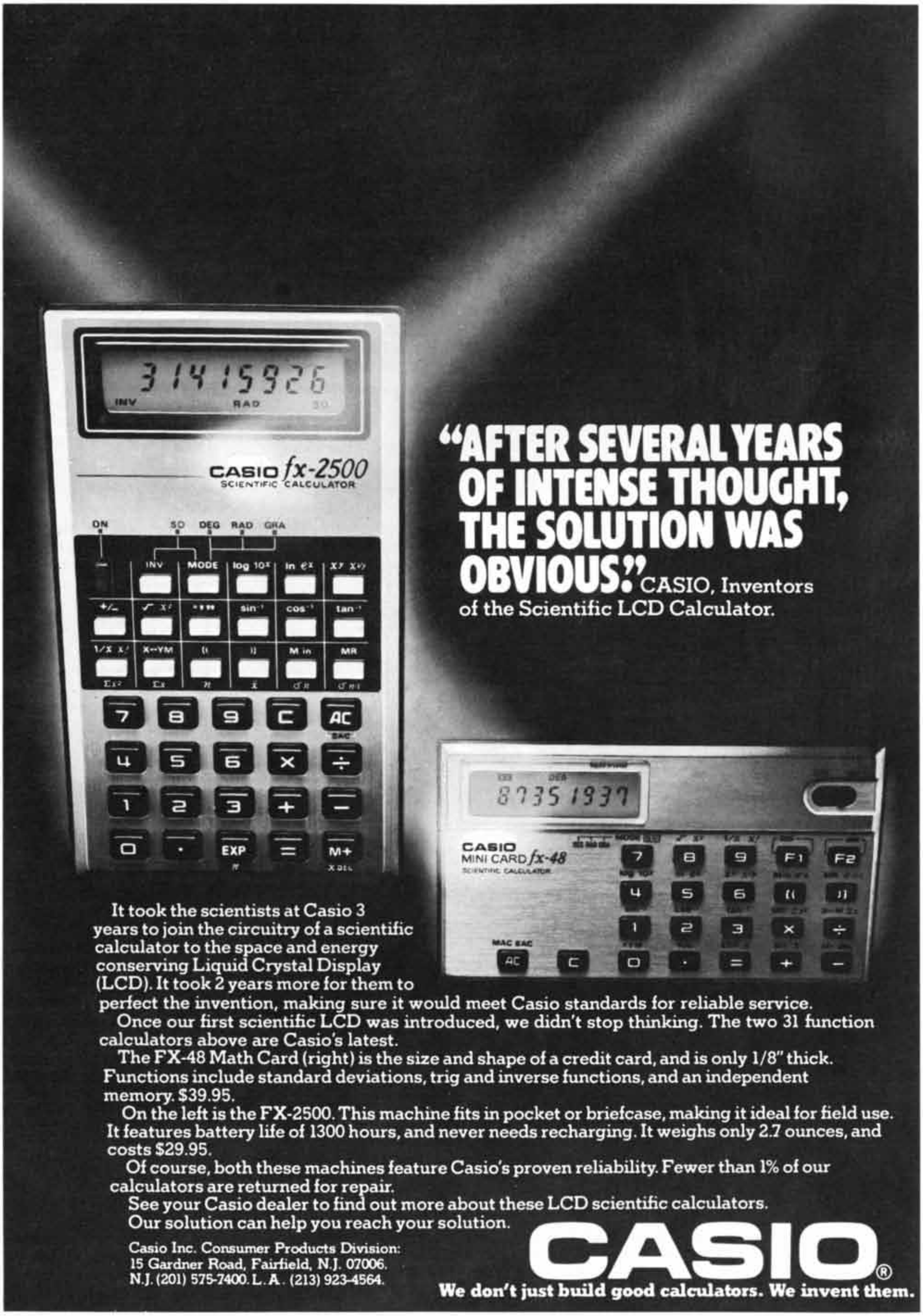
Carbon monoxide (CO) combines with the heme iron at the same site as oxygen, but its affinity for that site is 150 times greater; carbon monoxide therefore displaces oxygen, which explains why it is so toxic. In heavy smokers up to 20 percent of the oxygen combining sites can be blocked by carbon monoxide, so that less oxygen is carried by the blood. In addition carbon monoxide has an even more sinister effect. The combination of one of the four hemes in any hemoglobin molecule with carbon monoxide raises the oxygen affinity of the remaining three hemes by heme-heme interaction. The oxygen equilibrium curve is therefore shifted to the left, which diminishes the fraction of the oxygen carried that can be released to the tissues.

If protons lower the affinity of hemoglobin for oxygen, then the laws of action and reaction demand that oxygen lower the affinity of hemoglobin for protons. Liberation of oxygen causes hemoglobin to combine with protons and vice versa; about two protons are taken up for every four molecules of oxygen released, and two protons are liberated again when four molecules of oxygen are taken up. This reciprocal action is known as the Bohr effect and is the key to the mechanism of carbon dioxide transport. The carbon dioxide released by respiring tissues is too insoluble to be transported as such, but it can be rendered more soluble by combining with water to form a bicarbonate ion and a proton. The chemical reaction is written

$$CO_2 + H_2O \rightarrow HCO_3^- + H^+$$

In the absence of hemoglobin this reaction would soon be brought to a halt by the excess of protons produced, like a fire going out when the chimney is blocked. Deoxyhemoglobin acts as a buffer, mopping up the protons and tipping the balance toward the formation of soluble bicarbonate. In the lungs the process is reversed. There, as oxygen binds to hemoglobin, protons are cast off, driving carbon dioxide out of solution so that it can be exhaled. The reaction between carbon dioxide and water is catalyzed by carbonic anhydrase, an enzyme in the red cells. The enzyme speeds up the reaction to a rate of about half a million molecules per second, one of the fastest of all known biological reactions.

There is a second but less important mechanism for transporting carbon dioxide. The gas binds more readily to deoxyhemoglobin than it does to oxyhemoglobin, so that it tends to be taken up when oxygen is liberated and cast off when oxygen is bound. The two mechanisms of carbon dioxide transport are antagonistic: for each molecule of carbon dioxide bound to deoxyhemoglobin either one or two protons are released, which oppose the conversion of other molecules of carbon dioxide to bicarbonate. Positively charged protons entering the red cell draw negatively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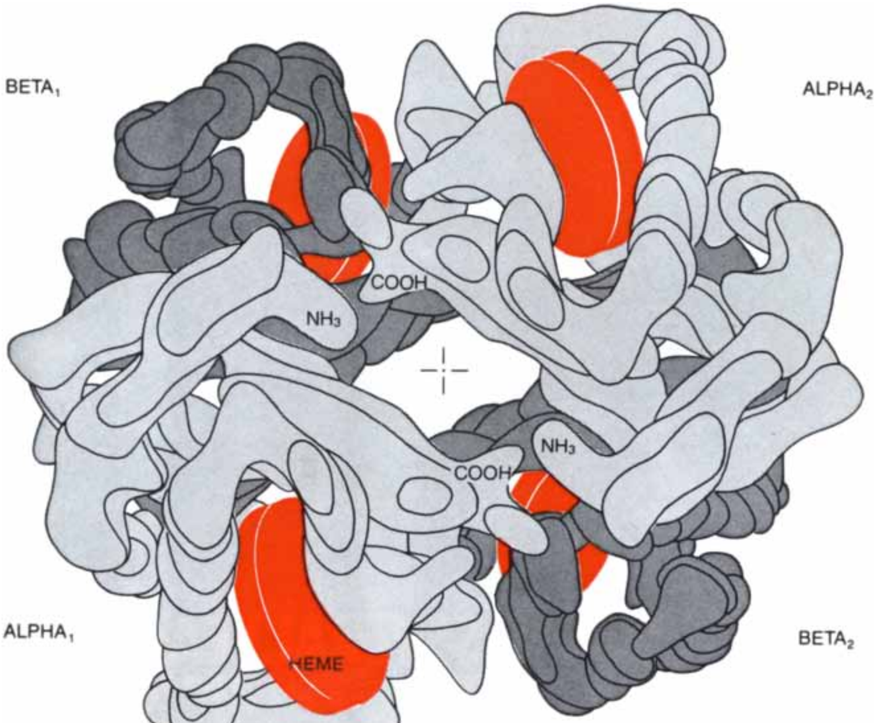

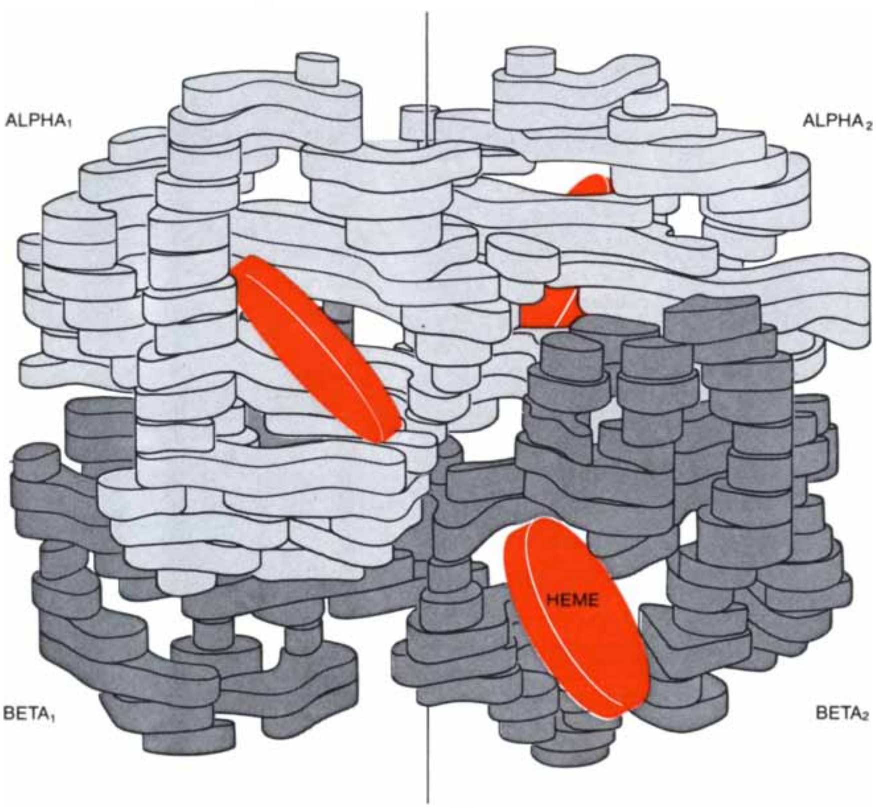

COMPLETE MOLECULE of hemoglobin is made up of four subunits, each of which consists of one polypeptide chain and one heme. There are two kinds of subunit, designated alpha (*white*) and beta (*gray*), which have different sequences of amino acid residues but similar three-dimensional structures. The beta chain also has one short extra helix. The four subunits, seen here in two views, are arranged at the vertexes of a tetrahedron around an axis of two-fold symmetry. Each heme (*color*) lies in a separate pocket at the surface of the molecule.

charged chloride ions in with them, and these ions too are bound more readily by deoxyhemoglobin than by oxyhemoglobin. DPG is synthesized in the red cell itself and cannot leak out through the cell membrane. It is strongly bound by deoxyhemoglobin and only very weakly bound by oxyhemoglobin.

Heme-heme interaction and the interplay between oxygen and the other four ligands are known collectively as the cooperative effects of hemoglobin. Their discovery by a succession of able physiologists and biochemists took more than half a century and aroused many controversies. In 1938 Felix Haurowitz of the Charles University in Prague made another vital observation. He discovered that deoxyhemoglobin and oxyhemoglobin form different crystals, as though they were different chemical substances, which implied that hemoglobin is not an oxygen tank but a molecular lung because it changes its structure every time it takes up oxygen or releases it.

Theory of Allostery

The discovery of an interaction among the four hemes made it obvious that they must be touching, but in science what is obvious is not necessarily true. When the structure of hemoglobin was finally solved, the hemes were found to lie in isolated pockets on the surface of the subunits. Without contact between them how could one of them sense whether the others had combined with oxygen? And how could as heterogeneous a collection of chemical agents as protons, chloride ions, carbon dioxide and diphosphoglycerate influence the oxygen equilibrium curve in a similar way? It did not seem plausible that any of them could bind directly to the hemes, that all of them could bind at any other common site, although there again it turned out we were wrong. To add to the mystery, none of these agents affected the oxygen equilibrium of myoglobin or of isolated subunits of hemoglobin. We now know that all the cooperative effects disappear if the hemoglobin molecule is merely split in half, but this vital clue was missed. Like Agatha Christie, nature kept it to the last to make the story more exciting.

There are two ways out of an impasse in science: to experiment or to think. By temperament, perhaps, I experimented, whereas Jacques Monod thought. In the end our paths converged.

Monod's scientific life had been devoted to finding out what regulates the growth of bacteria. The key to this problem appeared to be regulation of the synthesis and catalytic activity of enzymes. Monod and François Jacob had discovered that the activity of certain enzymes is controlled by switching their synthesis on and off at the gene; they and others then found a second mode of reg-


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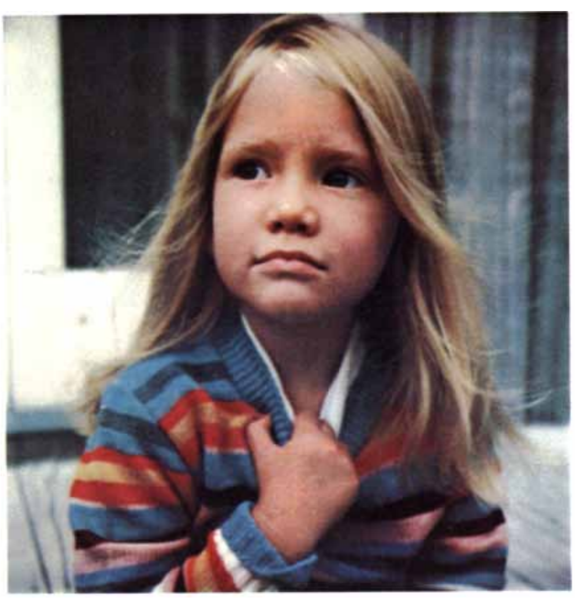

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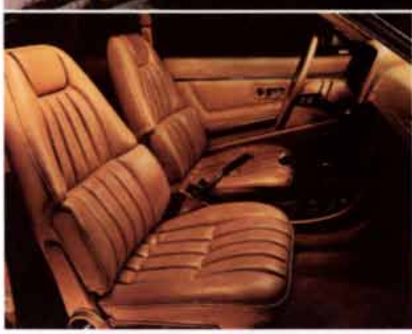

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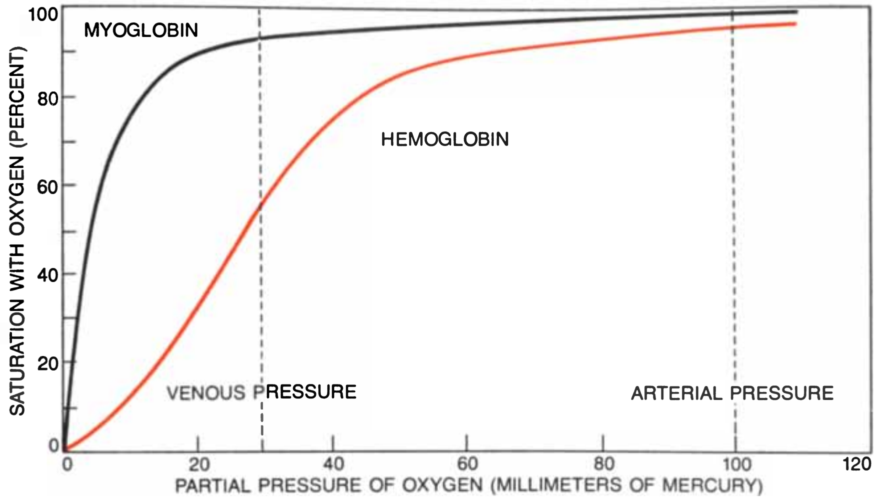
THAT'S IMAGINATION. THAT'S PLYMOUTH.

ulation that appeared to operate switches on the enzymes themselves.

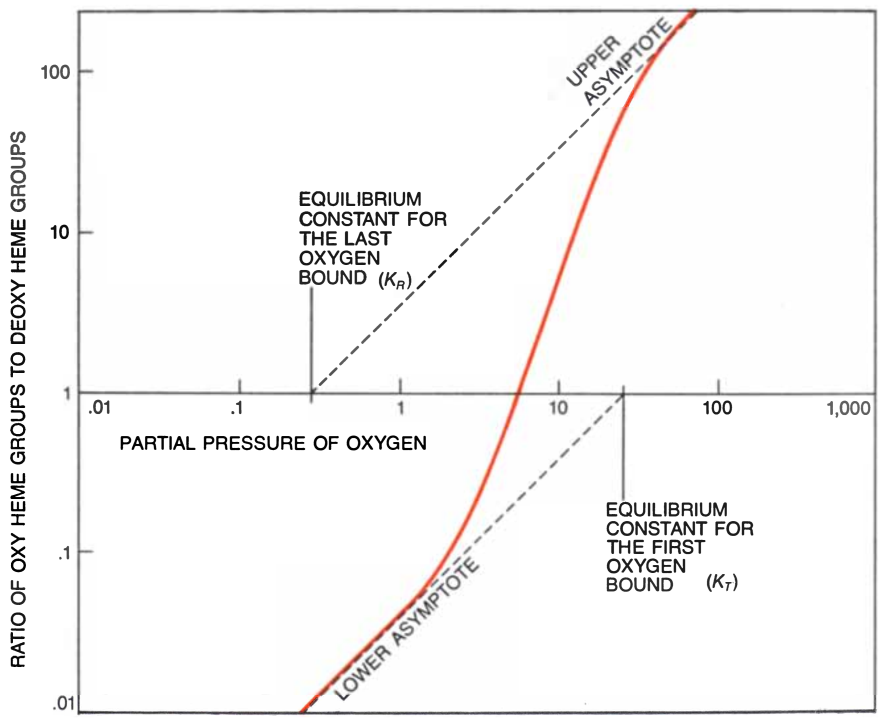
In 1965 Monod and Jean-Pierre Changeux of the Pasteur Institute in Paris, together with Jeffries Wyman of the University of Rome, recognized that the enzymes in the latter class have certain features in common with hemoglobin. They are all made of several subunits, so that each molecule includes several sites with the same catalytic activity, just as hemoglobin includes several hemes that bind oxygen, and they all show similar cooperative effects. Monod and his colleagues knew that deoxyhemoglobin and oxyhemoglobin have different structures, which made them suspect that the enzymes too may exist in two (or at least two) structures. They postulated that these structures should be distinguished by the arrangement of the subunits and by the number and strength of the bonds between them.

If there are only two alternative structures, the one with fewer and weaker bonds between the subunits would be free to develop its full catalytic activity (or oxygen affinity); this structure has therefore been labeled *R*, for "relaxed." The activity would be damped in the structure with more and stronger bonds between the subunits; this form is called *T*, for "tense." In either of these structures the catalytic activity (or oxygen affinity) of all the subunits in one molecule should always remain equal. This postulate of symmetry allowed the properties of allosteric enzymes to be described by a neat mathematical theory with only three independent variables: K_R and K_T, which in hemoglobin denote the oxygen equilibrium constants of the *R* and *T* structures respectively, and *L*, which stands for the number of molecules in the *T* structure divided by the number in the *R* structure, the ratio being measured in the absence of oxygen. The term allostery (from the Greek roots *allos*, "other," and *stereos*, "solid") was coined because the regulator molecule that switches the activity of the enzyme on or off has a structure different from that of the molecule whose chemical transformation the enzyme catalyzes.

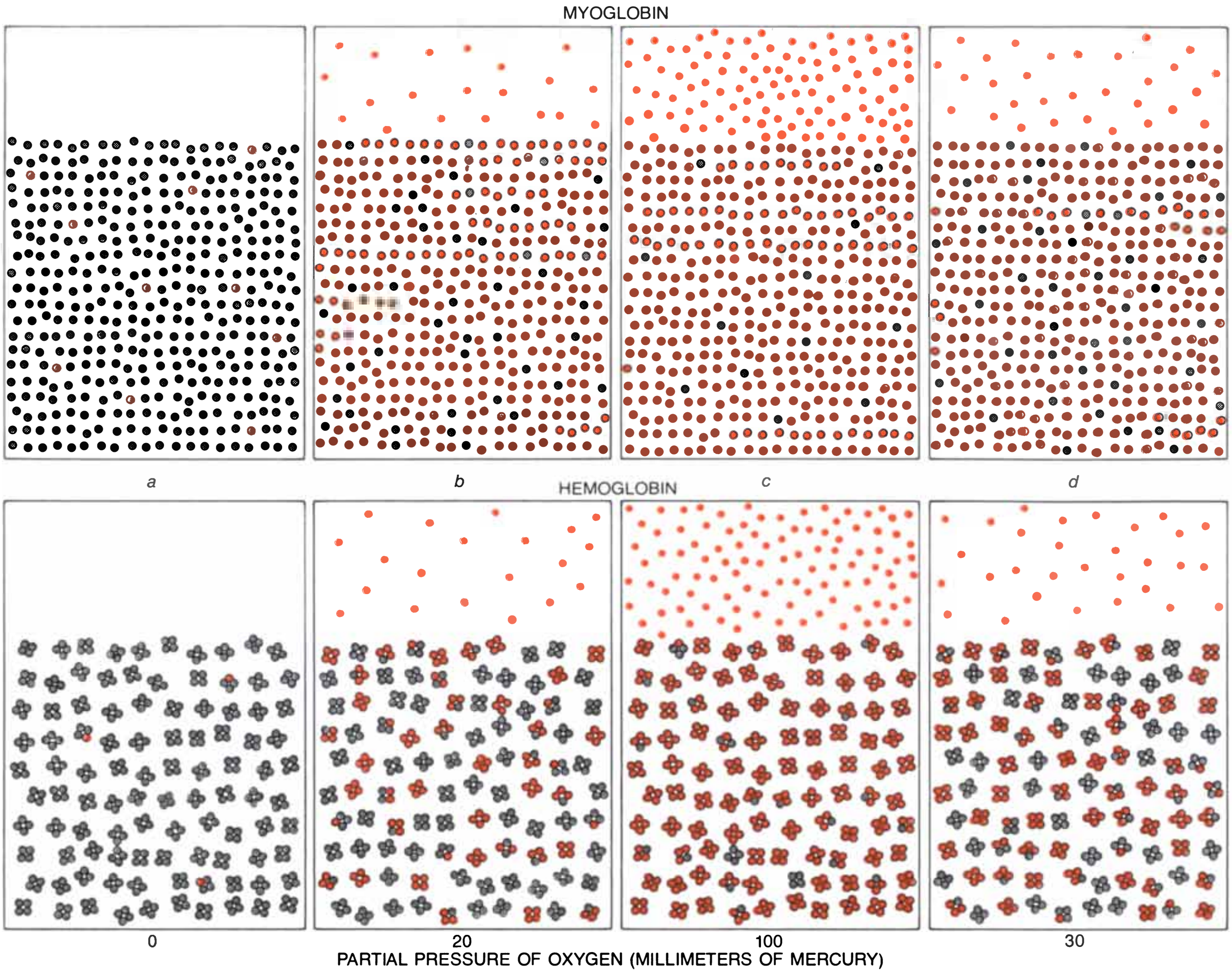
This ingenious theory simplified the interpretation of the cooperative effects enormously. The progressive increase in oxygen affinity illustrated by the parable of the rich and the poor now arises not from any direct interaction between the hemes but from the switchover from the *T* structure with low affinity to the *R* structure with high affinity. This transformation should take place either when the second molecule of oxygen is bound or when the third is bound. Chemical agents that do not bind to the hemes might lower the oxygen affinity by biasing the equilibrium between the two structures toward the *T* form, which would make the transition to the *R* structure come after, say, three mole-



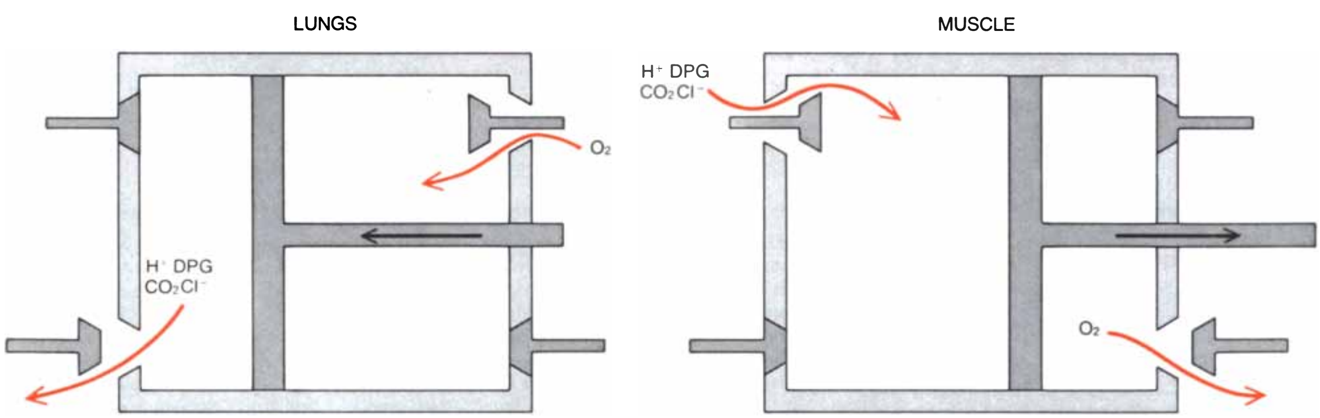
EQUILIBRIUM CURVES measure the affinity for oxygen of hemoglobin and of the simpler myoglobin molecule. Myoglobin, a protein of muscle, has just one heme group and one polypeptide chain and resembles a single subunit of hemoglobin. The vertical axis gives the amount of oxygen bound to one of these proteins, expressed as a percentage of the total amount that can be bound. The horizontal axis measures the partial pressure of oxygen in a mixture of gases with which the solution is allowed to reach equilibrium. For myoglobin (*black*) the equilibrium curve is hyperbolic. Myoglobin absorbs oxygen readily but becomes saturated at a low pressure. The hemoglobin curve (*color*) is sigmoid: initially hemoglobin is reluctant to take up oxygen, but its affinity increases with oxygen uptake. At arterial oxygen pressure both molecules are nearly saturated, but at venous pressure myoglobin would give up only about 10 percent of its oxygen, whereas hemoglobin releases roughly half. At any partial pressure myoglobin has a higher affinity than hemoglobin, which allows oxygen to be transferred from blood to muscle.



SIGMOID SHAPE of the oxygen equilibrium curve appears more pronounced when the fractional saturation and partial pressure of oxygen are plotted on logarithmic scales. On such a graph the equilibrium curve for myoglobin becomes a straight line at 45 degrees to the axes. The hemoglobin curve begins and ends with straight lines, called asymptotes, at the same angle. Their intercepts with the horizontal line drawn where the concentrations of deoxyhemoglobin and oxyhemoglobin are equal give the equilibrium constants for the first and last oxygen molecules to combine with hemoglobin. In the allosteric interpretation of the curve these are respectively the equilibrium constants of the *R* structure (K_R) and the *T* structure (K_T). For the curve shown the two constants are respectively 30 and .3, indicating that the affinity for the last oxygen bound is 100 times the affinity for the first. This ratio determines the free energy of the heme-heme interaction, which is a measure of the influence exerted by the combination of any one of the four hemes with oxygen on the oxygen affinity of the remaining hemes. If the beginning and end of the curve cannot be measured accurately, the maximum slope of the curve, known as Hill's coefficient, indicates the degree of the heme-heme interaction.



HEME-HEME INTERACTION facilitates the release of oxygen by hemoglobin but is not observed in myoglobin. The proteins are shown gray in the deoxy state and colored when oxygenated; there are four times as many molecules of myoglobin as hemoglobin but equal numbers of binding sites. In the absence of oxygen (*a*) almost all the binding sites are empty. As the oxygen pressure rises (*b*) myoglobin takes up oxygen more quickly, but when the pressure reaches that of the lungs (*c*), both carriers are approaching saturation. The distinction between the two molecules becomes most apparent when the oxygen pressure falls to a level typical of the capillary system (*d*). The oxygen equilibrium of myoglobin changes little, but hemoglobin sheds about 45 percent of the oxygen it carries. The difference is accounted for by the amplifying effect of the heme-heme interaction. Few hemoglobin molecules bear one or two oxygens: if a hemoglobin molecule takes up one oxygen, it tends to go on and acquire four oxygens, and if a saturated molecule loses one oxygen, two or three more oxygens are usually cast off. The data for hemoglobin are derived from curves calculated by Joyce M. Baldwin of Cambridge.



RECIPROCATING ENGINE serves as a model of the cooperative effects of hemoglobin. The piston is driven to the right by the energy liberated in the reaction of hemoglobin with oxygen (O_2) and to the left by the protons (H^+) and carbon dioxide (CO_2) liberated by respiring tissues. Diphosphoglycerate (DPG) and chloride ions (Cl^-) are passengers riding in company with protons and carbon dioxide.

cules of oxygen have been bound rather than after two molecules have been bound. In terms of allosteric theory such agents would raise *L*, the fraction of molecules in the *T* structure, without altering the oxygen equilibrium constants K_T and K_R of the two structures.

Atomic Structures

My own approach to the problem was also influenced by Haurowitz' discovery that oxyhemoglobin and deoxyhemoglobin have different structures. Gradually I came to realize that we would never explain the intricate functions of hemoglobin without solving the structures of both crystal forms at a resolution high enough to reveal atomic detail.

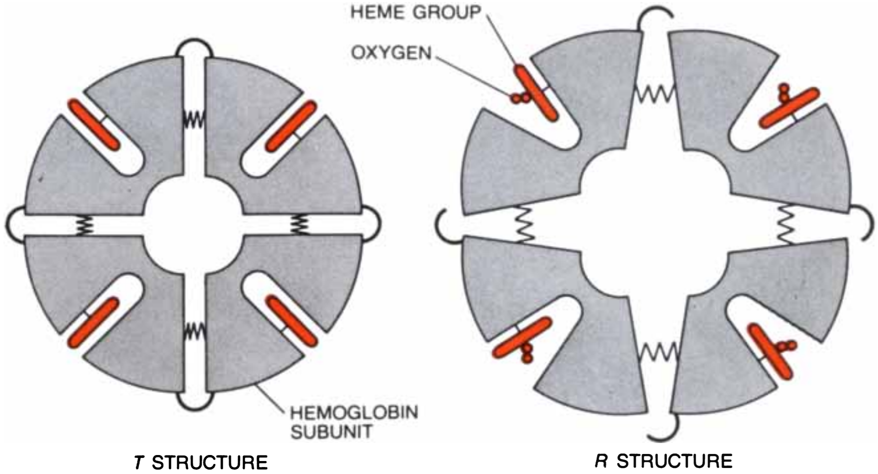
In 1970, 33 years after I had taken my first X-ray-diffraction pictures of hemoglobin, that stage was finally reached. Hilary Muirhead, Joyce M. Baldwin, Gwynne Goaman and I got a good map of the distribution of matter not in oxyhemoglobin but in the closely related methemoglobin of horse, in which the iron is ferric and the place of oxygen is taken by a water molecule. William Bolton and I got a map of horse deoxyhemoglobin, and Muirhead and Jonathan Greer got one of human deoxyhemoglobin. These maps served as guides for the construction of three atomic models, each a jungle of brass spokes and steel connectors supported on brass scaffolding, edifices of labyrinthine complexity nearly four feet in diameter. At first it was hard to see the trees for the forest.

In allosteric terms our methemoglobin model represented the *R* structure and our two deoxyhemoglobin models the *T* structure. We scanned them eagerly for clues to the allosteric mechanism but could not see any at first because the general structure of the subunits was similar in all three models. The alpha chains included seven helical segments and the beta chains eight helical segments interrupted by corners and nonhelical segments. Each chain enveloped its heme in a deep pocket, which exposed only the edge where two propionic acid side chains of the porphyrin dip into the surrounding water.

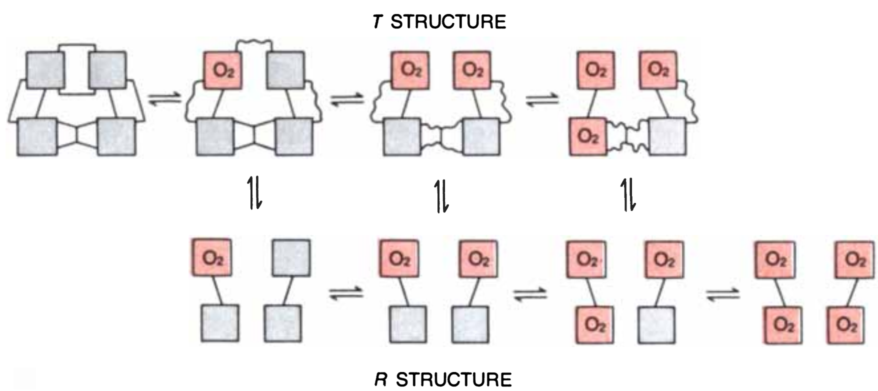
The heme makes contact with 16 amino acid side chains from seven segments of the chain. Most of these side chains are hydrocarbons; the two exceptions are the heme-linked histidines, which lie on each side of the heme and play an important part in the binding of oxygen. The side chain of histidine ends in an imidazole ring made of three carbon atoms, two nitrogen atoms and either four or five hydrogen atoms. One of these histidines, called the proximal histidine, forms a chemical bond with the heme iron [*see illustrations on pages 93 and 95*]. The other histidine, called the distal one, lies on the opposite side of the heme, in contact with it and with the bound oxygen but without forming a covalent chemical bond with either. Apart from these histidines, most of the side chains in the interior of the subunits, like those near the hemes, are hydrocarbons. The exterior of the hemoglobin molecule is lined with side chains of all kinds, but electrically charged and dipolar ones predominate. Thus each subunit is waxy inside and soapy outside, which makes it soluble in water but impermeable to it.

The four subunits are arranged at the vertexes of a tetrahedron around a twofold symmetry axis. Since a tetrahedron has six edges, there are six areas of contact between the subunits. The twofold symmetry leaves four distinct contacts, which cover about a fifth of the surface area of the subunits. Sixty percent of that area is made up of the alpha$_1$-beta$_1$ and alpha$_2$-beta$_2$ contacts, each of which includes about 35 amino acid side chains tightly linked by from 17 to 19 hydrogen bonds. [Hydrogen bonds are made between atoms of nitrogen (N) and oxygen (O) through an intermediate hydrogen atom (H), for instance N–H...N, N–H...O, O–H...O or O–H...N. The hydrogen is bonded strongly to the atom on the left and weakly to the one on the right.]

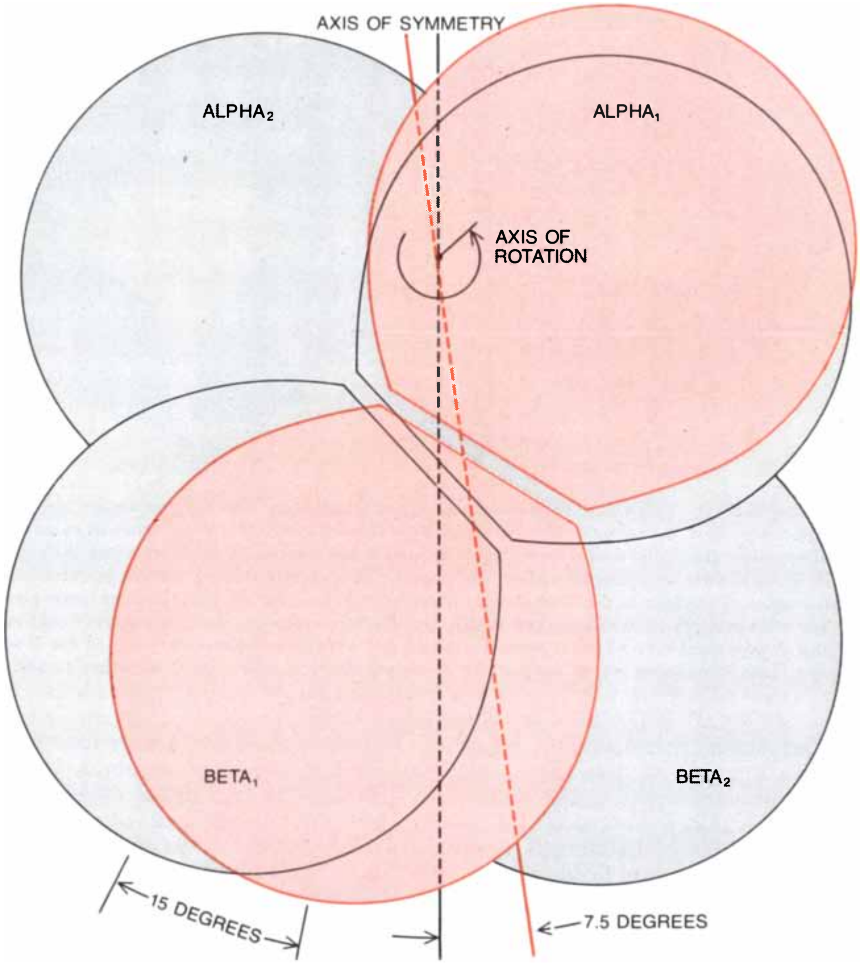
The numerous hydrogen bonds between the alpha$_1$-beta$_1$ and alpha$_2$-beta$_2$



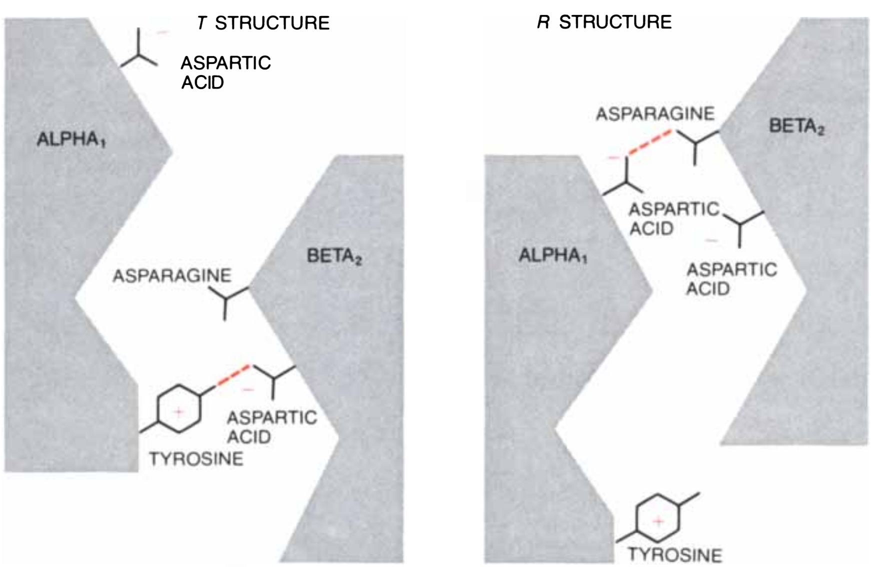
ALLOSTERIC THEORY explains heme-heme interaction without postulating any direct communication between the heme groups. The hemoglobin molecule is assumed to have two alternative structures, designated *T* for tense and *R* for relaxed. In the *T* structure the subunits of the molecule are clamped against the pressure of springs and their narrow pockets impede the entry of oxygen. In the *R* structure all the clamps have sprung open and the heme pockets are wide enough to admit oxygen easily. Uptake of oxygen by the *T* structure would strain the clamps until they all burst open in concert and allow the molecule to relax to the *R* structure. Loss of oxygen would narrow the heme pockets and allow the *T* structure to re-form.



TRANSITION from the *T* structure to the *R* structure increases in likelihood as each of the four heme groups is oxygenated. In this more realistic model, salt bridges linking the subunits in the *T* structure break progressively as oxygen is added, and even those salt bridges that have not yet ruptured are weakened, a process that is represented here by making the lines wavy. The transition from *T* to *R* does not take place after a fixed number of oxygen molecules have been bound, but it becomes more probable with each successive oxygen bound. The transition between the two structures is influenced by several factors, including protons, carbon dioxide, chloride and DPG. The higher their concentration is, the more oxygen must be bound to trigger the transition. Fully saturated molecules in the *T* structure and fully deoxygenated molecules in the *R* structure are not shown because they are too unstable to exist in significant numbers.



REARRANGEMENT OF SUBUNITS during the transition from the *T* structure to the *R* structure consists mainly in a rotation of one pair of subunits with respect to the other pair. Each alpha chain is bonded strongly to one beta chain, and the dimers formed in this way move as rigid bodies. If one dimer is held fixed, the other turns by 15 degrees about an off-center axis and shifts slightly along it. The twofold symmetry of the molecule is preserved, but the axis of symmetry is rotated by 7.5 degrees. The diagram is based on one prepared by Baldwin.



CONTACT between the two dimers has two stable conformations, one for the *T* structure and the other for the *R* structure. On transition between the structures the dimers snap from one position to the other. They are stabilized by alternative sets of hydrogen bonds formed between amino acid side chains attached to the opposing faces of the dimers. The two bonds shown here were first discovered by X-ray crystallography. In 1975 Leslie Fung and Chien Ho at the University of Pittsburgh demonstrated the presence of these bonds in solution. This provides evidence that the two structures found in crystals are the same as the structures in red blood cells.

subunits make them cohere so strongly that their contact is hardly altered by the reaction with oxygen, and they move as rigid bodies in the transition between the *T* and the *R* structures. On the other hand, the contact alpha$_1$-beta$_2$ in the *R* structure looked quite different from that in the *T* structure. This contact includes fewer side chains than alpha$_1$-beta$_1$ and is designed so that it acts as a snap-action switch, with two alternative stable positions, each braced by a different set of hydrogen bonds. We wondered at first whether these bonds were stronger and more numerous in the *T* structure than they are in the *R* structure, but that did not seem to be the case.

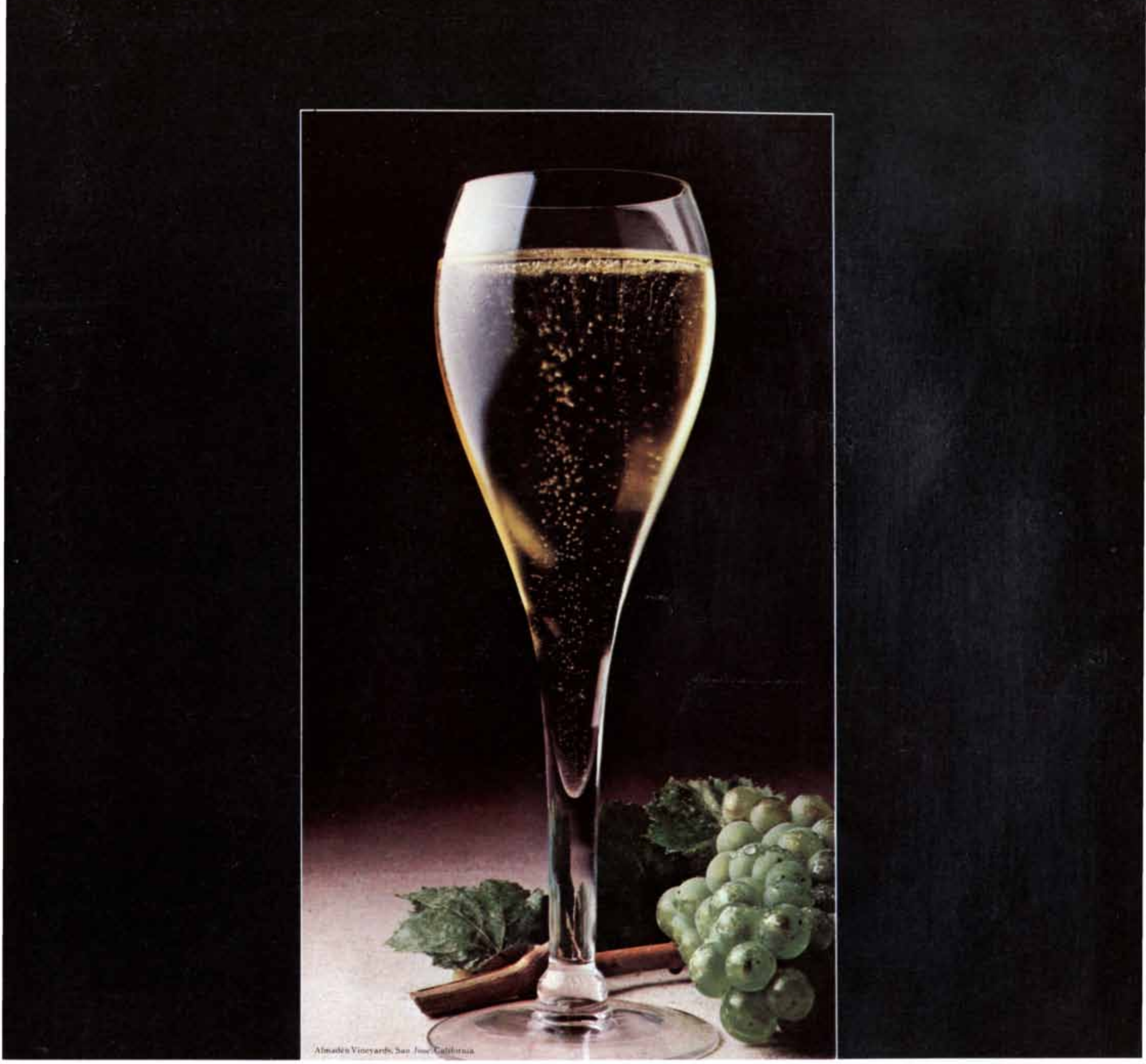
Where, then, were the extra bonds between the subunits in the *T* structure that allosteric theory demanded? We spotted them at the ends of the polypeptide chains. In the *T* structure the last amino acid residue of each chain forms salt bridges with neighboring subunits. (A salt bridge is a bond between a nitrogen atom, carrying a positive charge, and an oxygen atom, carrying a negative charge.) In our maps of the *R* structure the last two residues of each chain were blurred. At first I suspected this to be due to error, but improved maps made by my colleagues Elizabeth Heidner and Robert Ladner have convinced us that the final residues remain invisible because they are no longer tethered and wave about like reeds in the wind.

Geometrically, the transition between the two structures consists of a rock-and-roll movement of the dimer alpha$_1$-beta$_1$ with respect to the dimer alpha$_2$-beta$_2$. Baldwin has shown that if one dimer is held fixed, the movement of the other one can be represented by a rotation of some 15 degrees about a suitably placed axis together with a small shift along the same axis. The movement is brought about by subtle changes in the internal structure of the subunits that accompany the binding and dissociation of oxygen.

Function of the Salt Bridges

The salt bridges at the ends of the polypeptide chains clearly provide the extra bonds between the subunits in the *T* structure predicted by Monod, Changeux and Wyman. They also explain the influence on the oxygen equilibrium curve of all the chemical factors that had puzzled us so much. All agents that lower the oxygen affinity do so either by strengthening existing salt bridges in the *T* structure or by adding new ones. Not all these extra bonds, however, are between the subunits; some are within the subunits and oppose the subtle structural changes the subunits undergo on combination with oxygen.

The salt bridges explain both the lowering of the oxygen affinity by protons and the uptake of protons on release of oxygen. Protons increase the number



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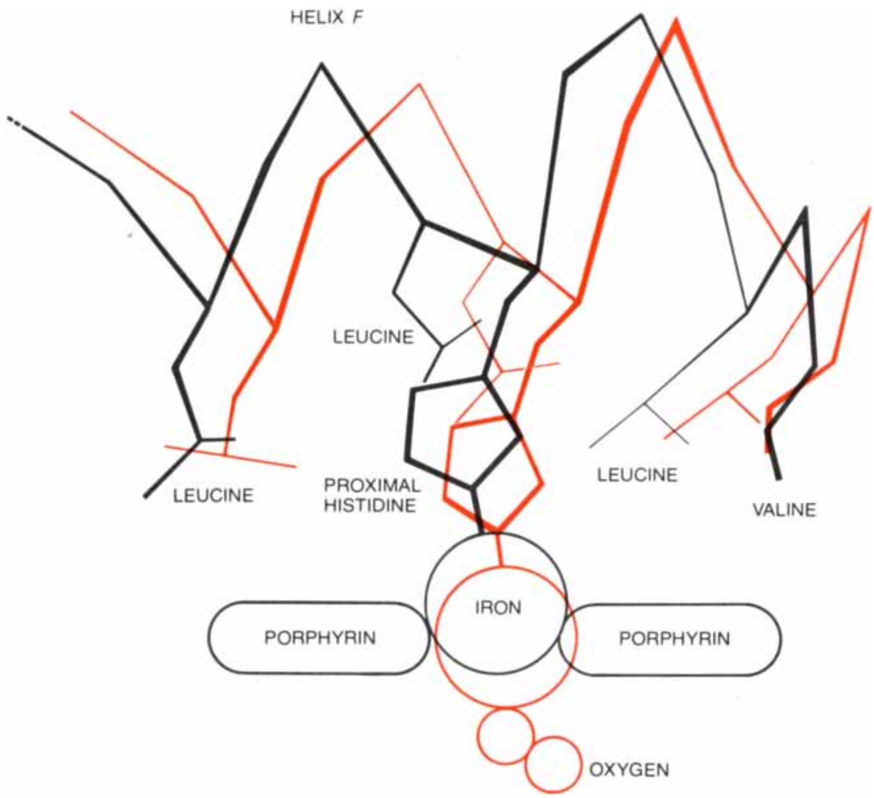
of nitrogen atoms carrying a positive charge. For example, the imidazole ring of the amino acid histidine can exist in two states, uncharged when only one of its nitrogen atoms carries a proton and positively charged when both do. In neutral solution each histidine has a 50 percent chance of being positively charged. The more acid the solution, or in other words the higher the concentration of protons, the greater the chance of a histidine becoming positively charged and forming a salt bridge with an oxygen atom carrying a negative charge. Conversely, the transition from the *R* structure to the *T* structure brings negatively charged oxygen atoms into proximity with an uncharged nitrogen atom and thereby diminishes the work that has to be done to give the nitrogen atom a positive charge. As a result a histidine that has no more than a 50 percent chance of being positively charged in the *R* structure has a 90 percent chance in the *T* structure, so that more protons are taken up from the solution by hemoglobin in the *T* structure.

Hemoglobin includes one other set of groups that behave in this way: they are the amino groups at the start of the polypeptide chains, but their nitrogen atoms take up protons only if the concentration of carbon dioxide is low. If it is high, these nitrogens are liable to lose protons and to combine instead with carbon dioxide to form a carbamino compound. The physiologists F. J. W. Roughton and J. K. W. Ferguson proposed in 1934 that this mechanism plays a part in the transport of carbon dioxide, but their proposal was treated with skepticism until it was confirmed 35 years later by my colleague John Kilmartin, working with Luigi Rossi-Bernardi at the University of Milan. I was pleased that Roughton, who had fathered their experiment, was still alive to see his ideas vindicated. My colleague Arthur R. Arnone, now at the University of Iowa, then showed that in the *T* structure such carbamino groups, which carry a negative charge, form salt bridges with positively charged groups of the globin and are therefore more stable than they are in the *R* structure. This finding explains why deoxyhemoglobin has a higher affinity for carbon dioxide than oxyhemoglobin and conversely why carbon dioxide lowers the oxygen affinity of hemoglobin.

The positions in hemoglobin taken up by chloride ions are still uncertain. Arnone has spotted sites in the *T* structure where other negatively charged ions bind, and these might also be the chloride binding sites. If they are, then chloride ions also brace the *T* structure by forming additional salt bridges.

The most striking difference between the *T* and the *R* structures is the width of the gap between the two beta chains. In the *T* structure the two chains are widely separated and the opening between them is lined by amino acid side chains carrying positive charges. This opening is tailor-made to fit the molecule of 2,3-diphosphoglycerate and to compensate its negative charges, so that the binding of DPG adds another set of salt bridges to the *T* structure. In the *R* structure the gap narrows, and DPG has to drop out.



TRIGGERING MECHANISM for the transition from the *T* to the *R* structure is a movement of the heme iron into the plane of the porphyrin ring. In the *T* structure (*black lines*) the center of the iron atom is about .6 angstrom unit above the plane. (One angstrom unit is 10^{-10} meter.) When the molecule switches to the *R* structure (*colored lines*), the iron moves into the plane, pulling with it the proximal histidine and helix *F*. Once the iron has descended into the plane it can readily bind an oxygen molecule. In the reverse transition (from *R* to *T*) the iron is pulled out of the plane and the oxygen cannot follow because it bumps against the porphyrin nitrogen atoms. The iron-oxygen bond is thereby weakened and usually breaks. These movements are transmitted to the contacts between the subunits and promote the transitions between the *T* and *R* structures. Diagram is based on a drawing by John Cresswell of University College London.

The Trigger

How does combination of the heme irons with oxygen make the subunits click from the *T* structure to the *R* structure? Compared with the hemoglobin molecule, an oxygen molecule is like the flea that makes the elephant jump. Conversely, how does the *T* structure impede the uptake of oxygen? What difference between the two structures is there at the heme that could bring about a several-hundred-fold change in oxygen affinity?

In oxyhemoglobin the heme iron is bound to six atoms: four nitrogen atoms of the porphyrin, which neutralize the two positive charges of the ferrous iron; one nitrogen atom of the proximal histidine, which links the heme to one of the helical segments of the polypeptide chain (helix *F*), and one of the two atoms of the oxygen molecule. In deoxyhemoglobin the oxygen position remains empty, so that the iron is bound to only five atoms.

I wondered whether the heme pockets might be narrower in the *T* structure than in the *R* structure, so that they had to widen to let the oxygen in. This widening might be geared to break the salt bridges, rather like the childish mechanism shown in the illustration at the top of page 105. When the atomic model of horse deoxyhemoglobin emerged, Bolton and I saw some truth in this idea because in the beta subunits a side chain of the amino acid valine next to the distal histidine blocked the site that oxygen would have to occupy. The alpha subunits, however, showed no such obstruction. Then we noticed the odd positions of the iron atoms. In methemoglobin, which has the *R* structure, the iron atoms had been displaced very slightly from the porphyrin plane toward the proximal histidine, but in deoxyhemoglobin (with the *T* structure) the displacement stood out as one of the most striking features of our maps. In each subunit the iron atom had carried the proximal histidine and helix *F* with it, so that they too had moved away from the porphyrin plane. I quickly realized that this might be the long-sought trigger.

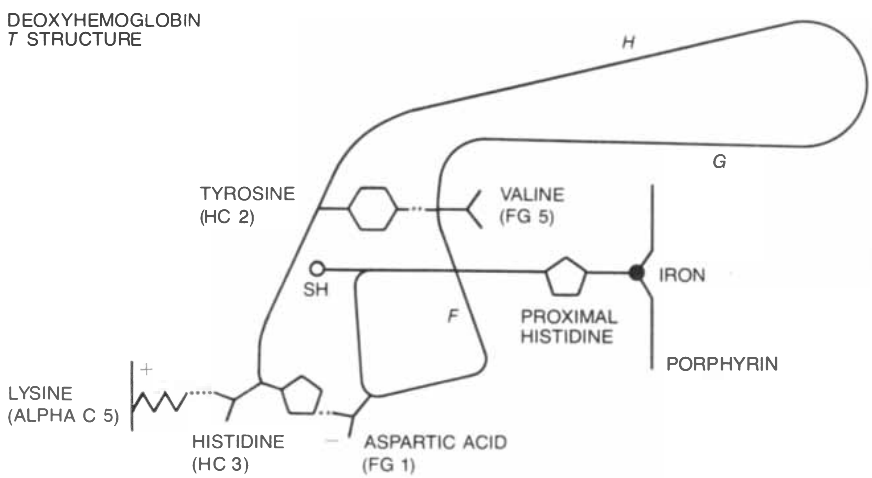
Recently Arnone and my colleague Lynn Ten Eyck have obtained an excellent map of human deoxyhemoglobin to which Giulio Fermi fitted an atomic model of heme by computer methods. Fermi's calculations show that each iron atom is displaced by .6 ($\pm$.1) angstrom unit from the mean plane of the porphyrin. (One angstrom unit is 10^{-10} meter.) The nitrogen atom of the proximal histidine, to which the iron atom is bound, lies at a distance of 2.7 ($\pm$.1) angstroms from the same plane. So far we have no direct measure of the corresponding displacements in oxyhemoglobin because oxyhemoglobin oxidizes to methemoglobin in the X-ray beam. There the iron atoms are displaced from the porphyrin plane by .1 angstrom in the alpha subunits and by .2 angstrom in the beta subunits; the corresponding displacements of the histidine nitrogens are 2.2 and 2.4 angstroms. Judging by the structures of model compounds, the displacement of the histidine nitrogen in oxyhemoglobin should be 2.1 angstroms, which means that the nitrogen would be .6 angstrom closer to the porphyrin plane than it is in deoxyhemoglobin. This shift would trigger the transition from the *T* structure to the *R* structure.

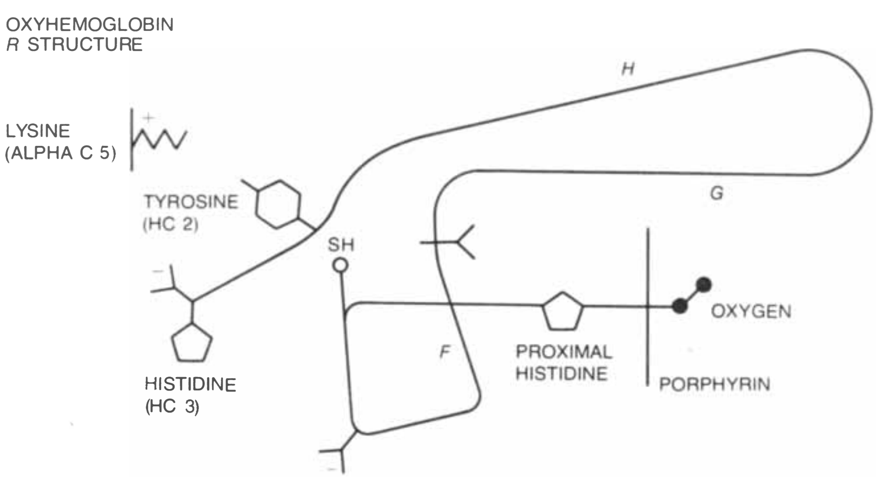
How is this movement transmitted to the contacts between the subunits and to the salt bridges? One might as well puzzle out how a cat jumps off a wall from one picture of the cat on the wall and another of it on the ground, because our static models of deoxyhemoglobin and methemoglobin do not show what happens in the transition between the *T* and the *R* structures. I tried a bold guess. The second amino acid residue from the end in each chain is a tyrosine whose side chain carries a phenol group, that is, a benzene ring with a hydroxyl group (OH) attached. In the *T* structure the tyrosine in each subunit is wedged into a pocket between helixes *F* and *H* and its hydroxyl group is tethered by a hydrogen bond to an oxygen atom in the *FG* segment of the main polypeptide chain. In carbonmonoxyhemoglobin, which is the nearest relative of oxyhemoglobin and which has the *R* structure, the tyrosines are free. Hence there must be some mechanism that loosens the tyrosines when oxygen is bound.

As I wondered what this mechanism might be I saw that the movement of the proximal histidine toward the porphyrin plane that accompanies oxygen binding pulls helix *F* in a direction that narrows the pocket into which the tyrosine must fit. If the tyrosine were squeezed out of its pocket, it would tear the last amino acid residue of the chain away from its salt-bridged partner. In this way one salt bridge might be broken for each heme that combined with oxygen in the *T* structure. When enough salt bridges have been broken, the *T* structure would become unstable and click to the *R* structure.

If movement of the proximal histidine and the iron toward the porphyrin puts into motion a set of levers that loosens the tyrosines and breaks the salt bridges, then the making of the bridges and the binding of the tyrosines into their pockets must cause the same set of levers to go into reverse and move the histidine and the iron away from the porphyrin. The oxygen molecule on the other side cannot follow because it bumps against the four porphyrin nitrogen atoms, and so the iron-oxygen bond is stretched until it finally snaps.

To be guided by the atomic models toward the molecular mechanism of respiratory transport seemed like a dream. But was it true? Would the mechanism stand the cold scrutiny of experiment? It has been said that scientists do not pursue the truth, it pursues them.





EXTRA BONDS in deoxyhemoglobin are formed by the last two residues of the beta chain. In oxyhemoglobin the iron atom lies in the plane of the porphyrin, the sulfhydryl group (SH) of the amino acid cysteine lies in the pocket between helixes *F* and *H*, and tyrosine *HC* 2, histidine *HC* 3 and lysine *C* 5 are free. In deoxyhemoglobin the iron is displaced from the plane of the porphyrin toward helix *F*, and the tyrosine has displaced the SH group from the pocket between *F* and *H* and forms a hydrogen bond with valine *FG* 5. Finally, the terminal histidine forms salt bridges with aspartic acid *FG* 1 of the same chain and with lysine *C* 5 of the alpha chain. Formation of bridge causes histidine to take up a proton and become positively charged.

Testing the Salt Bridges

According to allosteric theory, there should be no heme-heme interaction without a transition between the *T* and the *R* structures. This prediction was also tested by Kilmartin. He cleaved the final amino acid residue from the ends of all four polypeptide chains, so that

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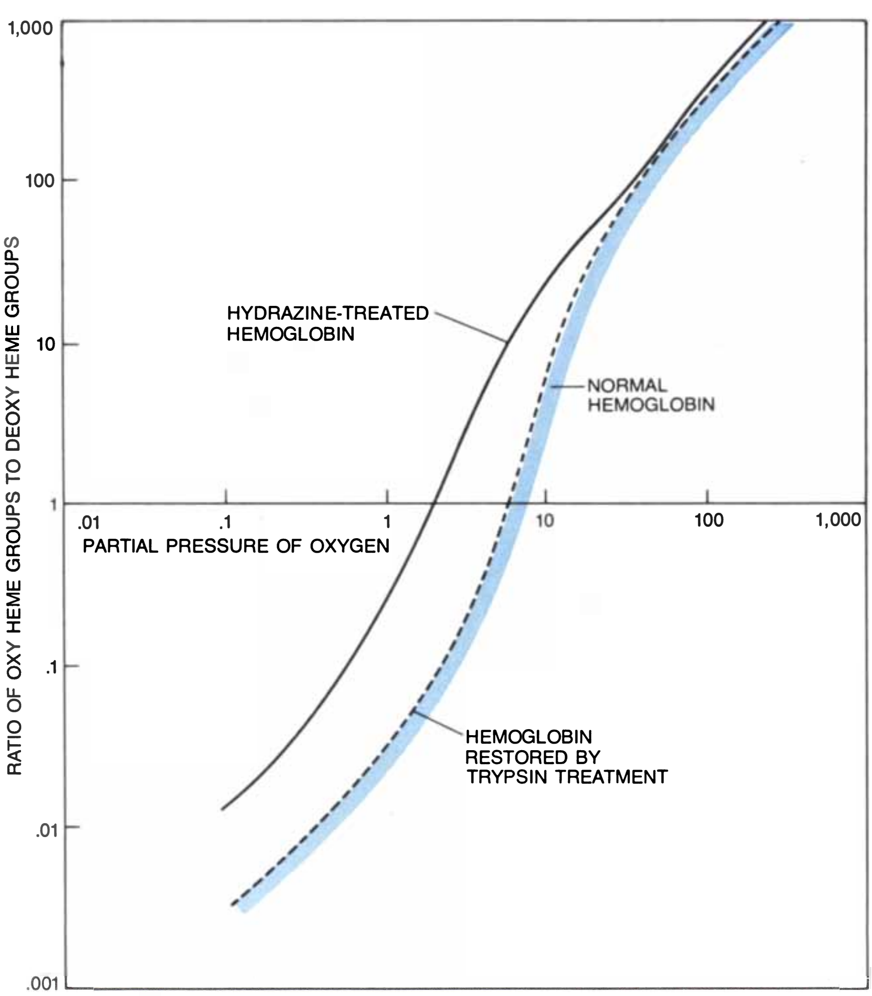
there should be no salt bridges to stabilize the T structure. This modified hemoglobin maintained the R structure even in the absence of oxygen and showed a hyperbolic oxygen equilibrium curve with high oxygen affinity. Kilmartin then selected an abnormal human hemoglobin that can be made to maintain the T structure even when it is saturated with oxygen. Again the curve was hyperbolic, but it was shifted to lower oxygen affinity, so that the central thesis of allostery was proved.

The next question concerned the exact role of the salt bridges. At one extreme the strain arising from the combination of any one heme with oxygen might be distributed uniformly throughout the molecule, so that there would be no change in oxygen affinity until all the salt bridges broke in unison, when the structure clicked from T to R. This would fit pure allosteric theory, according to which the salt bridges should do no more than raise L, the fraction of molecules in the T structure. According to my mechanism, on the other hand, a salt bridge should break every time an oxygen combines with the T structure. If that were true, the salt bridges should raise K_T as well as L, that is to say, they should also lower the oxygen affinity of the T structure. To the general reader this may seem like a fine distinction, but to the workers in the field it seemed to cut at the roots of the mechanism and raised passionate controversies that are still going on.



BLOCKING OF SALT BRIDGES in the open position shifts the oxygen equilibrium curve to the left, toward higher oxygen affinity. The initial equilibrium curve for normal hemoglobin is shown in color. The hemoglobin was then treated with hydrazine (NH_2–NH_2), which prevents the carboxyl terminus of each alpha chain from forming a salt bridge with a lysine on the neighboring alpha chain. When the salt bridge cannot form, the stability of the *T* structure is diminished. The resulting equilibrium curve is shown in black: affinity for oxygen at low oxygen pressures, when hemoglobin has the *T* structure, is increased by a factor of about five and the transition from the *T* to the *R* structure comes earlier in the reaction. (Both K_T and *L* are reduced.) There is no effect at high oxygen pressures, where both normal molecules and treated ones are in the *R* structure. The normal equilibrium was restored (*broken line*) by treating the altered protein with trypsin, which removes hydrazine. The experiment was carried out by John Kilmartin and Janice Fogg of Cambridge and Arthur R. Arnone of University of Iowa.

Several experimental results favor my version of the mechanism. In 1965 Eraldo Antonini, Todd M. Schuster, Maurizio Brunori and Jeffries Wyman at the University of Rome, and in 1970 R. D. Gray at Cornell University, showed that binding of oxygen and liberation of Bohr protons go hand in hand right from the start, while hemoglobin is still in the T structure. Kilmartin then showed that most of the Bohr protons come from the rupture of salt bridges. Taken together, the two results prove that salt bridges are broken on binding of oxygen by the T structure, which implies that they lower its oxygen affinity. To test whether they really do we had to make an accurate comparison of the oxygen equilibrium curves of normal hemoglobin and a hemoglobin that lacks one of the salt bridges. Kiyohiro Imai and Hideki Morimoto of the University of Osaka had just developed an ingenious method that allows an oxygen equilibrium curve to be measured precisely and fast with only .1 milliliter of hemoglobin solution. Imai came to Cambridge to build one of his new machines and with Kilmartin measured the equilibrium curves of hemoglobins that lacked specific salt bridges. They found that the absence of any of the bridges left K_R unchanged but lowered both L and K_T, in accord with my mechanism.

Paradoxically, another set of observations contradicts these findings. My colleagues Leigh Anderson and Kilmartin, together with Seiji Ogawa of Bell Laboratories, have shown that the salt bridges break only if the hemoglobin molecule is free to click to the R structure but not if that transition is stopped. This happens in certain abnormal human hemoglobins and in fish hemoglobins in acid solution, where the T structure is unusually stable. It seems the T structure must be free to bend and stretch so as to shake off its shackles; if it is laced too tightly, it fails to respond.

I have suggested that the transition from the T to the R structure is triggered mainly by the movement of the heme iron toward the porphyrin ring. What makes the iron move? There are two reasons, one steric and the other electronic. If the iron is bound to atoms on both sides of the heme, then their attraction by the iron and repulsion by the porphyrin nitrogens tend to balance the iron in the center of the ring. On the other hand, if the iron is bound only to the proximal histidine while the oxygen site is empty, then repulsion between the porphyrin nitrogens and the histidine is not balanced by repulsion between the porphyrin nitrogens and the oxygen, so that the histidine is pushed away from the porphyrin and pulls the iron with it.

The electronic story is more complex. The ferrous iron atom has six outermost

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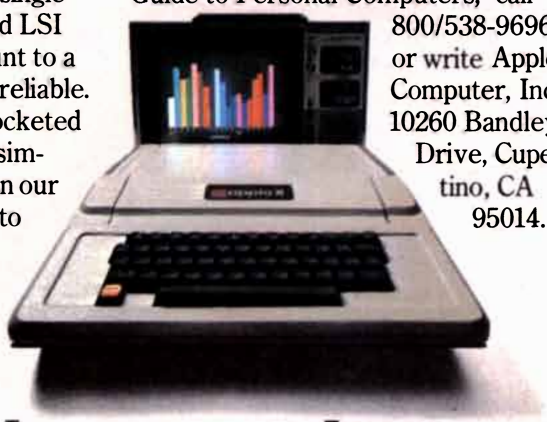

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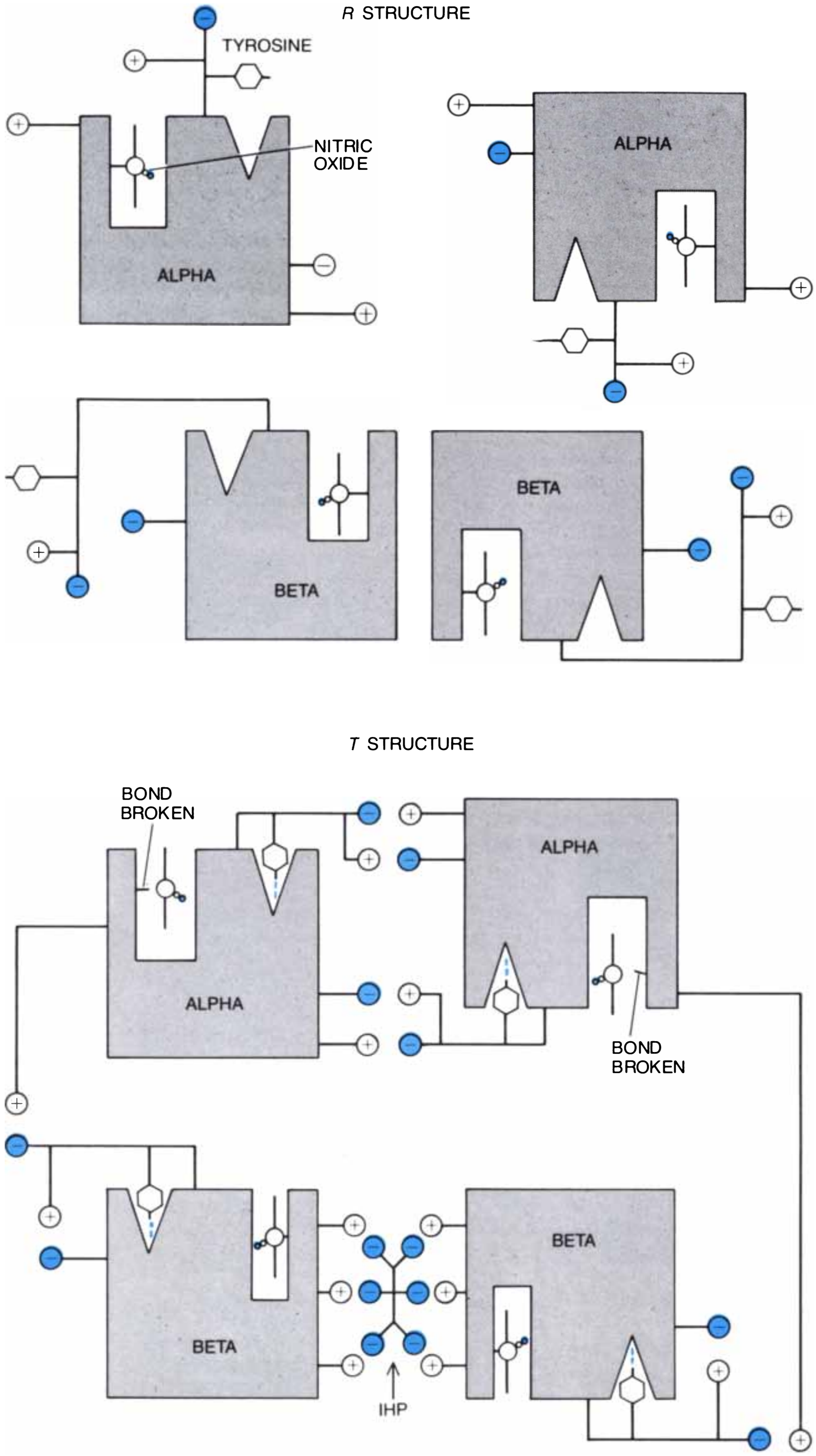


TENSION in the *T* structure was demonstrated by a forced transition from the *R* to the *T* structure. The effect was discovered when the author tested the effect of the transition on all known hemoglobin derivatives. The transition was forced by the addition of inositol hexaphosphate (IHP), which replaces DPG but forms more salt bridges with the beta chains. Oxygen was replaced by nitric oxide (NO), which binds to iron very strongly and also weakens the iron-histidine bond. At the top all the heme irons have bound NO, the molecules are in the *R* structure and there are no salt bridges between the subunits. At the bottom IHP has converted the molecule to the *T* structure and the subunits are clamped by salt bridges. The resulting tension has broken the bonds between the iron atoms and the proximal histidines in the alpha subunits, which are much farther away from the IHP binding site than those of the beta subunits, showing that proteins can transmit mechanical effects over large distances.

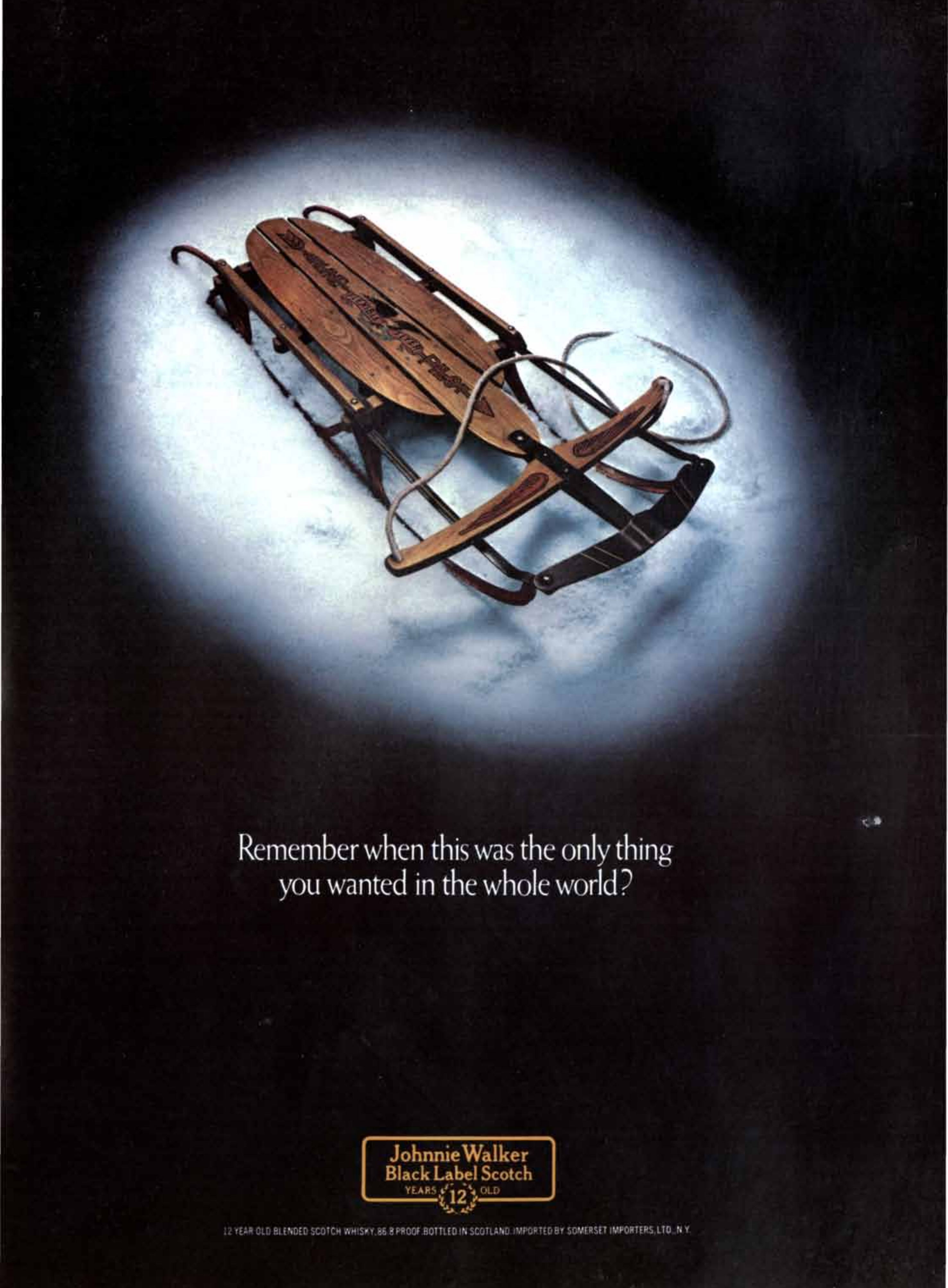
electrons. In oxyhemoglobin these form three pairs located halfway between the bonds that join the iron to its six surrounding atoms. Repulsion between the electrons of the iron and the electrons of the surrounding atoms is thereby minimized. In deoxyhemoglobin, on the other hand, four of the six electrons are unpaired and two of them lie along bond directions, where they repel the surrounding atoms of the porphyrin ring. This repulsion tends to push the iron farther out of the porphyrin plane than the repulsion between the proximal histidine and the porphyrin nitrogen atoms would do on its own.

Testing the Trigger

Suppose the iron does move in and out of the porphyrin plane every time it combines with or loses a molecule of oxygen. How could we find out if it is really this movement that triggers the allosteric transition between the two structures? I could think of no experiment that would answer the question directly, but I argued that if my proposition were true, then by the laws of action and reaction a forced transition from *R* to *T* must put the gears into reverse and pull the iron and the histidine away from the porphyrin ring. In that case the *T* structure should exercise a tension on the heme, which should be detectable by physical methods. My teacher David Keilin always told me to work with colored proteins because the spectra of the light they absorb can reveal so much. Hemoglobin is doubly blessed because one can feel its pulse both by its absorption spectrum and by the magnetic properties of its iron atoms.

Before we could exploit these properties we had to find a way of switching the structure from *R* to *T* other than the usual way of removing the oxygen. Sanford R. Simon of the State University of New York at Stony Brook and I found that this could be done with an analogue of DPG, a substance called inositol hexaphosphate (IHP), which has six phosphate groups in place of the two of DPG and therefore binds to the *T* structure more strongly.

When IHP was added to oxyhemoglobin, it caused some of the oxygen to be cast off, as was to be expected. I then replaced the oxygen with nitric oxide (NO) because this gas binds to the iron so strongly that the bond, once formed, cannot be broken. When I added IHP to nitric oxide hemoglobin, the structure switched from *R* to *T* and the spectrum changed drastically. Analysis of these and other spectral changes told us what had happened: because the strong bond to nitric oxide had held the iron atom tightly to the plane of the porphyrin, the tension exercised by the *T* structure had snapped the weaker bond between the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iron and the proximal histidine instead. Most remarkably, this had happened primarily in the alpha subunits, whose hemes are 35 angstroms away from the phosphate binding site, rather than in the beta subunits, to which the IHP was actually bound. This experiment was done by Kyoshi Nagai, Attila Szabo and me at Cambridge together with John C. Maxwell and Winslow S. Caughey of Colorado State University at Fort Collins. Robert Cassoly of the Institute of Physicochemical Biology in Paris discovered the spectral changes at the same time we did.

Our experiment proved that the tension exists but did not tell us how large it is. To measure it I decided to exploit certain hemoglobin compounds in which the iron atoms are in a state of equilibrium between a weakly and a strongly paramagnetic state. (A paramagnetic substance cannot be permanently magnetized, as metallic iron can, but is drawn into a magnetic field.) At low temperature all the iron atoms are weakly paramagnetic, and the paramagnetism falls as the temperature rises; above a certain temperature the iron atoms begin to oscillate between the two magnetic states, which causes the total paramagnetism to rise as the temperature rises. Today it is known that the bonds between the iron and its surrounding atoms are slightly longer in the strongly paramagnetic state than they are in the weakly paramagnetic one. Therefore if tension in the *T* structure stretches the bonds to the iron, it should make the proportion of iron atoms in the strongly paramagnetic state larger in the *T* structure than it is in the *R* structure and thereby raise the total paramagnetism of the solution.

After several false starts a lucky coincidence finally brought this experiment off. Robert W. Noble appeared at Cambridge from the State University of New York at Buffalo with his pockets full of carp hemoglobin. He showed me how easily the structure of any of the derivatives of this hemoglobin could be switched from *R* to *T* by adding a little acid and IHP. Together we set out for Rome, where Massimo Cerdonio and Calogero Messana had just built a highly sensitive superconducting magnetometer at the Snamprogetti Laboratory, but while changing trains at a London Underground station, I left the thermos with our precious samples on the platform and never saw it again. Luckily we had some more carp hemoglobin in our deep freeze at Cambridge, and with it I started off once more for Rome.

The most useful derivative of carp hemoglobin was a ferric form in which the place of oxygen is taken by an azide ion (N_3^-). We measured its paramagnetism in both the *R* and *T* structures between −180 and +30 degrees Celsius. The re-

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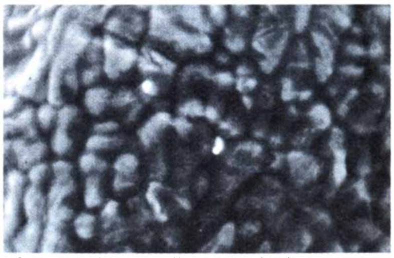

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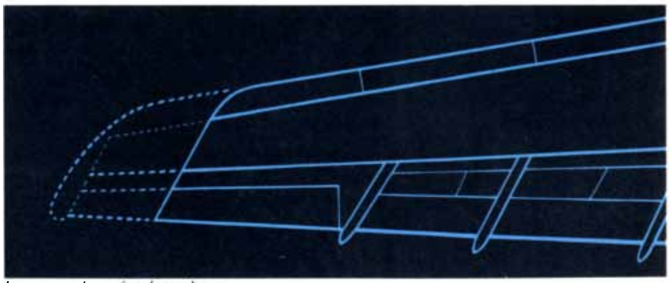

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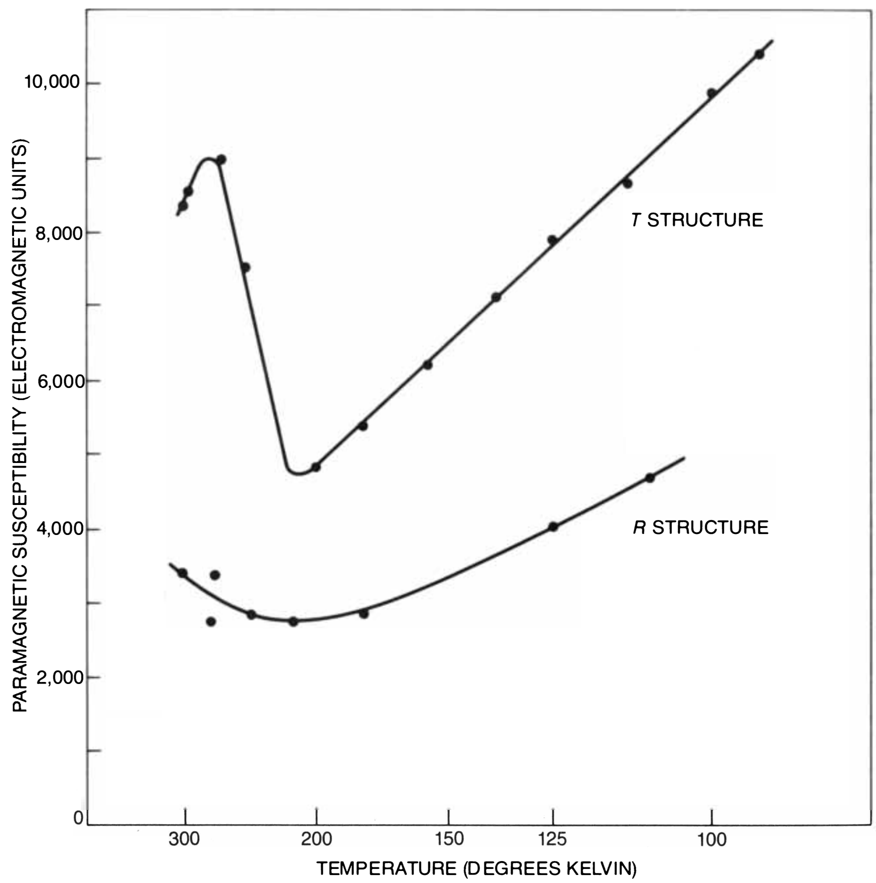
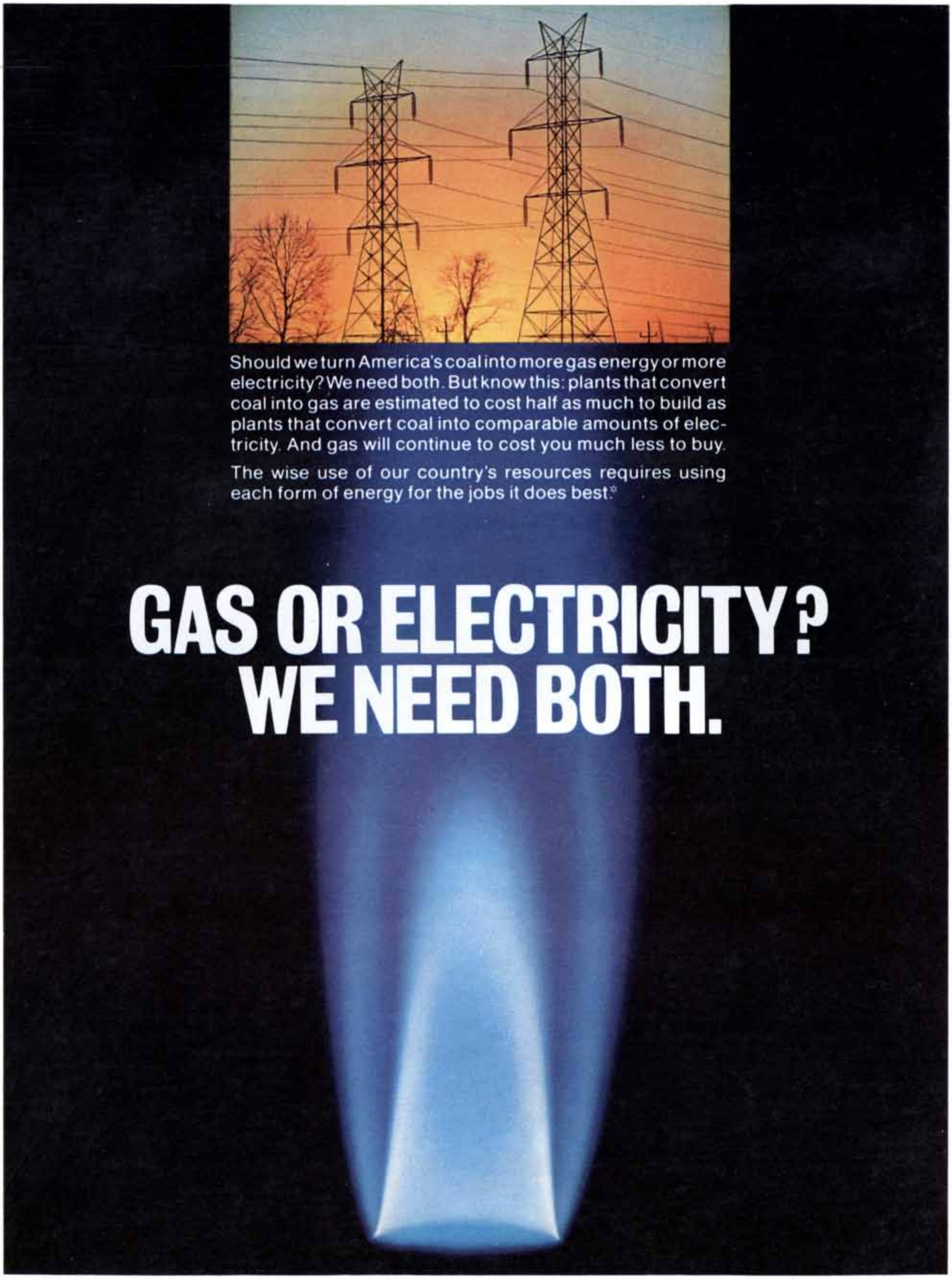
sults gave us a tremendous thrill: at all temperatures azide methemoglobin of carp was far more strongly paramagnetic in the *T* structure than in the *R* structure, which proved that the *T* structure does favor the state of the heme with the longer iron-nitrogen bonds. The tension at the heme can be gauged from the difference in energy between the two magnetic equilibriums. My colleague Fermi, with my son Robin Perutz of the University of Oxford, worked out that the difference amounts to about 1,000 calories, a third of the free energy of heme-heme interaction. We are not sure where the remaining two-thirds comes from but suspect that the *R*-to-*T* transition produces a smaller change of heme structure, and therefore also a smaller change of tension, in azide methemoglobin than uptake and loss of oxygen does.

In the meantime Arieh Warshel of the University of Southern California, Bruce W. Gelin and Martin Karplus of Harvard University, my own colleague Joyce Baldwin and Cyrus Chothia of University College London have tried to disentangle the set of atomic levers that generates the tension in the *T* structure and relieves it on transition to the *R* structure. They have demolished some of my early ideas and elaborated others.

All agree that the *T* structure exerts little or no tension on the deoxygenated heme and that the tension arises only when the iron tries to move toward the porphyrin plane on combination with oxygen, rather as the spring of a screen door is relaxed when it is closed but exerts increasing tension as it is opened. James P. Collman of Stanford University has therefore suggested that one should speak of restraint rather than tension. The restraint may be generated by a lopsided orientation of the proximal histidine with respect to the porphy-



MAGNETIC CHANGES are observed on switching carp azide methemoglobin from the *R* to the *T* structure. Paramagnetic susceptibility is plotted on the vertical axis and absolute temperature on the horizontal axis. The paramagnetism of the iron atoms is higher in the *T* structure than it is in the *R* structure at all temperatures. In the *R* structure at low temperatures all the iron atoms are in a weakly paramagnetic state and the susceptibility drops with rising temperature. At about 200 degrees Kelvin the iron atoms begin to oscillate between a strongly and a weakly paramagnetic state, so that the susceptibility rises with rising temperature. In the *T* structure at low temperature a random mixture of strongly and weakly paramagnetic iron atoms is frozen in. At about 250 degrees K. the fraction of strongly paramagnetic iron atoms begins to rise sharply, only to fall again at higher temperatures for reasons that are not clear. The free-energy equivalent of the tension in the *T* structure is calculated from the difference in height between the two curves. The magnetic susceptibility measures the force that is exerted on one gram equivalent of iron (55.8 grams) by a magnetic field of one gauss.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rin, which brings one of the histidine carbon atoms close to one of the porphyrin nitrogen atoms. Repulsion between these two atoms would restrain the histidine from moving closer to the porphyrin ring. On transition to the *R* structure a shift and rotation of the heme in relation to helix *F* straightens out the histidine, so that it and the iron atom can move toward the porphyrin without restraint.

In the beta subunits a movement of the heme with respect to helix *E*, which carries the distal valine and distal histidine, may be more important. In the *T* structure the valine blocks the oxygen combining site, but after the shift to the *R* structure the site is uncovered. We do not yet know how much this bolting and unbolting contributes to the free energy of the heme-heme interaction.

All these mechanisms are consistent with my early ideas, but my suggestion that the movement of the proximal histidine is transmitted to the salt bridges by squeezing the penultimate tyrosine out of its crevice was too simplistic. Instead the hydrogen bond that holds the tyrosine in place may be stretched, but this loosening may not be enough to break the salt bridges. They may be loosened further by small perturbations of the bonds between the subunits that have so far eluded analysis.

One of the strangest features of both the *T* and the *R* structures is the absence of any entrance to the heme pocket wide enough to allow an oxygen molecule to pass. Either the distal histidine or some other group must swing out of the way, but we do not know how this is done because our X-ray analyses portray static structures, which allow us only to guess at the dynamics of the molecule.

John J. Hopfield of Princeton University once said that hemoglobin plays the same role in biochemistry that the hydrogen atom does in physics, because it serves as a touchstone for new theories and experimental techniques. Hemoglobin is the prototype of protein molecules that change their structure in response to chemical stimuli. Scientists will therefore continue to explore its many-faceted behavior. The mechanism I have outlined here will need further refinement before it can explain all their observations, but I am pleased that its main features have stood up to experimental tests and that it accounts reasonably well for the physiological properties of hemoglobin. I have not mentioned here that it also explains the symptoms of patients who have inherited abnormal hemoglobins, because that is another story. I hope that understanding of the structure and mechanism of the hemoglobin molecule will eventually help to alleviate those symptoms and to interpret the behavior of more complex biological systems.

Animal Eyes with Mirror Optics

Some man-made mirrors now have reflecting surfaces made up of multiple thin layers instead of metal. It turns out that several kinds of animals have eyes based on the same system

by Michael F. Land

The realization that the image in the human eye is formed by a lens goes back to the late Middle Ages, as does the use of glass lenses for spectacles. Over the succeeding centuries mirrors also became important components of optical instruments such as the astronomical telescope, but no one suspected that reflective surfaces might provide the basic optical mechanism of certain animal eyes. In the past few years some remarkable examples of eyes based on mirror optics have become apparent, among them the simple eyes of scallops and the compound eyes of shrimps, crayfishes and lobsters.

None of these animals is particularly exotic, and indeed the anatomy of their eyes had been described many times. Why then was the role of mirrors in forming the visual image overlooked, in view of the wealth of anatomical and optical talent that has been devoted to the study of the eyes of invertebrate animals? The reason may be that until fairly recently mirrors of optical quality, as opposed to shiny bits of tissue, were considered a biological impossibility. The logic was simple: the surface of a mirror is polished metal, and organisms do not make metal surfaces. Since the late 1940's, however, methods of making high-quality mirrors have changed. Instead of consisting of a single layer of silver or aluminum they are made up of multilayered stacks of very thin films of alternating high and low refractive index. This turns out to be the way living organisms have made mirrors all along! Technological progress has therefore removed a major mental block to the concept of animal mirrors.

The operation of multilayer mirrors is easy to understand. The simplest examples are provided by thin films such as soap bubbles, whose reflectance results from the interference of light waves reflected from the outside and inside surfaces of the film. If two wave fronts are reflected from the two interfaces in phase, the reflectance is high, but if the wave fronts are out of phase, the crests of the waves cancel the troughs and the reflectance is reduced to zero. For the wave fronts to emerge in phase the total optical thickness of the film (the actual thickness times the refractive index) must be one-quarter of the wavelength of the illuminating light. The reason is that the waves reflected from the upper surface are phase-shifted by half a wavelength, whereas the waves reflected from the lower surface are not; moreover, the waves reflected from the inside surface pass through the film in both directions.

A single quarter-wavelength film reflects about 8 percent of the incident light, but mirrors reflecting most or all of the incident light can be obtained by stacking several quarter-wavelength films with quarter-wavelength spaces between them. This arrangement ensures that light of the appropriate wavelength is reflected in phase from all the interfaces in the stack, yielding a reflectance higher than that of polished metal when the number of films exceeds about eight.

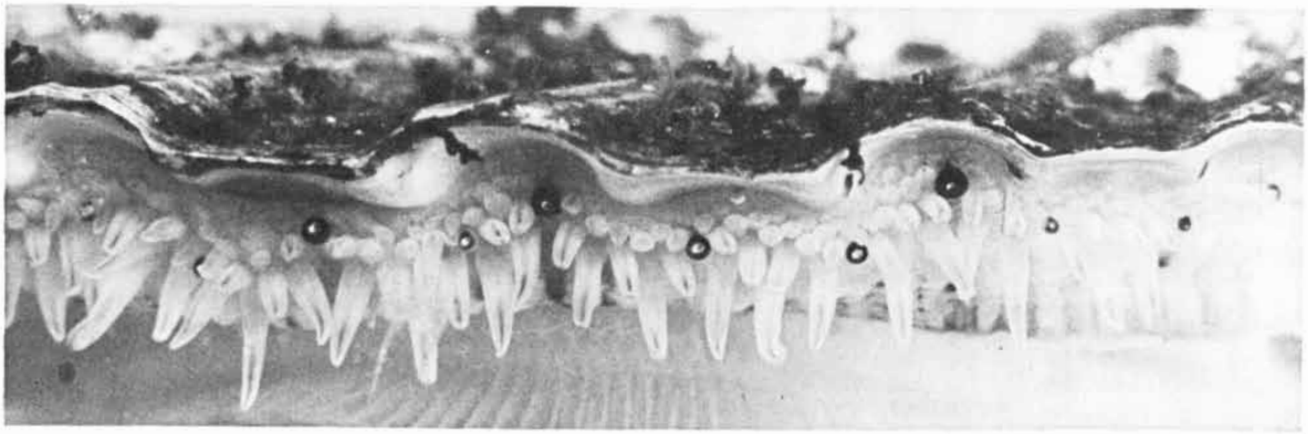
Multilayer mirrors can be made from a variety of materials, provided there is a large difference in the refractive index between the adjacent layers in the stack. Commercial multilayer mirrors are typically made of alternating coats of vapor-deposited magnesium fluoride (refractive index 1.36) and zinc sulfide (2.40). Such a large difference in refractive index is not possible with biological materials, but a common biological combination, found both in the scales of fishes and in the eye of the scallop, is cytoplasm (1.34) and crystals of guanine (1.83). Insect mirrors are often constructed from alternating layers of air (1.00) and the polysaccharide material chitin (1.56).

Multilayer mirrors have a number of interesting properties not possessed by metallic mirrors. Because one wavelength of light is four times the optical thickness of the films in the stack, the reflected light is colored; a particularly striking biological example is provided by the iridescent blue wing scales of *Morpho* butterflies. "White" mirrors can also be made with multilayers, either in nature or in the laboratory, by varying the thickness of the films through the depth of the stack or by piling on top of one another three stacks reflecting respectively blue, green and red light. Some fishes are able to achieve a white appearance in this way even though their individual multilayered scales are highly colored.

The color of a multilayer mirror changes toward the shorter wavelengths (blue and purple) as the angle of the incident light is increased. This phenomenon results from the changing length of the path of the light through the layers of the stack. Moreover, multilayer mirrors are unlike filters in that they absorb no light; the wavelengths that are not reflected are transmitted as the complementary color. Such mirrors are employed in color-television cameras to separate out the three primary colors without loss of light.

The common scallop *Pecten* has about 60 blue or dark brown eyes (depending on the species), each about a millimeter in diameter and evenly spaced along the mantle of the mollusk, which is exposed to light by a slight gaping of the two valves, or shells. The eyes serve to detect movement: if a large scallop is approached by a potential predator in a tank or on the sea bed, it will bury itself in the sand; the smaller species will swim away by clapping their valves together.

In cross section the eye of the scallop does not look very different from that of vertebrate animals, which is probably why its peculiar optics were overlooked for so long. There is a large transparent lens in front of a two-layered retina with about 5,000 photoreceptor cells in each layer. Behind the retina is a hemispherical reflector and then a layer of brown pigment. One feature of the anatomy of the scallop eye suggests that its optics are unconventional. In the eyes of vertebrates there is always a space behind the lens that allows the image to come to a focus on the retina. Even in the eye of fishes, which has a lens with an extremely short focal length in relation to its diameter, there is a space



EYES OF THE SCALLOP ***Pecten*** **are the small globules in this view of the mollusk's mantle, which is exposed by a gaping of the two valves, or shells. One of the valves is at the top. In each of the eyes, which are about a millimeter in diameter, is a shiny hemispherical mirror. The eyes detect the movement of a shadow or a dark edge across the animal's field of view. In this way the approach of a predator is detected. The eyes may also play a role in phototaxis: migration of the scallop toward areas of darkness or light in its environment.**

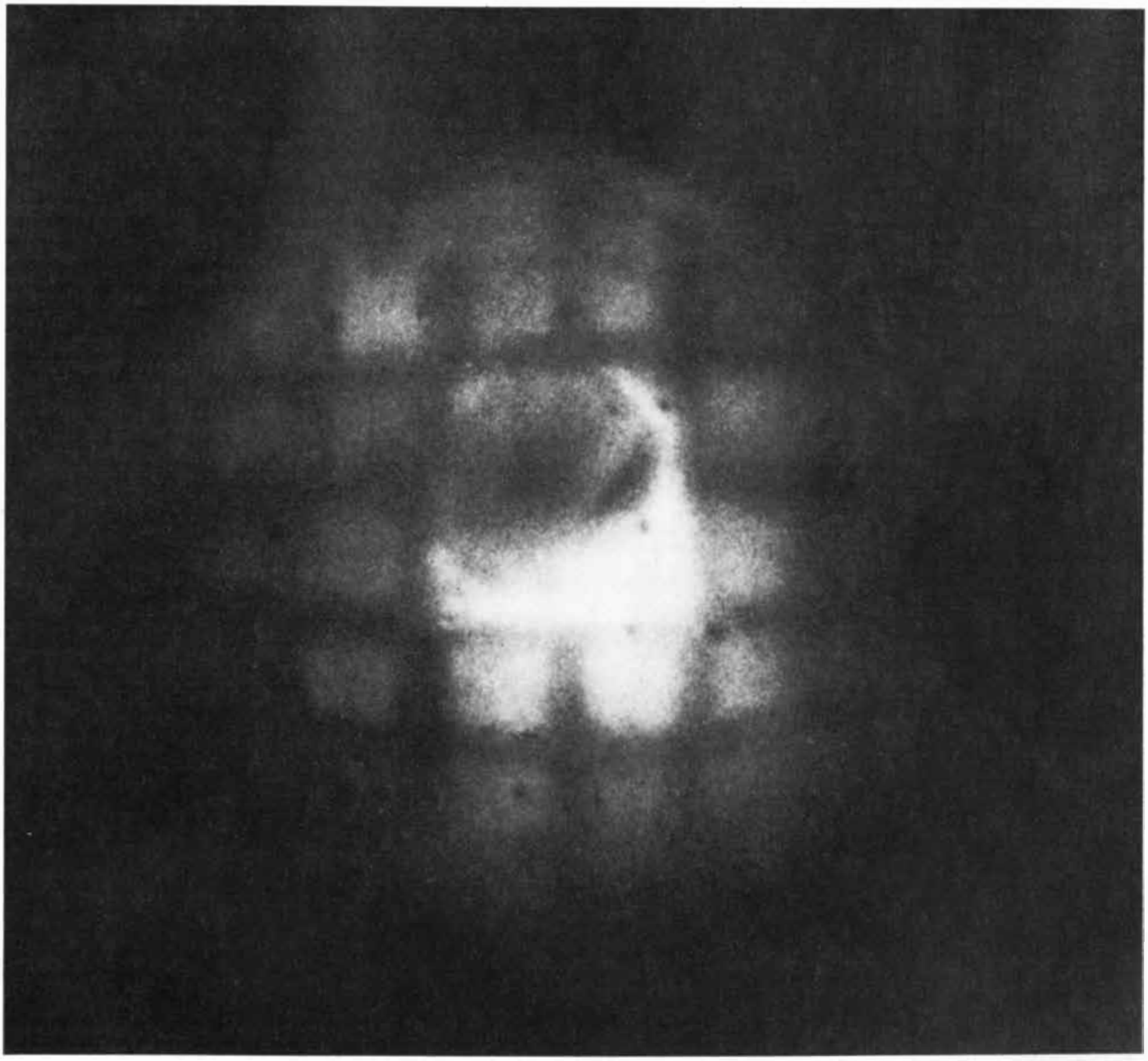


IMAGE WITHIN A SCALLOP EYE is of a square grid between the eye and the objective of the dissecting microscope with which the picture was made. Grid is focused by the mirror at the back of the eye. The eye also has a lens that corrects spherical aberration of mirror.

about two lens radii wide between the lens and the retina. In the scallop eye the back of the lens is actually touching the retina, so that the focused image would be beyond the back of the eye. Clearly either the scallop eye yields no useful image or the image is formed in some other way.

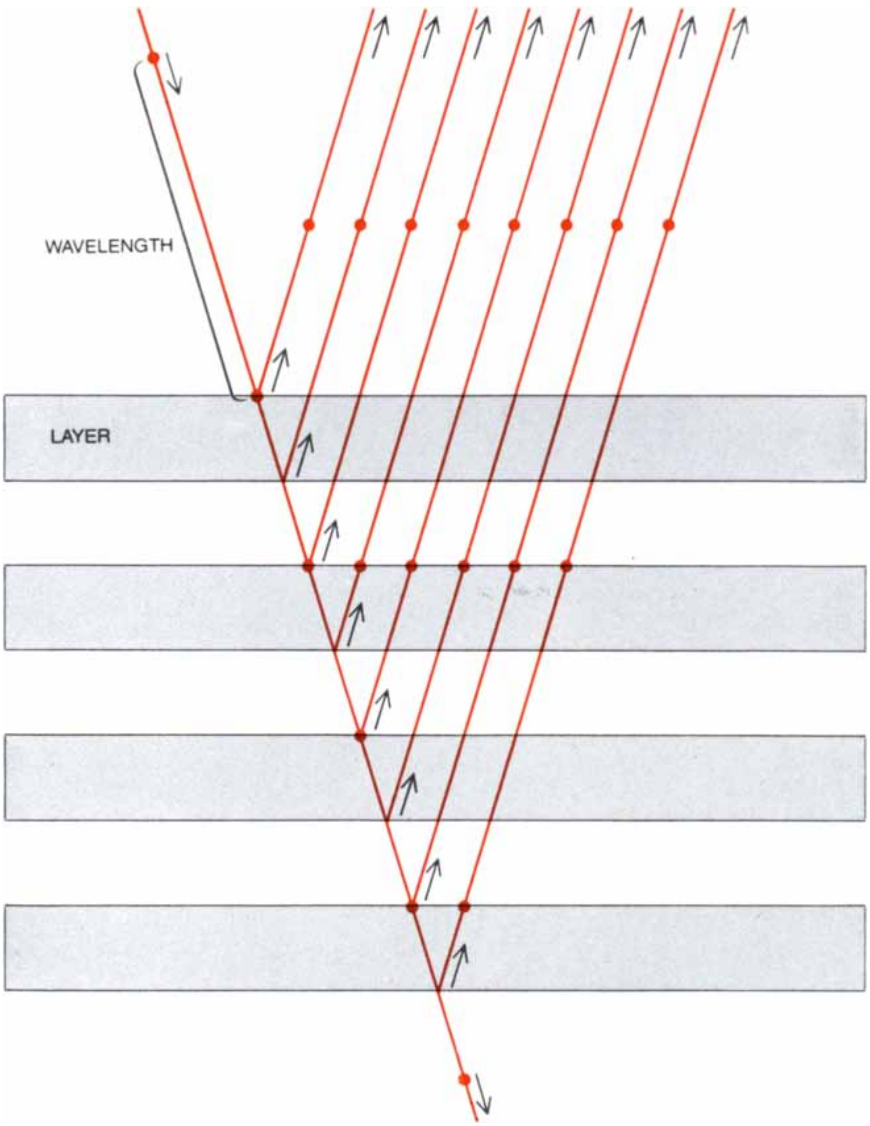
If you look directly into the eye of a fresh scallop through a dissecting microscope, you will see a rather startling sight: a small, bright and somewhat distorted upside-down image of yourself peering through the microscope. The image seems to lie somewhere within the scallop eye, between the mirror and the lens. This observation is by no means a new one; the American zoologist William Patten made it nearly a century ago, and he went so far as to paint lines on his microscope objective in order to examine the image more clearly. Patten came to the mistaken conclusion that it was the lens of the scallop eye that formed the image, and that the mirror merely reflected it back out again, much as a cat's eye reflects light. This cannot be the case, for the same reason that one cannot see an image in the eye of a cat: if one views an image through the same lens that formed it, the position of the image will necessarily be outside the eye. Yet both Patten and I observed that the image is located in the interior of the scallop eye.

The solution to the puzzle became obvious when I realized that the lens does not do very much. The mirror is almost a perfect hemisphere, and like any other concave mirror it forms an inverted image of distant objects, situated halfway between the center of curvature of the mirror and the mirror itself. The reflector in the scallop eye has a radius of curvature of 410 micrometers, and so the focal length of the mirror should be 205 micrometers. Measurements I made when I was a graduate student at University College London showed that the position of the inverted image indeed corresponds to this predicted value, although the focal length of the mirror is 50 micrometers shorter than the "pure reflector" concept would suggest. The discrepancy can be accounted for by the refracting power of the lens of the scallop eye. Although the lens has a focal length of 1.5 millimeters and would by itself form an image far beyond the back of the retina, it does have the effect of making the entering light rays converge slightly before they reach the mirror, thereby somewhat shortening the mirror-to-image distance.

The shape of the front surface of the lens is rather odd: it is convex at the center and concave at the edges, so that its function appears to be not so much to focus light as to correct for an optical defect of the mirror. A hemispherical mirror is subject to spherical aberration because the rays reflected from the inner part of the mirror converge to a focus that is farther out than the focus of rays from the outer parts of the mirror. In astronomical telescopes of the Schmidt type the spherical aberration of a hemispherical mirror is corrected by a thin, weak lens called a corrector plate at the center of curvature of the mirror. Remarkably, the lens of the scallop eye appears to perform much the same function as the corrector plate of the Schmidt telescope.

The image formed by the reflector of the scallop eye comes into focus on the part of the retina just behind the rear surface of the lens. The obvious question is whether or not there are cells in this part of the retina that are specialized to receive light. As a matter of fact the retina has two sets of light-sensitive cells: a distal cell layer directly behind the rear surface of the lens and a proximal cell layer directly in front of the mirror. The image formed by the mirror comes into focus on the distal photoreceptors, whereas the proximal photoreceptors receive an unfocused image.

As early as 1938 H. K. Hartline of the Cornell University Medical College made electrophysiological recordings from the distal photoreceptors of the scallop and found that the photoreceptors fire only in response to the removal of illumination (an "off" response). These cells would therefore be activated by the image of the leading edge of a dark object crossing the field of view. If the object is lighter than the back-



MULTIPLE LAYERS of alternating high and low refractive-index materials yield a mirror surface with a high degree of reflectance. This approach is currently utilized to make high-quality mirrors for telescopes and other instruments; it is also the way living organisms make mirrors. Each layer in the stack must have a thickness that is one-quarter the wavelength of the illuminating light, so that the light waves are reflected in phase from all the interfaces in the stack. Because only one wavelength of light is reflected in phase, the mirror is brightly colored. Color shifts toward blue end of the spectrum as the angle of incidence of the illuminating light increases and as the path length of the rays through the layers of the stack decreases.

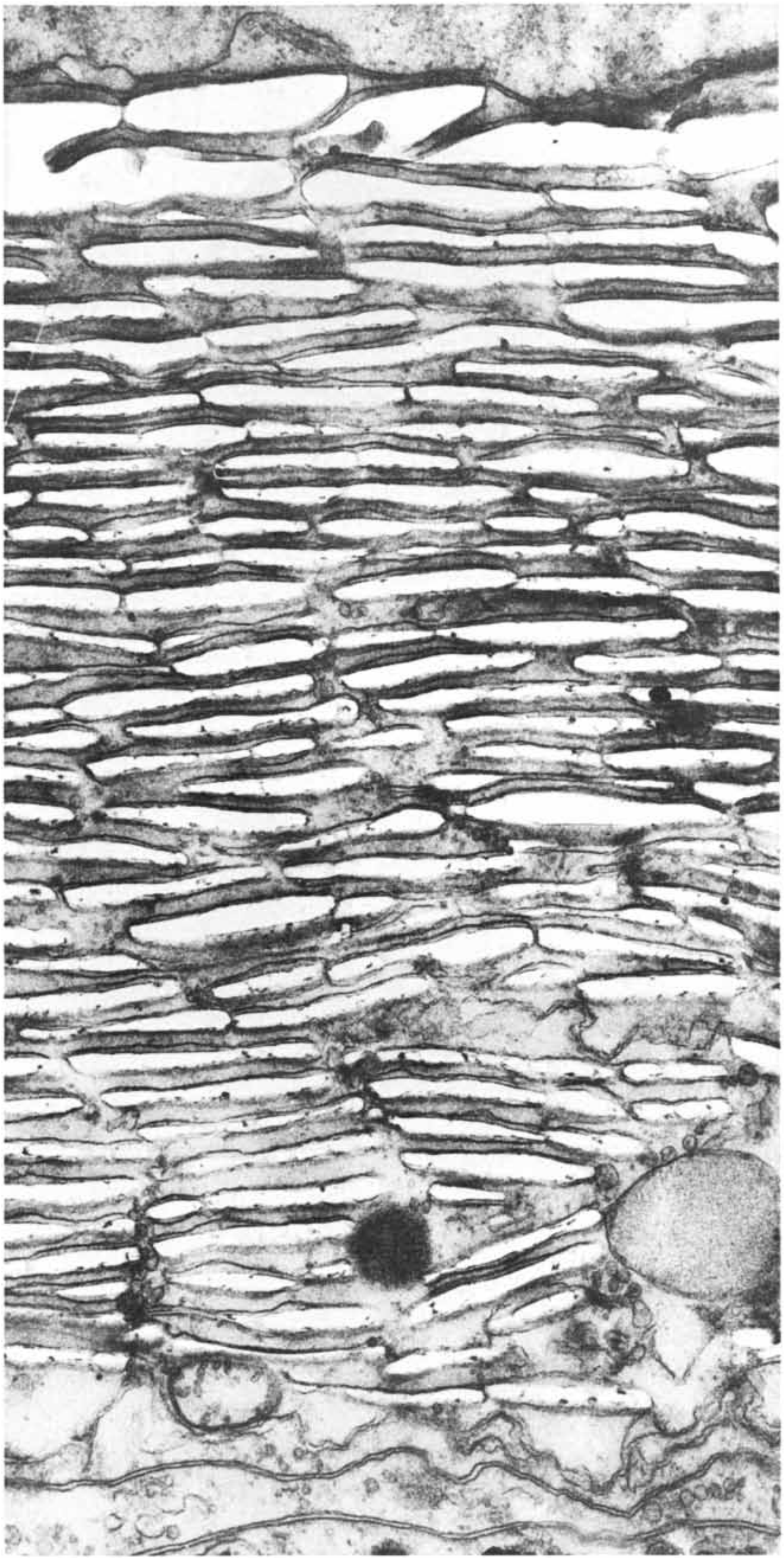
ground, the trailing edge would be the stimulus. Light objects are generally less effective stimuli, however, because the distal photoreceptors require several seconds of steady illumination before they can generate an "off" response.

I have further explored the function of the scallop retina. In one experiment the electrophysiological activity of the distal photoreceptors was monitored while a pattern of black and white stripes, each 16 degrees wide, was moved in front of one scallop eye. When the pattern was moved through one stripe width (so that the areas that had been light were now dark and vice versa) without changing the level of illumination, there was a massive and sustained firing of the distal photoreceptors. When the pattern was moved through two stripe widths (so that any point on the retina was briefly darkened or lightened before the original pattern was restored), there was only a brief firing of the distal photoreceptors. These results suggest that the avoidance response of the scallop is triggered not by the detection of motion per se but rather by the sequential dimming of adjacent photoreceptor cells in the distal cell layer of the retina.

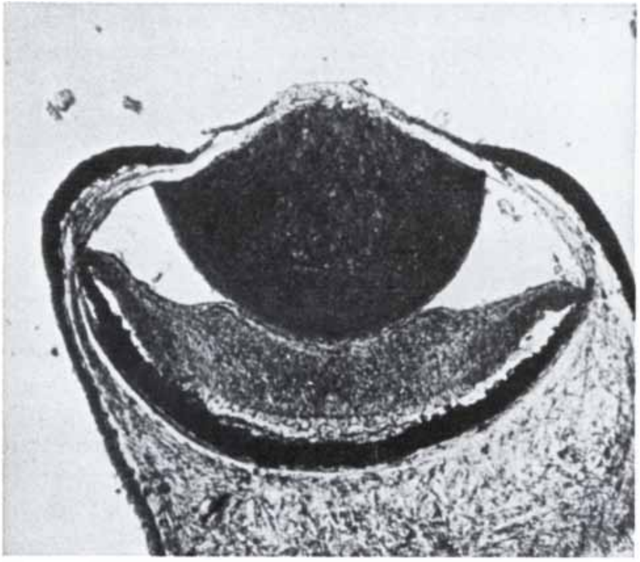
What is the role of the photoreceptors in the proximal layer, which receive an out-of-focus image from the mirror? Hartline also made recordings from these cells and found that they fire in response to illumination (an "on" response), but they do so only when the object entering the scene is so large and luminous that it causes a gross brightening of several percent over the entire field of view. In spite of the low resolution of these cells in detecting movement, they may play another important role. Some of the smaller species of scallop are known to swim toward lighter or darker regions of their surroundings, and it is likely that this phototaxic behavior is mediated by the proximal photoreceptors, whose response is generally sustained, rather than by the distal photoreceptors, whose reponse is always transient. Therefore the proximal photoreceptors may provide relatively long-term information about environmental light levels.

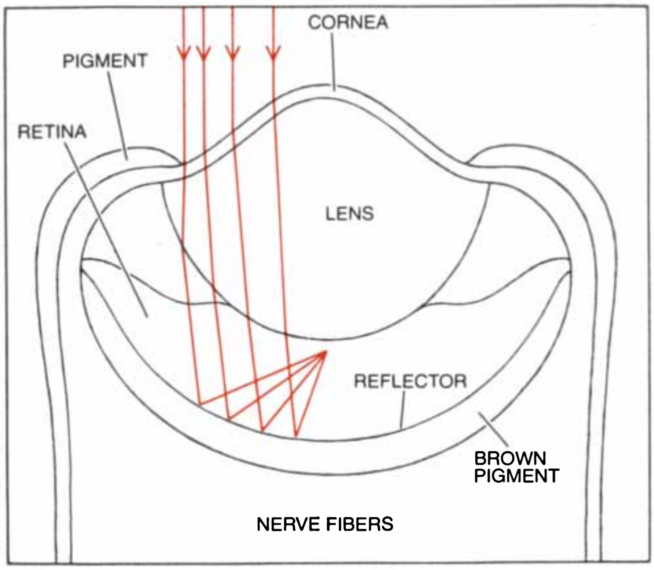
Why there are so many proximal photoreceptors in the scallop eye remains a mystery. With 60 eyes and 5,000 proximal photoreceptors per eye, the mollusk has some 300,000 cells doing a job that could be done adequately by perhaps a dozen. The distal photoreceptors are not utilized much more economically: each eye has a field of view of about 100 degrees, and it does not take 60 such fields to cover 360 degrees!

A search of the animal kingdom for other eyes that work on the same optical principles as those of *Pecten* yielded surprisingly few. A number of cockles and a few copepod crustaceans have eyes in-

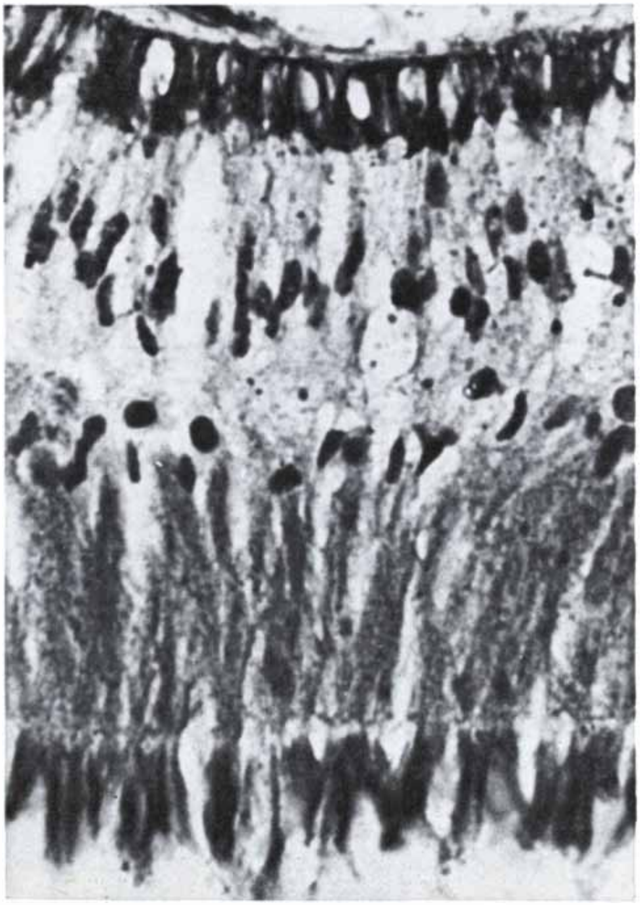


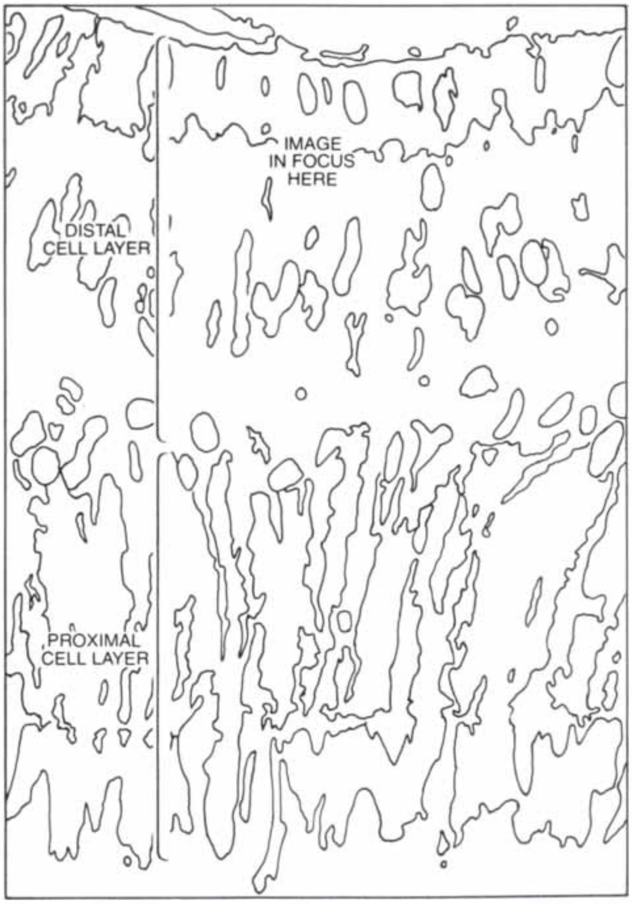
MIRROR OF THE SCALLOP EYE consists of alternating layers of cytoplasm (refractive index 1.34) and guanine crystals (1.83), as is revealed in this electron micrograph of a cross section through the mirror. (The flattened holes were previously occupied by the guanine crystals, which were removed in the fixation process.) The reflector is six micrometers (thousandths of a millimeter) thick. Micrograph was made by Vernon Barber of University College London.





CROSS SECTION THROUGH THE SCALLOP EYE suggests that its optics are unusual. Unlike the lens eyes of vertebrate animals, which have a clear zone between the lens and the retina across which light rays are focused, the lens of the scallop eye is in contact with a crescent-shaped retina. Behind the retina is the extremely thin mirror (not apparent at this magnification) and then a thick layer of dark pigment. The diagram at the right represents the paths of light rays within the eye. The rays, which are only weakly refracted by the lens, pass through the retina to the hemispherical reflector, which focuses them back to the distal photoreceptor cells in the upper layer of the retina. Because the light must pass through the retina once before it is detected, the scallop eye does not have good contrast acuity.





LAYERS IN THE RETINA OF THE SCALLOP EYE, containing the cells that detect light, are apparent in this cross section. In the distal cell layer located just behind the lens some 5,000 photoreceptor cells receive a focused image from the reflector. These cells respond to a dark edge passing over the field of view; movement is detected by the successive dimming at adjacent photoreceptors. The proximal cell layer in the lower part of the retina receives an unfocused image from the reflector. These cells respond selectively to a gross brightening of several percent over entire field of view. They appear to be involved in phototaxic behavior rather than in discrimination.

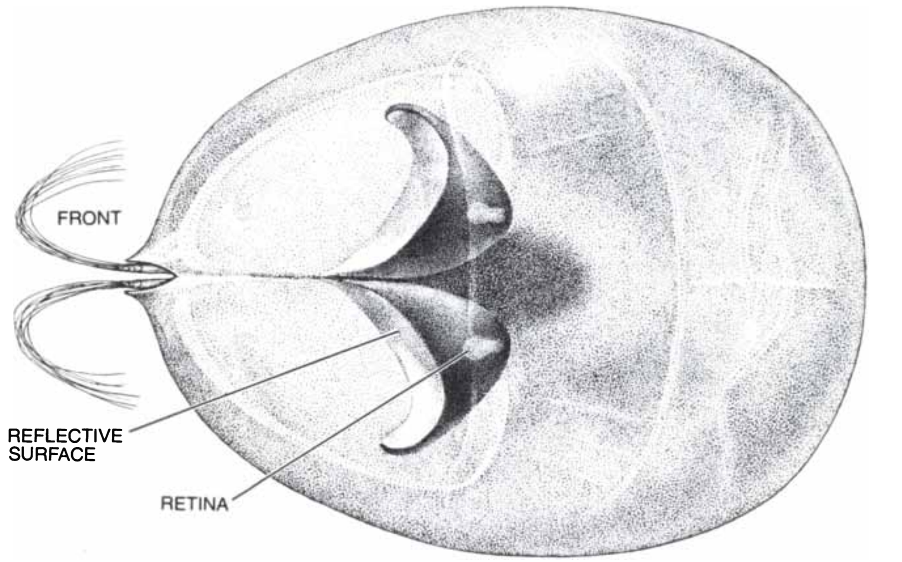
corporating reflectors, but the eyes are so tiny that it is not possible or even meaningful to try to determine whether the mirror actually forms the image or merely doubles the light path.

There is one invertebrate, however, with large reflecting eyes: the deep-sea crustacean *Gigantocypris,* which, at one centimeter in length, is truly gigantic on the scale of its fellow plankton. Sir Alister Hardy of the University of Oxford described the animal in 1956, remarking that "the paired eyes have huge metallic-looking reflectors behind them, making them appear like the headlamps of a large car; they look out through glass-like windows in the otherwise orange carapace, and no doubt these concave mirrors behind serve instead of a lens in front." I believe this was the first serious suggestion of mirror optics to appear in the biological literature. Earlier investigators had argued that the rounded carapace over the eyes acted as a lens, but since the carapace is thin and parallel-sided and has water on both faces, that cannot possibly be the case. If there is an optical system, it must be as Hardy suggested.

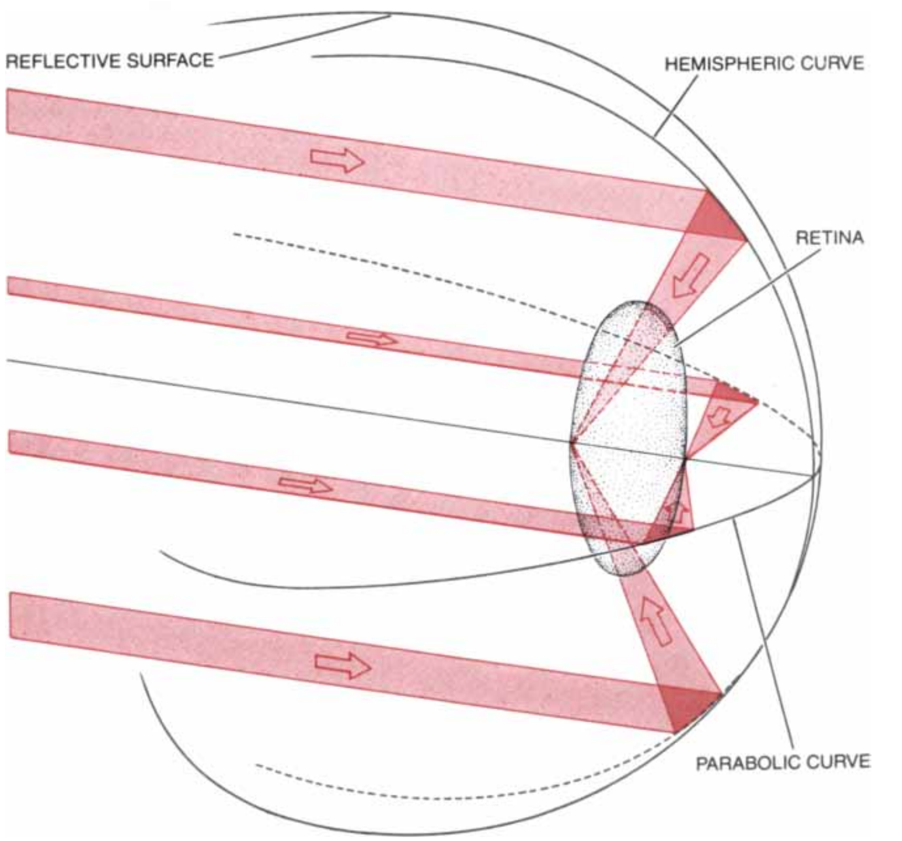
Recently in my laboratory at the University of Sussex I have had an opportunity to study living and preserved specimens of *Gigantocypris,* thanks to the generosity of the Institute of Oceanographic Sciences at Wormley, and I can now add an interesting twist to Hardy's speculations. When these eyes are viewed from above, they are distinctly parabolic in shape, with the focal point of the parabola lying at a very short distance from the front of the mirror (about 350 micrometers). Seen from the side, however, the configuration of the mirror is hemispheric, like that of *Pecten,* and hence has a much longer focal length (about 670 micrometers).

What this peculiar shape may mean can be deduced by imagining a horizontal slit of light directed at the eye. This slit is then slowly rotated until it is oriented vertically. As it rotates, the image of the slit will move out from the focus of the parabolic surface of the mirror to the focus of the hemispheric surface. A further 90-degree rotation will cause the image to move back again along the same line. This unusual geometry means that a parallel beam of light (which obviously includes all possible slits) will be brought into focus along a line perpendicular to the mirror surface and extending between the two focal points.

What is the purpose of this strange astigmatic image? The structure of the *Gigantocypris* retina provides the answer. It is a sausage-shaped organ that occupies a relatively small region in the center of each eye just in front of the mirror. The photoreceptor cells are enormous (about 700 micrometers long and 25 micrometers in diameter) and have their long axes oriented at right



DEEP-SEA CRUSTACEAN ***Gigantocypris*** **has large reflecting eyes that enable it to concentrate the extremely faint light available at a depth of 1,000 meters in the ocean (primarily from the light organs of luminescent crustaceans and fishes). The animal is about a centimeter long, which is large on the scale of its fellow plankton, and its head makes up about half of its body. The two reflecting eyes are covered by transparent windows in the orange carapace that completely encloses the animal. Sir Alister Hardy of the University of Oxford likened its eyes to the "headlamps of a large car." Hardy was the first to speculate the mirrors serve to focus light.**

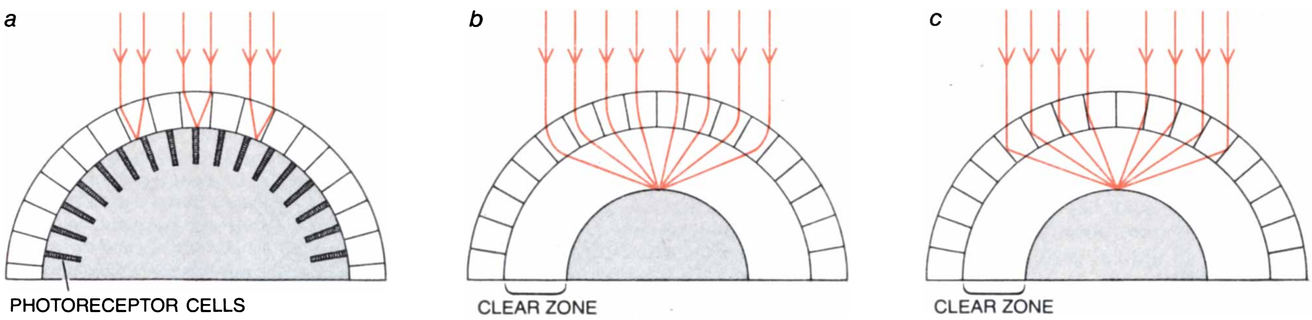


OPTICS OF THE REFLECTING EYE **of** ***Gigantocypris*** **are quite complex. In the horizontal dimension the reflector in the back of the eye is parabolic, with the focal point of the parabola lying at a short distance in front of the mirror. In the vertical dimension, however, the reflector is hemispherical and has a focal point farther out, so that the mirror as a whole focuses light along a line between the focus of the parabolic reflector and that of the hemispherical reflector. This line of focus coincides with the large photoreceptor cells in the sausage-shaped retina, which is directly in front of the mirror. Although the acuity of this reflecting eye is low, it forms an image that is 17 times brighter than the image formed by the lens eye of fishes.**

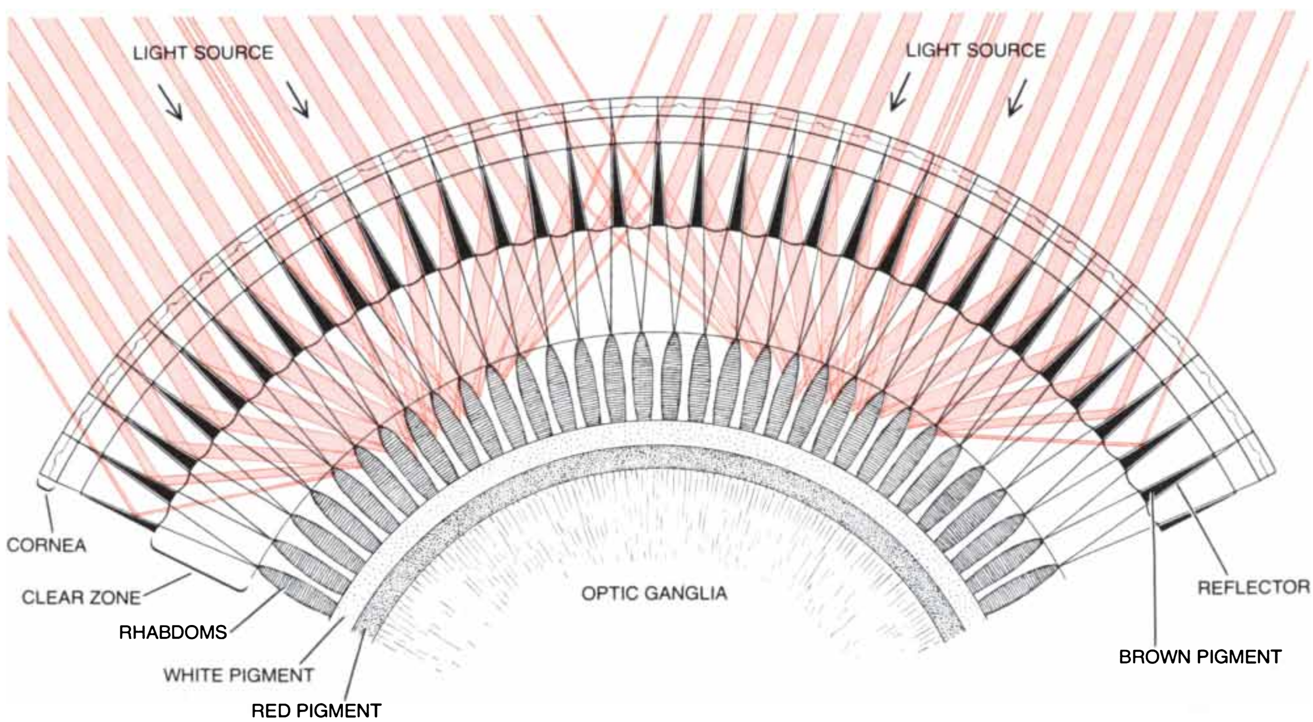
angles to the mirror surface, so that they lie approximately along the focal line formed by the mirror. It is fairly certain that the image quality of the eye is poor, but the combination of the massive aperture (*f* number about .3) and the long photoreceptors ensures that the eye captures a very large proportion of the available light, and at a depth of 1,000 meters in the ocean there is little light indeed. The *f* number of the lens in the eye of a fish is 1.25, so that the advantage of this particular mirror eye would seem to be a gain in image brightness over that of a typical lens eye by a factor of about 17.

The rarity of simple mirror eyes, whether they are of the *Pecten* or the *Gigantocypris* type, suggests that there is something unsatisfactory about them that more than offsets the advantage they provide in terms of light-gathering power. The most likely explanation is that they are poor at resolving low-contrast patterns. In the *Pecten* eye light passes through the distal receptor layer once, unfocused, before it returns from the mirror as a focused image. The effect of this arrangement is to halve the image contrast compared with that of a lens eye, so that the world is seen as if through a fog.

Crustaceans of the suborder Macrura, such as shrimps, crayfishes and lobsters, also have mirror eyes, but they are many-faceted compound eyes and their optical principle is quite different from that of the simple mirror eyes of *Pecten* and *Gigantocypris*. The history of the discovery of the compound mirror eye is perhaps as interesting as the optical mechanism itself. In 1891 Sigmund Exner of the University of Vienna demonstrated that an erect image could be photographed in the eye of nocturnal insects such as the firefly after the internal contents of the eye had been removed. He also showed that the image is formed by



THREE TYPES OF COMPOUND EYE are observed in diurnal insects, nocturnal insects and crustaceans of the suborder Macrura (lobsters, shrimps and crayfishes). The eyes of diurnal insects (*a*) are made up of a hexagonal array of lenslets, each of which has its own set of photoreceptor cells. The eyes of nocturnal insects (*b*) are also made up of a hexagonal array of lenslets, but (because each lenslet has a radial gradient of refractive index) they bend light continuously so as to focus the multiple rays entering the array at a single spot on the retina, thereby enhancing the brightness of the image under nighttime conditions. Unlike the eyes of diurnal insects, the superposition eyes of nocturnal insects have a clear zone between the lens array and the retina across which the light rays are focused. The eyes of the macruran crustaceans (*c*) consist of a square array of mirror-lined plugs, which act to superpose light rays on a single spot on the retina. Because these eyes superpose light and also have a clear zone, anatomists postulated incorrectly that they shared the optical mechanism of nocturnal-insect eyes. The fact that in such crustaceans the image is formed by an array of mirrors was not realized until 1975.



SUPERPOSITION OF RAYS in the eye of the macruran crustaceans is diagrammed, showing the effect of illumination with beams of light from two directions. In each case the rays are focused at a single spot on the retina, where they are detected by photoreceptor cells.

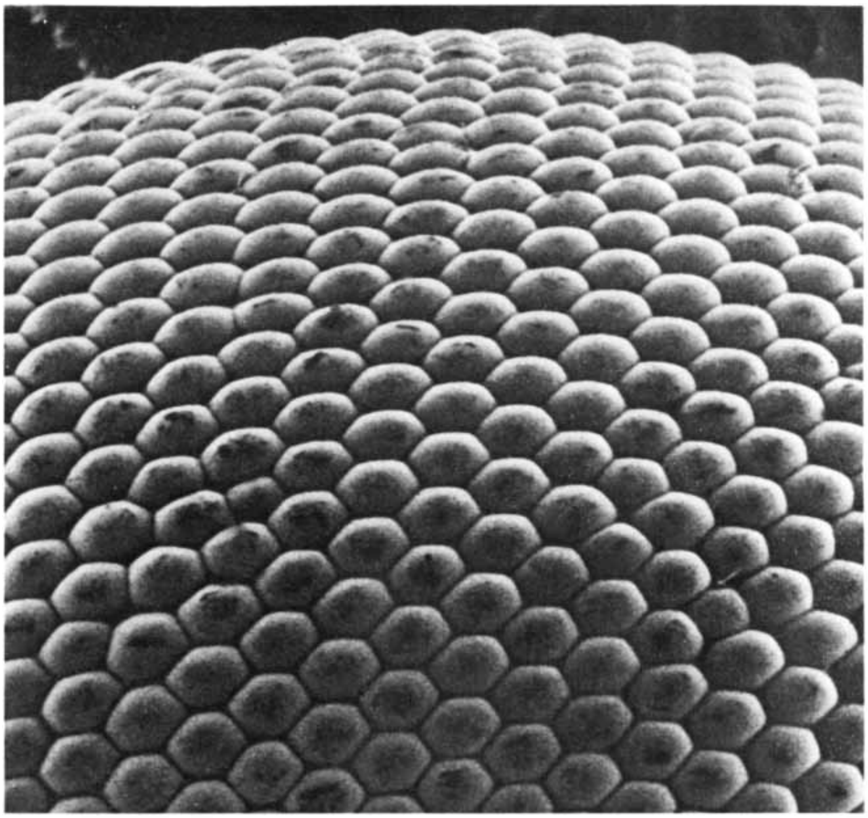
superposition, that is, the focusing of the light rays entering the many facets of the eye at a single spot on the retina. This design greatly intensifies the image under low-light conditions, a feature of obvious adaptive significance to nocturnal insects. The compound eyes of diurnal insects, on the other hand, are made up of a hexagonal array of lens elements, each of which has its own set of photoreceptor cells.

The optical properties required of the tiny lenslets in the superposition eye are not those of simple lenses. The light rays must be bent fully across the axis of the lens, meaning that each optical element must behave like a two-lens telescope. Exner proposed that the cylindrical lenslets have a sophisticated internal structure, with the refractive index high along the axis of the cylinder but decreasing in a defined way toward the periphery. Because of this radial gradient of refractive index the lenslets are able to bend light continuously, giving them the required telescopelike properties and making it possible for all the elements in the superposition eye to have a common focus.

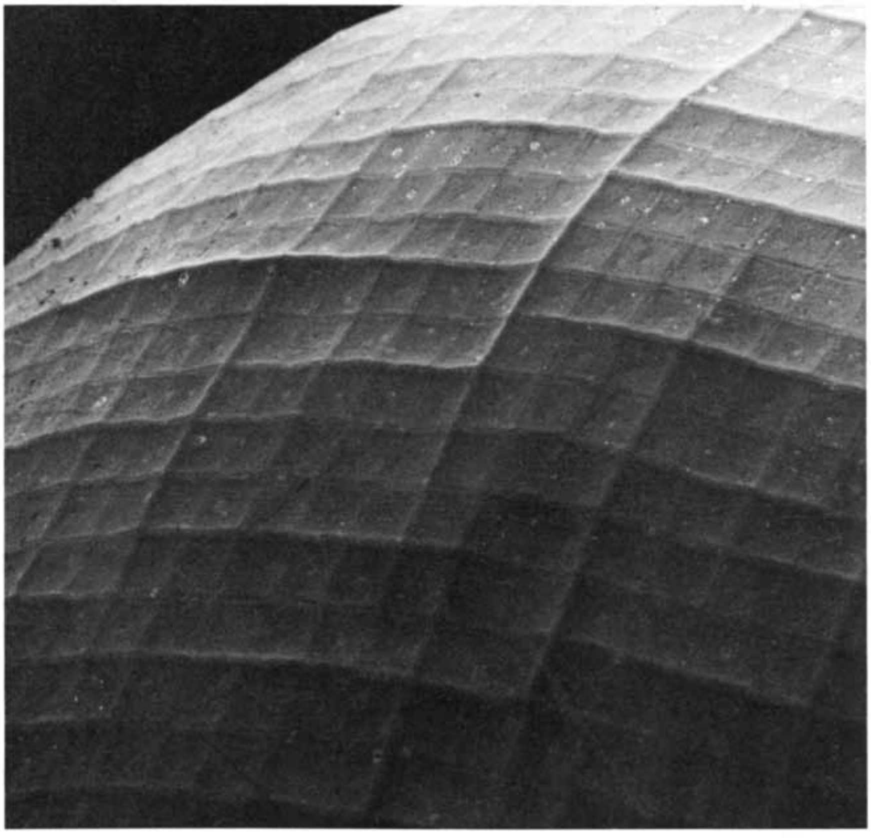
A characteristic of the superposition eyes of nocturnal insects is that they have a transparent space between the optical array and the retina that is essential if the rays from the many lenslets are to be brought together. (Most diurnal insects have no such clear zone, since each lenslet has its own private set of photoreceptors.) The fact that the eyes of both nocturnal insects and the macruran crustaceans have clear zones led Exner to postulate that they share the same optical mechanism: superposition lens cylinders.

After 70 years as the textbook account of image formation in the arthropod eye Exner's ideas were challenged in 1962 by the Dutch biophysicist Jan W. Kuiper, partly on the ground that the optical elements in the eyes of the macruran crustaceans simply do not have refractive indexes high enough or inhomogeneous enough to provide lens-cylinder optics. Kuiper's observations were confirmed in 1975 by P. Carricaburu of the National Museum of Natural History in Paris, who found a low and uniform refractive index in the optical elements of the crayfish eye and concluded that it cannot give rise to superposition images.

A paradox therefore arose: the eyes of the macruran crustaceans resemble the classical superposition eyes of nocturnal insects, yet the crustacean eyes lack the adequate optics for superposition to be accomplished. The solution to the dilemma was that the superposition is achieved not by cylindrical lenses but by arrays of mirrors! This conclusion was reached independently by Klaus Vogt of the University of Stuttgart and by me. I was not aware of Vogt's 1975 paper



HEXAGONAL ARRAY of lenslets in the refracting compound eye of the diamondback moth (family Plutellidae) is clearly visible in a scanning electron micrograph. This arrangement of lenslets is geometrically the most economical one and is shared by the eyes of diurnal insects.



SQUARE ARRAY of mirrored plugs in the reflecting compound eye of the lobster *Palinurus vulgaris* is visible in this micrograph. Mirrors of the square plugs act as corner reflectors, which have the property of behaving like a single mirror always at right angles to the incident ray.

when I first observed mirrors in the eye of the deep-sea shrimp *Oplophorus*, and I believed then (in 1976) that I was the first to do so. It turned out that in effect I was seconding Vogt's proposal.

In the reflecting compound eye the mirror surfaces are in front of the photoreceptors rather than behind them, and the image is erect rather than inverted. Moreover, instead of consisting of a single mirror the surface of the eye is divided into a square matrix of small rectangular plugs with reflecting sides, giving rise to an array of mirrored facets. The geometry of the array has the property of focusing light onto the surface of a sphere whose radius is about half that of the eye itself.

Again the mystery is why the mirrors were not noticed before. One factor is certainly the high regard in which Exner's ideas had been held for a long time, but it is also true that the reflecting surfaces in the compound eye are not at all obvious. The mirrors are very thin (less than a micrometer thick) and are easily disrupted by fixation procedures, so that they are impossible to find in conventionally prepared biological material. Even in fresh eyes they are not apparent because the outer face of each mirror is lined with dark pigment; the green reflecting surfaces can be seen only by looking through a slice of the eye from the inside outward.

Once the mirrors were spotted, however, it was an easy task to work out the ray paths and demonstrate that the formation of a superposition image was possible. Indeed, one of the attractive features of the mirror array is that it is obvious why it works. Exner's lens cylinders, which do essentially the same thing, are quite difficult to explain.

There is one feature of all eyes of the reflecting compound type that immediately and reliably distinguishes them from those of the refracting compound type: the reflecting eyes have square facets whereas the refracting eyes have hexagonal facets. Hexagons are the most economical way of packing many units together, so that squares are an oddity. Could a mirror system be based on hexagons? Vogt has recently explained why the square array is important. The ideal way of focusing all the light from a given direction at a single point would be with a series of "saucer rim" mirrors, which can be thought of as slices through a series of cones whose apexes are all at the center of curvature of the eye. These mirrors will automatically have the property that the incident ray and the reflected ray to the focus lie in the same plane. The problem is that such a set of mirrors would focus only light parallel to the axis of the array; light from other directions would be reflected away. Therefore what is required is a structure that behaves optically like a stack of saucer-rim mirrors but that can form images from light rays impinging on it from all directions.

The solution is provided by the eye itself. It is covered by an array of corner reflectors: pairs of mirrors set at right angles. These reflectors have the property of behaving like a single mirror that is always at right angles to the incident ray. (Corner reflectors are utilized as radar reflectors on buoys at sea; they always return the radar beam straight to the ship transmitting it.) An array of corner reflectors will therefore behave like the saucer rims but will do so for light from any direction. The only major constraint on this arrangement is that the silvered boxes making up the array must be sufficiently deep for most of the light rays to encounter two walls but not so deep that the light is reflected more than twice.

Experiments with models suggest that the boxes should be twice as deep as they are wide, which is very close to what is actually observed in the eyes of shrimps and crayfishes. Hexagonal mirrors would not act as corner reflectors and hence would be incapable of focusing light. The square packing of the facets in the eyes of the macruran crustaceans is far from being an adventitious characteristic of the group; it is crucial to the functioning of the optical system.

An interesting sideline that emerges from these observations is that the structure of the compound eye, whether it is hexagonal- or square-faceted, provides an important clue to the evolutionary history of the crustaceans. To change over from the refracting type of superposition eye to the reflecting type would require so many coordinated modifications that it is likely the two types are only distantly related. It is interesting to note that two shrimplike groups, the mysids and the euphausiids (best known as the krill that are the main food of the baleen whales), have refracting superposition eyes with hexagonal facets. I am not much of a taxonomist, but I would guess from this item of evidence that these two families of crustaceans are phylogenetically much more distant from the macrurans than current accounts of crustacean evolution suggest. On the other hand, the galatheids (the squat-lobsters, a group intermediate between the macrurans and the true crabs) have reflecting superposition eyes with square facets, a feature that puts them phylogenetically closer to the macrurans.

Fifteen years ago most zoologists would have accepted the conclusion that all the important optical mechanisms employed by animals were understood and had been for half a century or more. Now two mechanisms fundamentally different from all the others have emerged. I am fairly well convinced that this is the end of the road, but it would be nice to be proved wrong.

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The Razed Temple of Akhenaten

The Pharaoh who wanted Egypt to worship one god erected imposing monuments at Karnak. His successors took great pains to level them. What they were like is now being pieced together from the fragments

by Donald B. Redford

In 1375 B.C. a remarkable Pharaoh's reign over Egypt came to an end. A member of the 18th Dynasty to hold power in the Nile valley since royal rule began there in about 3000 B.C., Amenophis III had controlled the empire for nearly 40 prosperous years. His authority extended far beyond Egypt: from the Sudan in the south to Palestine, Syria and the frontier of Mesopotamia in the east. It could hardly have been foreseen that within five years of the Pharaoh's death his son and successor, Amenophis IV, would revolutionize Egypt and that then, before the end of the century, nearly every trace of the royal revolution would have been obliterated.

The principal scene of these dramatic events was the seat of royal authority: Thebes, the royal capital 350 miles south of the Nile delta. The capital consisted of two cult centers on the east bank of the Nile, Karnak and Luxor, and a vast city of the dead on the west bank. Since 1966 archaeological investigations on the east bank have helped to illuminate both the revolutionary acts of Amenophis IV (who soon changed his name to the one we know him by today: Akhenaten) and the harsh retaliations of his successors. Here I shall relate what has been learned over the past several seasons of work, with particular reference to the search for traces of the temple and the other royal structures Akhenaten built at Karnak.

In the formative years of Egyptian religion the gods were local deities. Osiris was worshiped at Busiris, Ptah at the Old Kingdom capital of Memphis and so on. The local deity at Thebes was Amun-re, represented as a human figure with the head and horns of a ram. The construction of the god's major temple, at Karnak, seems to have begun in about 2000 B.C. during Middle Kingdom times. A similar local deity, enshrined at On (the Heliopolis of the Greeks), was Atum-re. Although worshiped in the form of a bull, as Ptah was at Memphis, Atum-re was regarded as a solar deity. By the beginning of Middle Kingdom times (2445 B.C.) Atum-re, or simply Re, the sun god, had become identified with many of Egypt's local deities, particularly with Amun-re at Thebes.

The greater part of Amun's temple at Karnak was built early in New Kingdom times (1580 B.C. and later), particularly in the years after the founder of the 18th Dynasty, Amosis, expelled the Hyksos interlopers who had ruled over Egypt during the 15th and 16th dynasties. Six of the temple's 10 great pylons, or ceremonial masonry arches, the third through the eighth, were built during the 18th Dynasty (1580–1350 B.C.). During his long and prosperous rule Amenophis III (1411–1375) also added to the splendors of the sun god's temple. Three more pylons, the second, ninth and 10th, were built under different circumstances during the 19th Dynasty (1350–1200 B.C.).

Amenophis III, the "King of Upper and Lower Egypt, Nebmaatre, Son of the Sun" (to give him his official title), was a man with a refined taste for large buildings, antiquities and women. He took several high-born wives, at least partly for reasons of state. One was a princess from Babylon, a second a princess from Arzawa (in what is now southwestern Turkey) and a third a princess from Mitanni (roughly the area of modern Kurdistan).

His chief queen, however, was a commoner named Tiy. She bore the significant title "Great Heiress" and retained the status of "Great King's Wife" to the end of Amenophis' reign. Tiy survived her husband by at least a decade. Six children were born of the union, four girls and two boys. This main stem of the Amenophid family provided Egypt with rulers for two generations.

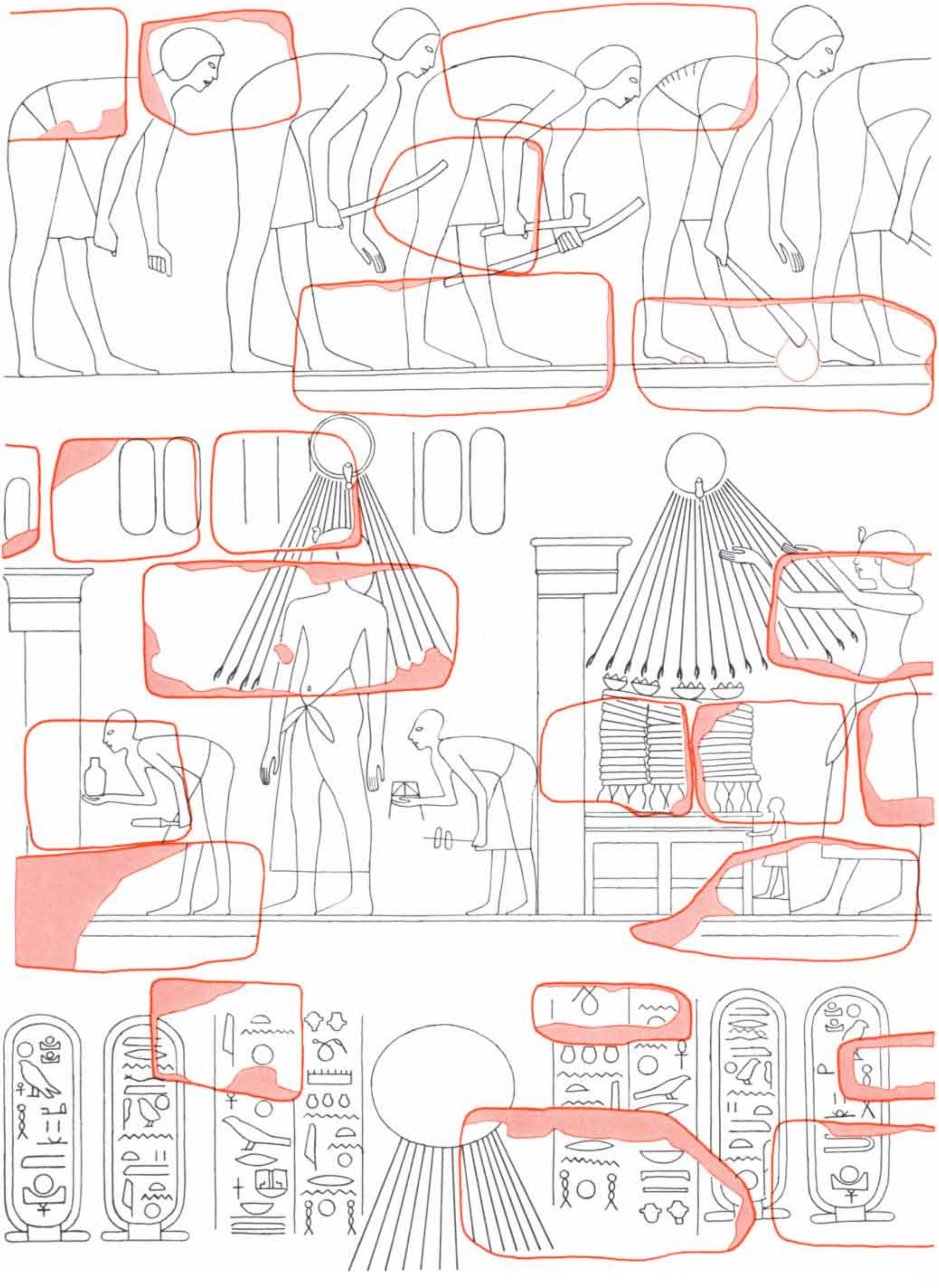
The younger of Tiy's two sons, also named Amenophis, was weak and misshapen. Some modern scholars, basing their diagnosis on unflattering representations of his appearance, believe the prince suffered a pituitary abnormality known today as Froehlich's syndrome. On the unexpected death of his elder brother this unprepossessing youth found himself crown prince. When his father succumbed to various ailments in 1375 B.C., the prince, largely unknown except to his mother, ascended the throne as Amenophis IV.

If, like his father before him, the new king was to be "Son of the Sun," it was a responsibility he did not take lightly. At the beginning of his reign he determined to worship only one god: the Sun Disk, Re-horakhte. Within his first year animal representations of the deity were outlawed; hawk's heads and ram's heads on human bodies were no longer acceptable as personifications of the divine sun. In a parallel administrative act the new Pharaoh decreed that the revenues of all the other Egyptian gods were to be directed into a single treasury, that of the Sun Disk. The royal decrees hit hardest at the priests of Amun-re at Thebes, who had been the chief financial beneficiaries of more than a century of foreign conquest.

The Pharaoh's new order was expressed in works as well as in decrees. In the second and third years of his reign Amenophis IV celebrated a great jubilee at the royal capital. At least eight masonry structures were built or begun for the celebration, and the site the new ruler selected for most of the new buildings was Amun-re's temple at Karnak.

We know the names of five of these structures. The most elaborate one was called Gem-po-aten: "[the] Sun Disk Is

SUN-DISK WORSHIP is pictured twice in the middle row of this reconstruction of a three-row relief that shows Akhenaten, accompanied by two priests, bathed in the rays of the Sun Disk (*left*) and alone, arms upraised (*right*), offering an altar load of foodstuffs to the Sun Disk. In the top row bowing courtiers, holding their wands of office, pay their respects to Akhenaten. The hieroglyphs in the bottom row identify the solar deity in his Sun Disk manifestation. Colored lines show individual sandstone blocks in outline; light color indicates erosion.



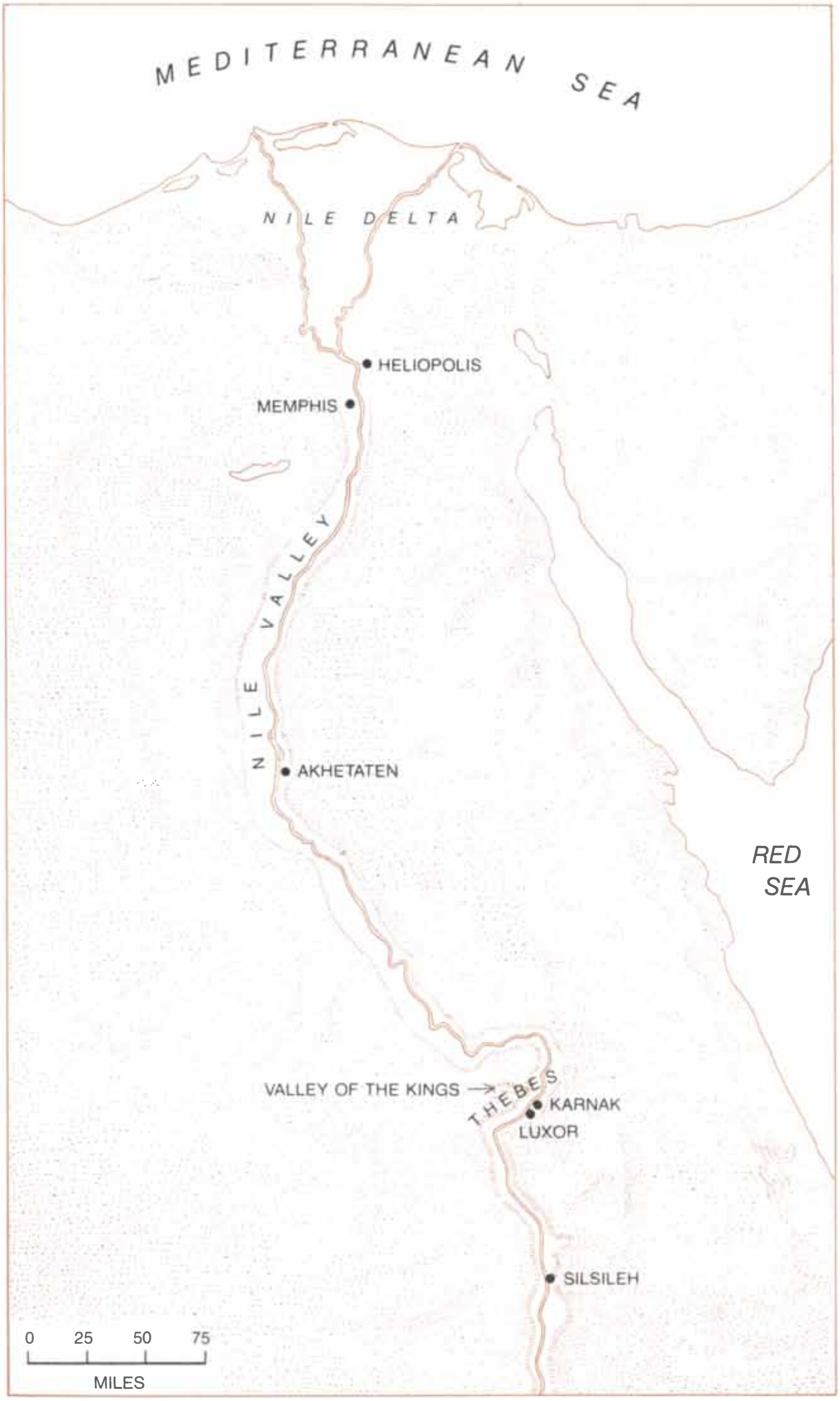
Found." Engraved in relief on the sandstone walls of the structure were scenes from the jubilee celebration and scenes showing the king's wife, Queen Nefertity, and one or both of the two daughters she had borne by then making offerings to the sun. Another structure, possibly built inside the first, was Hat-ben-ben: the "Mansion of the Ben-ben Stone." The title is an ancient one; it had long been applied to a very early temple at Heliopolis, the city where the solar deity Atum-re was worshiped. The reliefs on the sandstone walls of the "Mansion" showed Nefertity in the act of making sun offerings; she is not accompanied by her daughters. The Mansion was not built until at least the fourth year of the new king's reign.

Two shrines were built soon after the jubilee. One was named "Exalted Are the Monuments of the Sun Disk Forever" and the other "Sturdy Are the Monuments of the Sun Disk Forever." The reliefs engraved on the sandstone walls of the "Exalted" shrine depicted many scenes of palace domestic life; those in the "Sturdy" shrine showed arrays of braziers for offerings to the sun, chariot processions, soldiers and scenes with palace attendants. A few of the engravings showed the new king making sun offerings. The name of a fifth structure, the "Booth of the Sun Disk," is known from inscriptions. Nothing is known about the names, the decorations or the locations of the other three royal structures raised by Amenophis IV in the first five years of his reign.

It was in his fifth year on the throne that the new ruler formally changed his name to Akhenaten ("Useful for the Sun Disk"). He ordered the closing of Amun-re's Karnak temple and as an added touch directed that Amun-re's name should be obliterated from all the temple monuments. With his queen and their daughters (now three) Akhenaten moved from Thebes to a new city he had constructed on the east bank of the Nile 150 miles to the north. The new city (modern Amarna) he named Akhetaten: "Horizon of the Sun Disk." There he celebrated the 12th year of his rule with a great display of tribute and a gathering of foreign dignitaries.

Akhenaten was not his father's equal as a diplomat. The Hittites eroded Egypt's Syrian frontier and even conquered Egypt's ally, Mitanni, without any strong response from Akhenaten. In 1358 B.C., during the 17th year of his reign, the religious reformer died.

For the next 11 years the throne was occupied in succession by Akhenaten's sons-in-law, Smenkhkare (1360–1357 B.C.) and the famous Tutankhamen (1357–1347 B.C.). Smenkhkare seems to have supported his father-in-law's religious reforms during his brief reign, but after three years on the throne Tutankhamen weakened to the extent of moving the royal seat from Akhenaten's newly built city back to Thebes. Tutankhamen was succeeded in 1347 B.C. by Ay, the last of the Amenophids. On Ay's death in 1344 B.C., Tutankhamen's army chief, Horemheb, assumed royal authority as the founder of the 19th Dynasty. For a short time Horemheb, who ruled from 1344 to 1315 B.C., honored the Amenophid commitment to the Sun Disk and may even have added to Akhenaten's structures at Karnak. It was not long, however, before the situation



NILE VALLEY NORTH OF ASWAN is hemmed in by desert to the east and west. The royal capital, Thebes, consisted of two ceremonial centers on the east bank of the Nile, Karnak and Luxor, and a vast city of the dead on the west bank. Silsileh, to the south, is the site of the sandstone quarry that furnished the blocks used to construct Akhenaten's ceremonial structures at Karnak. Akhetaten, to the north, is the capital built when Thebes was abandoned. Farther north are Heliopolis, where Atum-re was worshiped, and Memphis, the capital of the Old Kingdom.

HOUSE WALLS of a residential quarter located east of the Temple of Amun-re were unearthed in 1976 and 1977. The quarter was occupied in three successive phases over a period of some 500 years during the first millennium B.C. Junior priests and scribes lived here.

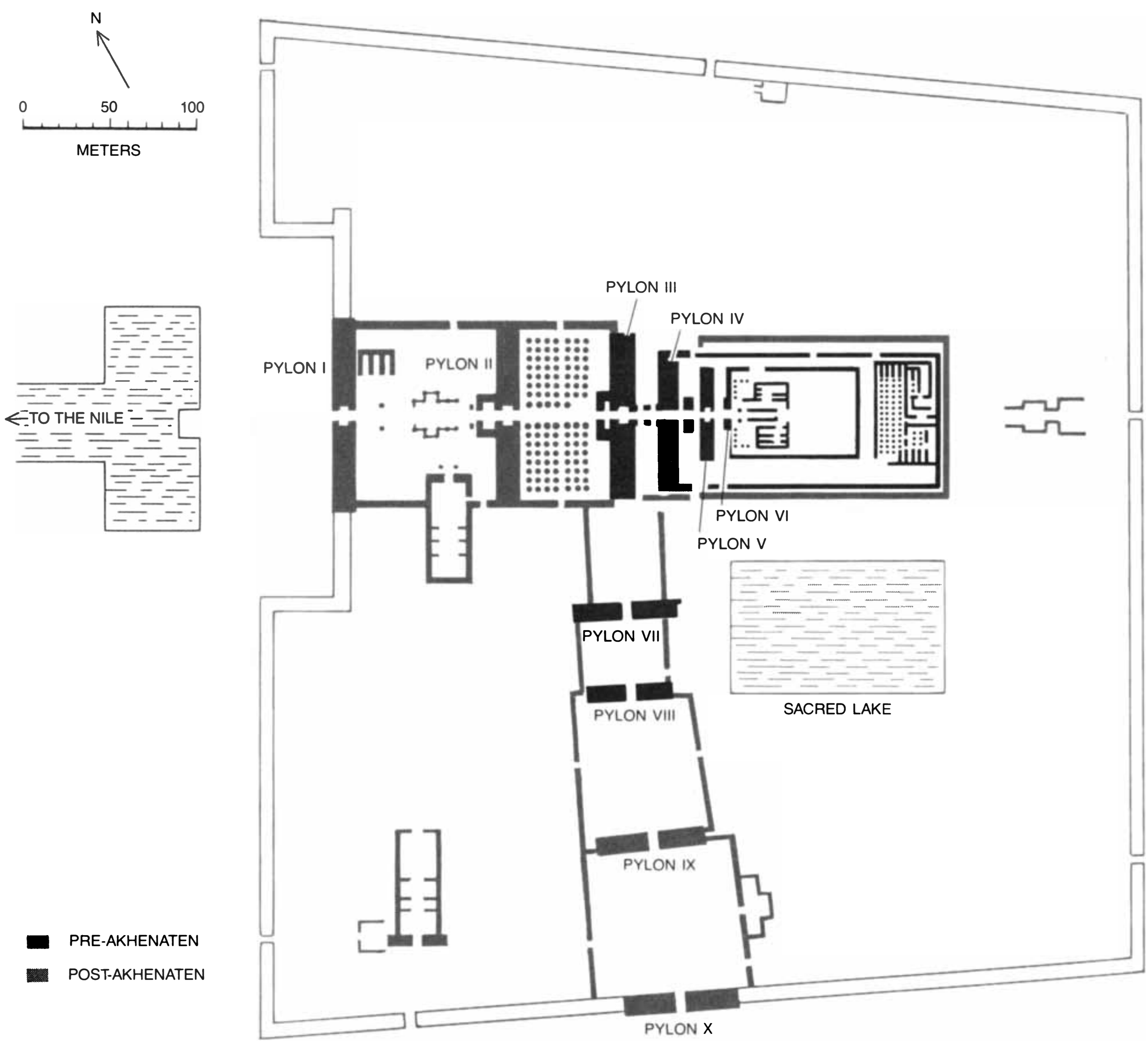
RECTANGULAR PIERS, dismantled almost to the foundation level, mark the southern colonnade of Akhenaten's jubilee temple; the view is toward the west. The south wall of the temple, running behind the colonnade, was completely demolished but much rubble remained.

changed. With a thoroughness that almost suggested personal animosity the sun temples and the royal palace at Akhetaten were systematically dismantled and their foundations uprooted. The same fate befell Akhenaten's structures at Thebes and Luxor and in particular the series of buildings adjacent to Amun-re's temple at Karnak. Akhenaten's sun cult ceased to exist; his name and those of his three immediate successors were even struck from the official list of Egypt's kings.

The demolition work was not wasteful. For example, when Horemheb added the second, ninth and 10th pylons to Amun-re's rehabilitated temple at Karnak, the fill that provided a base and core for the second pylon and the foundation for a great pillared hall just to the east of the pylon almost exclusively consisted of the sandstone masonry from Akhenaten's demolished jubilee temple "[the] Sun Disk Is Found." The base of the ninth pylon consisted largely of sandstone masonry salvaged from the two demolished shrines, "Exalted" and "Sturdy."

When Ramesses II (1304–1239 B.C.), the third Pharaoh after Horemheb, undertook construction in the vicinity of Thebes, his masons removed to Luxor several thousand additional sandstone blocks left over from the demolition of Akhenaten's structures at Karnak. More than a millennium later, when Rome ruled Egypt, a number of Akhenaten's leftover blocks found their way into private construction; some are still to be seen in the walls of old buildings in Cairo, some 300 miles downstream from Karnak. Sadder to relate, many of the most elegantly sculptured blocks found their way into the hands of private collectors both in Egypt and abroad.

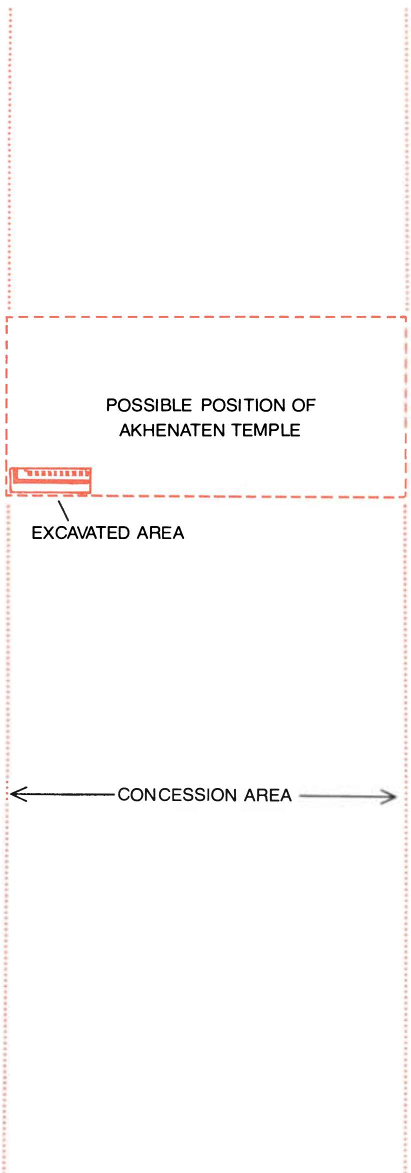
Today more than 40,000 of Akhenaten's blocks are preserved in the vicinity of Thebes: there are seven storehouses full of them at Karnak and one storehouse at Luxor. Most if not all of them were brought to Akhenaten's construction sites from sandstone quarries at Silsileh, on the east bank of the Nile 80 miles south of Karnak. They were chiseled to size by the thousands at the quarry; the basic specification was a block 22 centimeters deep, 25 centimeters high and 52 centimeters long. The walls of Akhenaten's Karnak structures



TEMPLE OF AMUN-RE AT KARNAK, the array of major structures shown on this plan, includes construction, undertaken after the demolition of Akhenaten's Sun Disk monuments in the vicinity, that used masonry from the overthrown walls. The bulk of the ceremonial gateway labeled Pylon II on the plan and the foundation for the hall of pillars to the east of it consist almost entirely of masonry from Akhenaten's demolished jubilee temple, salvaged and reused by the Pharaoh Horemheb's builders. The excavation concession given by

were built by laying the blocks in courses, alternating headers and stretchers, with gypsum serving as mortar. After a wall was built skilled stoneworkers executed the decorative relief engravings and other inscriptions on its inner face.

Thebes and its vicinity, which includes the dramatic Valley of the Kings where the Sahara escarpment borders the west bank of the Nile, was the site of active archaeological investigation long before Tutankhamen's tomb was discovered by Lord Carnarvon and Howard Carter in 1922. British, French and German expeditions worked in the area during the 19th century and both before and after World War I. Indeed, it was French restorative work at the temple of Amun-re at Karnak in the 1920's and 1930's that first brought to light the re-



the Egyptian Organization of Antiquities to the Akhenaten Temple Project in 1974 (*color*) extends for one kilometer north and south of the temple (*see illustration on next page*).

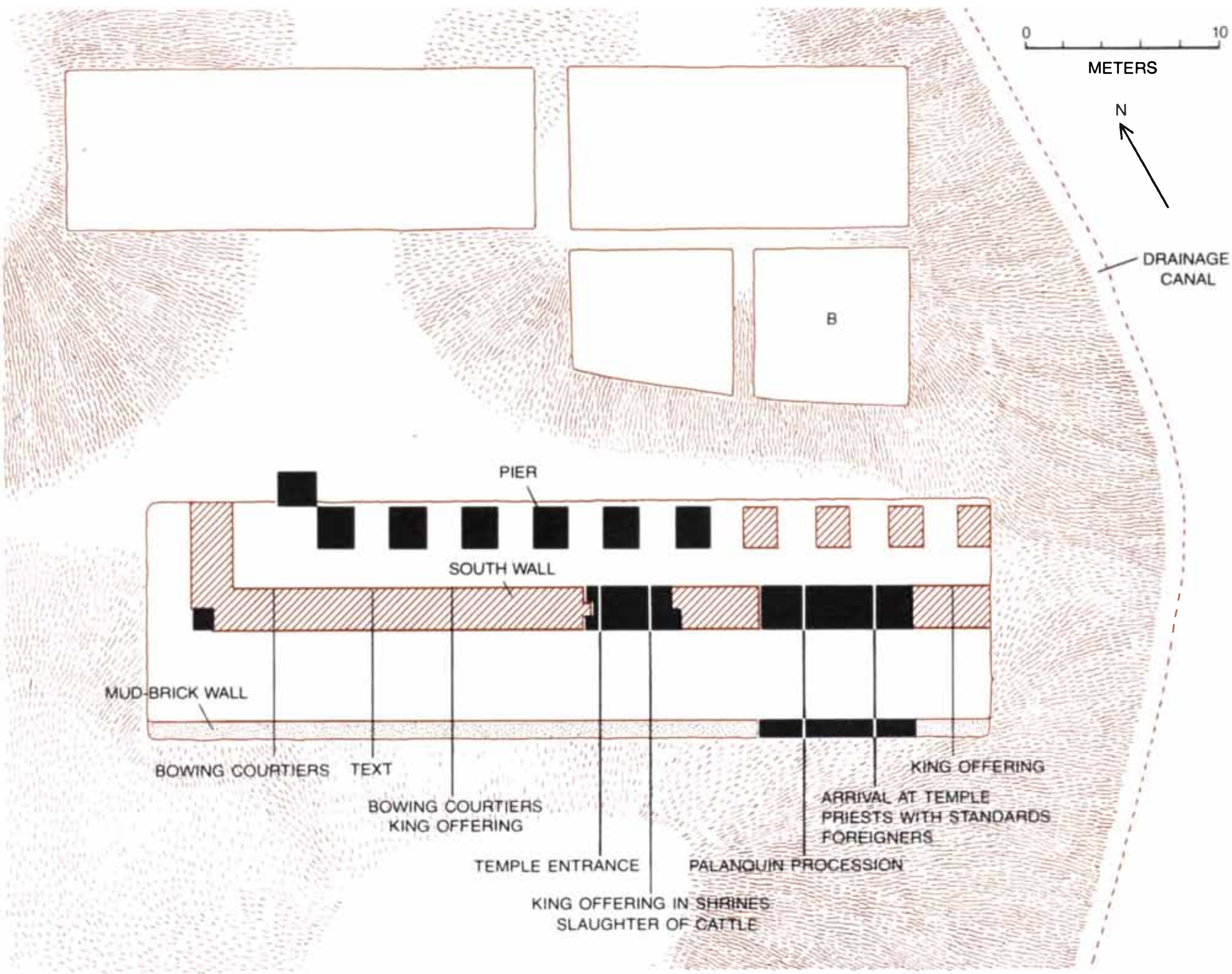
cycling of Akhenaten's blocks; they began to emerge by the thousands from the base and core of the second pylon and the pillared hall.

The fact that most of the blocks had some part of a relief scene on one face made it clear they were not just rubble but the remnants of former major structures. Because the striking art style introduced during Akhenaten's reign is readily recognized it soon became obvious that the avalanche of engraved sandstone had been part or perhaps nearly all of the structures the reformer had raised at Karnak in the first five years of his rule. As more of the blocks emerged the mere task of storing them so that they would be safe from pilferage, let alone the task of analyzing them, became increasingly formidable.

Almost nothing was done about the problem until two decades after World War II, when Ray Winfield Smith, a retired American foreign-service officer and a research associate of the University Museum of the University of Pennsylvania, launched the Akhenaten temple project. The project was sponsored by the University Museum with funding from the foreign-currency program of the Smithsonian Institution. Smith's approach was at once simple and heroic: to photograph each engraved block to a common scale, to index the engraved face in a manner suitable for computer analysis and then to have a computer program undertake the huge number of iterations required to match each engraved face to all its neighbors. Once that was done the assembly of the photographs would be a relatively simple task.

In the 11 years between the beginning of this vast analytical effort and its end in the spring of last year Smith and his international group of experts have succeeded beyond anyone's dreams. Thirty-six thousand blocks have been photographed, and thousands of scenes have been re-created. The results make it possible to trace Akhenaten's progress in developing at least the outward trappings of his radical monotheism. They also throw light on daily life during the five years he remained in Thebes and even raise interesting questions about his relations with his queen.

The earliest structure Akhenaten built at Karnak, probably during his first year on the throne, was a monumental gate, a pylon of which no remnant now stands. Its sandstone blocks were much larger than the standard wall blocks. Among the engraved areas that have survived is a long inscription. In this text the new king extols the matchless qualities of the



CONCESSION AREA immediately to the east of the Temple of Amun-re had been partially excavated by earlier investigators. The work begun in 1975 included probing the eight-meter-square plot marked *B* at top right on this plan and a second plot of the same size to the south (not outlined). Further work in 1976 extended the digging in the *B* line of plots and finally revealed the first traces of the jubilee temple (*bottom right*): the foundation of the south wall of the temple and the debris from its demolition, traces of the outer mud-brick enclosure of the temple and the base of one of the roof-supporting piers. Subsequent excavations have uncovered a series of pier bases; they once formed a colonnade just inside the south wall of the temple. Black rectangles identify pier bases that have been located, and black areas of wall are similarly identified by foundation remains and the debris of broken wall masonry. Portions of scenes preserved on masonry fragments, which match scenes assembled by study of the preserved temple masonry, appeared along the wall in the order shown.

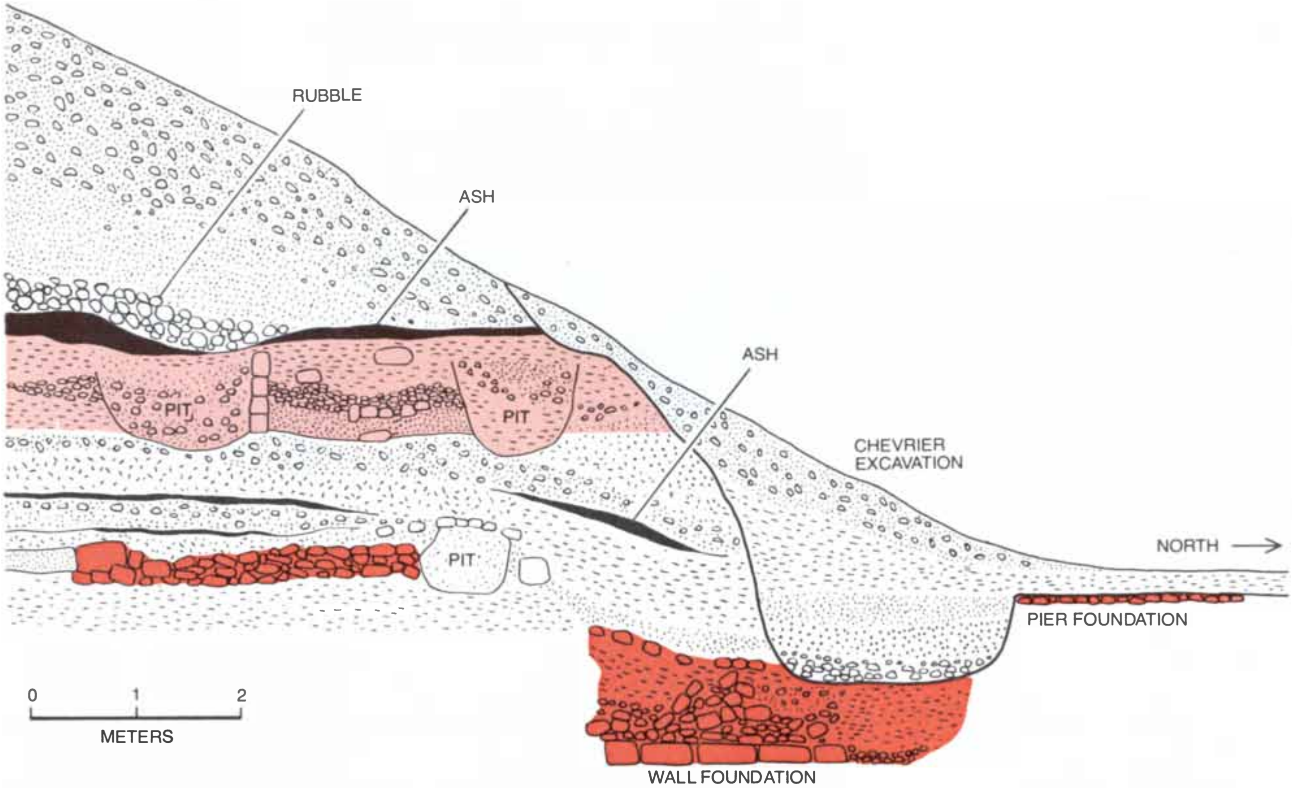
sun god at the expense of all the other divine cults of Egypt. Most of the representations of the sun god that appeared on the pylon follow the earlier iconographic tradition of representing the god with a human body and an animal head. Before the pylon's decoration was completed, however, Akhenaten had introduced his new sun image: a simple disk that sends out many narrow rays, each ending in the form of a human hand. Therefore the abandonment of the sun god's semianthropomorphic representation can be dated to probably before the end of Akhenaten's first year as the new Pharaoh.

As for the relations between Akhenaten and Nefertity, in the reliefs of the jubilee temple and also of the two shrines constructed soon thereafter the king is depicted as he makes offerings to the Sun Disk sometimes alone and sometimes accompanied by the queen, who is shown at a reduced scale. When, no earlier than the fourth year of their residence at Thebes, a colonnade was added to the jubilee temple and the Mansion of the Ben-ben Stone was constructed, the offering scenes had become almost exclusively the queen's. In the colonnade reliefs Nefertity is seen with one or both of her elder daughters but usually with the eldest, Meretaten. On the walls of the Mansion the queen makes the offerings alone.

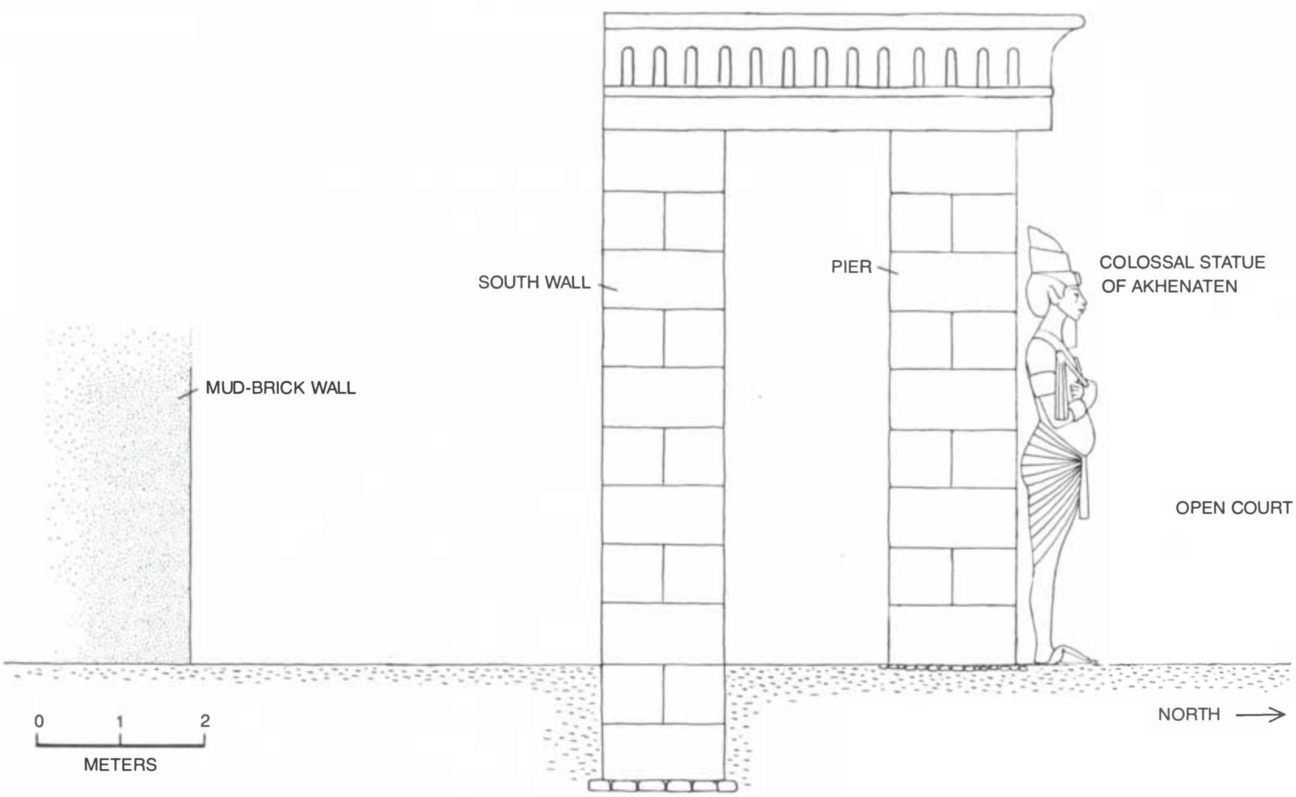
Why this should be is not clear. Perhaps these images of the queen as a mediator with heaven is associated with another oddity at Karnak: the queen's evident engagement in other activities normally associated with a Pharaoh's masculine prerogatives. Nefertity is portrayed not only making offerings but also receiving bound captives and even bashing in the heads of stylized victims.

By its 10th year the Akhenaten temple project had produced startling but lopsided results. A good deal was known about the relief decorations, their style and their themes but nothing had been learned about the temples and other structures whose walls had displayed the reliefs, about their architecture or even about their ground plan. Those who had been bent on rooting out every evidence of Akhenaten's works had so thoroughly dismantled his buildings that not even a trace of their foundations could be seen anywhere in Karnak. Scholars had no clear idea, even as late as 1974, where any of the reformer's structures had stood; they even disputed, often hotly, the functions the structures may have served. Therefore it was fortunate that in the fall of 1974 the project received a concession from the Egyptian Organization of Antiquities to excavate at Karnak.

Funding for the new operation was provided by the Smithsonian and later by the Killam Program of the Canada



INITIAL EXCAVATIONS in the East Karnak concession had to cut down through some 2,500 cubic meters of earlier excavators' dumpings before reaching remains of a residential quarter (*light color*) that was destroyed twice between the seventh and third centuries B.C. In August, 1976, the workers reached a zone of shattered sandstone and, beyond that zone, the bases of rectangular piers (*color*).



SOUTH WALL of Akhenaten's jubilee temple once stood close behind a row of squared piers some five meters inside a mud-brick enclosure (*left*). A colossal statue of Akhenaten, placed in front of each pier, looked out on an open earth-floored court; one such statue (none of them have been found in the excavations) appears in a line drawing in this profile view. The profile retains the south-to-north orientation of the excavation cross section illustrated at the top of the page. The height of the sandstone wall and the piers is not known, so that the roof shown here is conjectural. The roof must, however, have been higher than the six-meter-high colossal statues it covered.

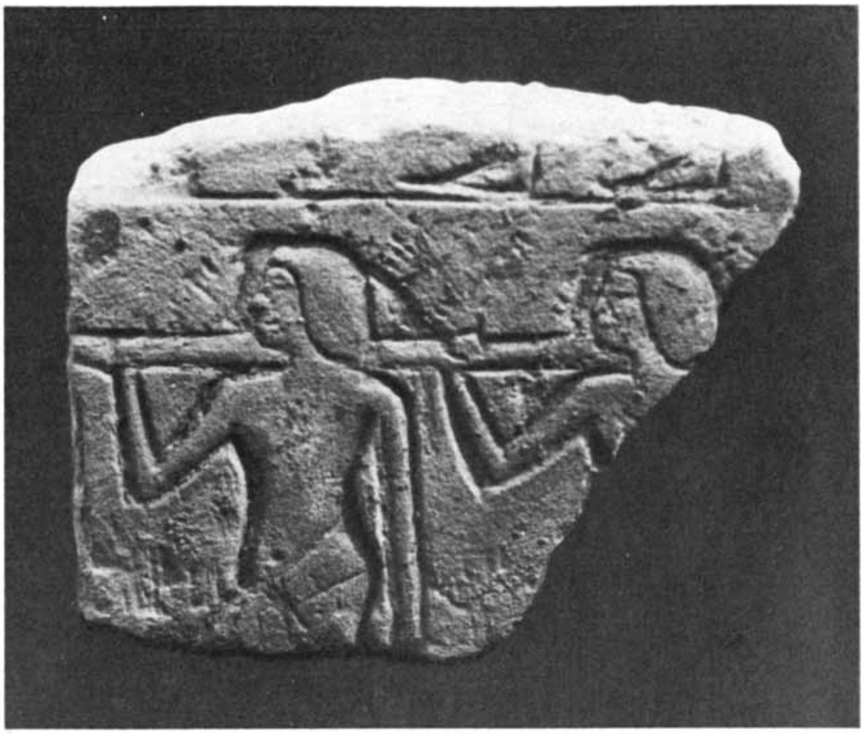
Council. In April, 1975, a group under my direction began excavation 100 meters east of the great enclosure wall that surrounds the temple of Amun-re at Karnak. We chose the area because in 1925 the municipality of Luxor had dug a drainage ditch there. In the process the excavators had uncovered a line of buried colossal statues of Akhenaten, along with traces of a wall built of the sandstone blocks that characterize Akhenaten's structures. In subsequent years the Inspector of Antiquities in Egypt, Henri Chevrier, attempted to follow the line of colossi eastward and westward, with indifferent success. His task was not an easy one because for more than a century the area had served as a dump for nearly all the archaeologists working at Karnak.

Our concession, 250 meters wide and almost a kilometer long, includes Chevrier's old excavation and dump. Because this is the only area known to have held something built by Akhenaten, it was a logical starting point, and at the start of the 1975 season we laid out two square plots, eight meters on a side, one to the south and one to the north, on the slopes of Chevrier's old excavation.

Mechanical earthmoving has yet to be introduced into Egyptian archaeology, leaving us with no recourse but the time-honored methods of hoeing and basket carrying. In our first three seasons we have nonetheless succeeded in removing about 5,000 cubic meters of earth from our squares (which were extended in the 1976 season by three additional squares on the south and one on the north). More than half of this amount consisted of other excavators' dumpings!

In all the areas we excavated we encountered below the level of the 1925 ditch substantial house walls dating roughly from the seventh through the third century B.C. It soon became clear that in this period our sector had been part of a residential quarter. The few inscriptions we found suggested that the quarter had been mainly a middle-class one, probably inhabited by overseers, junior priests and scribes. Potters also had been present in one area, as was indicated by the remains of two kilns. Analysis of fragmentary animal remains (recovered by flotation) shows that the diet of the residents was rich in beef: more than 75 percent of the animal bones are those of cattle.

During its 500-year occupation the settlement had been destroyed twice. The evidence of these disturbances was clear in the earliest building level and inescapable in the middle level. There the floors were strewn with debris: smashed pottery vessels and other evidence of violent activity. In contrast to these earlier episodes the top building level, the last to be occupied, was abandoned under conditions that suggested the inhabitants at least had time to pack.



FRAGMENT OF BLOCK **recovered from the rubble of the jubilee-temple wall shows a portion of the scene that decorated the face of the wall: two of the bearers who carried Akhenaten.**

The floors were swept clean, and few domestic artifacts had been left behind. Precise dating of any of these occupation levels is difficult, but it is tempting to attribute the violent destruction of the middle level to the Persian invasion of 525 B.C.

In our search for evidence of Akhenaten's structures we had to dig still further through the remains dating from the first millennium B.C. The first meter below the earliest of the three residential levels was occupied by fill, most of it clearly an ancient trash dump. Potsherds in this material could be assigned to the first three or four centuries of the millennium. In one sector we uncovered the remains of a structure built of fired brick. There were no inscriptions to help in identifying the structure, but some of the bricks were stamped with the name of Menkheperre, a high priest of Amun-re who is known to have flourished from about 1020 to 1000 B.C. We had come within three centuries of Akhenaten.

Not until August during our second season did we reach evidence of the revenge taken on Akhenaten by Horemheb and his successors. Digging down in summer heat of 120 degrees Fahrenheit we came to the top of an immense pile of shattered sandstone wall blocks, strewn helter-skelter in a six-meter swath that ran in an east-west direction. Next to be exposed, lying parallel to the strewn wall blocks, were the bases of several large rectangular piers, measuring two meters by 1.8 meters.

Lying face up in the sandstone pile was one wall-block fragment that bore part of a relief carving; the lines looked very familiar. They should have. The fragment was part of a carrying-chair scene we had long known from our nine years of work in matching up the wall-block photographs. The broken blocks, then, had once formed a wall built by Akhenaten.

Which wall? The next two seasons supplied the answer. In 1976 we recovered nearly 100 more relief fragments from one 12-meter trench, and the total rose to 250 when the trench was extended another 30 meters last year. Most of the wall-block reliefs could be instantly identified as coming from the decoration of the most elaborate of Akhenaten's Karnak structures, the temple Gem-po-aten. To clinch the matter, we later turned up two inscriptions that included the name of the temple.

By the end of our 1977 season the general configuration of what we had uncovered at Karnak was apparent. We had reached the south wall and interior colonnade of a great open court with a floor of packed earth. The piers of the colonnade were set two meters apart; against each pier, facing north into the court, a colossal statue of Akhenaten had once stood. These were the figures that had first been uncovered by the drainage ditch of 1925 and were then removed in the later 1920's and the 1930's.

The relief-decorated sandstone wall had stood some two meters south of the line of piers; its foundation trench extended a meter and a half below the packed-earth floor. The reliefs had been executed on the inner face of the wall, where they would have been partly concealed by the piers of the colonnade. The engraved scenes constituted a continuous sequence of decoration extending from the floor to the ceiling. Five meters to the south of the sandstone-block wall and running parallel to it had stood a second wall made of mud brick; this wall must have been part of a sacred enclosure surrounding the Sun Disk temple.

Our work has enabled us to reconstruct with some certainty just how the temple was destroyed. First the statues were thrown down on their faces. Then the piers of the colonnade were dismantled almost to ground level. The surrounding mud-brick wall was leveled before the decorated sandstone wall was attacked, evidently from the south. The sandstone wall was dismantled block by block, the mortar being loosened by hammering. A deep pile of sandstone debris accumulated along the wall, and in and around it were many shattered blocks. The dismantling of the wall, unlike the dismantling of the piers, was continued to well below ground level.

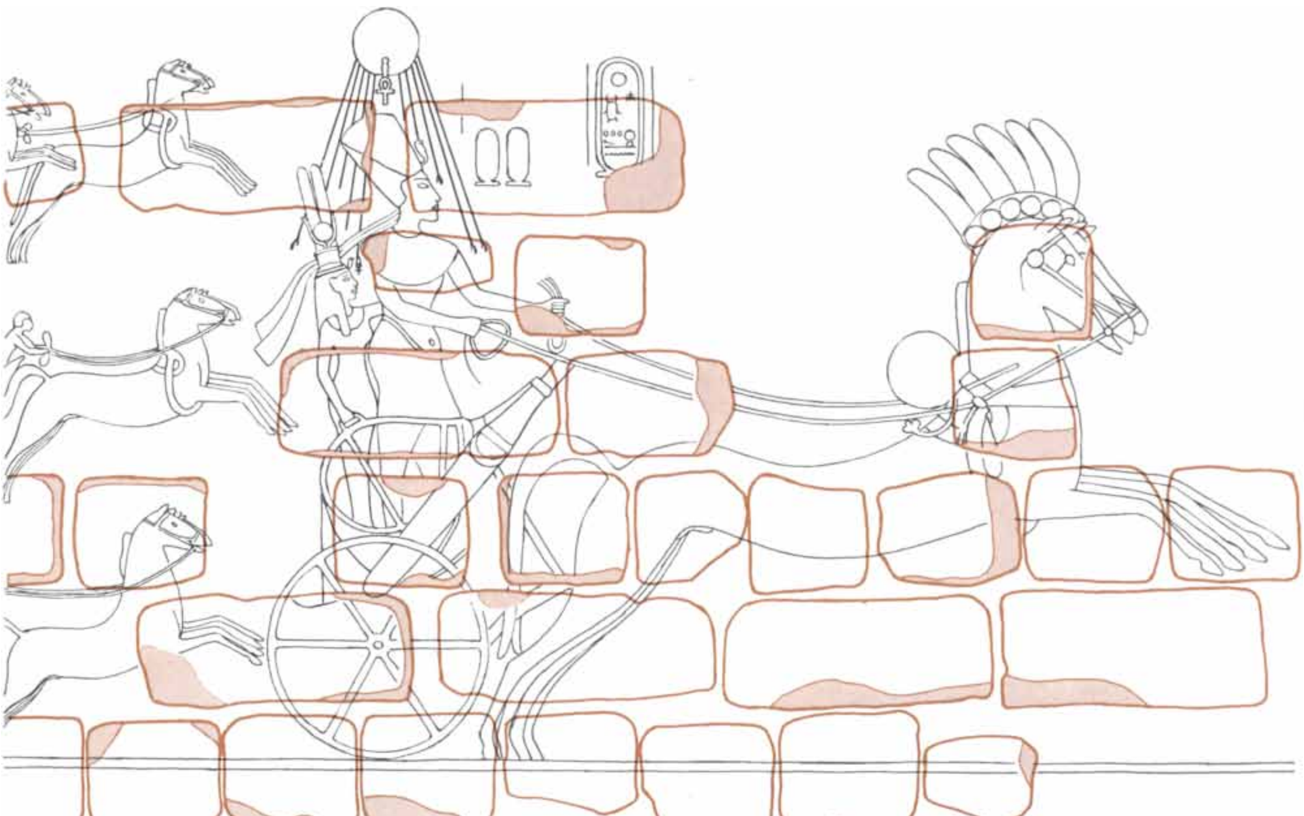
There is good reason to believe the abandoned sandstone-block fragments were left where they fell. This working hypothesis has offered us a unique opportunity: the possibility of reconstructing the sequence of the scenes that decorated the temple walls. It is just such information about the sequence of the scenes, as opposed to their internal composition, that is missing from our photographic mosaics.

We have therefore carefully plotted the position of each of the 250-odd decorated sandstone fragments we have recovered so far. On roughly half of the fragments the decoration is clear enough, although sometimes it is very small, to establish to what kind of scene and sometimes to what exact scene the fragment belongs. For example, we have been able to conclude that the fragments we uncovered first all belong to the motif most often repeated in the temple: a great procession of the royal family to the temple from the royal palace. The principals are moving from right to left and Akhenaten is wearing the white crown symbolic of Upper Egypt, that is, the Nile valley as opposed to the northern delta lands of Lower Egypt, which were symbolized by a red crown. The crown symbolic of southern Egypt was of course an appropriate decoration for the south wall of the temple.

Our fragments are correlated with scenes representing stages in the approach to the temple; the way is lined with foreign dignitaries and with priests holding standards. The fragments from our easternmost trench are correlated with a scene showing the temple's mud-brick enclosure wall; Akhenaten is inside the enclosure making an offering to the Sun Disk. Similarly, our westernmost trench has yielded fragments correlated with a scene of the procession emerging from the royal palace.

This sequence of scenes, from the palace to just within the sacred enclosure, occupied a stretch of wall some 13 meters long. What may have been portrayed beyond the easternmost scene we know about is suggested by what we have been able to reconstruct farther to the west. At the corner where the south and west walls met are the figures of bowing men. Beyond them to the east is a hieroglyphic text that alas is too poorly preserved to be read. Next is the pylon of the temple and after that a scene with two levels: bull slaughtering below and ritual offerings above.

If that is the last scene in the sequence, we should not be surprised to find it where it is; the artists merely repeated the procession motif. Perhaps it was their intention to convey the constant movement and colorfulness of several consecutive processions to the temple. After all, Akhenaten's jubilee, the event



PHARAOH AND QUEEN, Akhenaten and Nefertity (shown at a reduced scale behind him), are seen riding in a two-horse chariot on their way from their palace to one of their Sun Disk temples in Karnak. The rays of the Sun Disk descend on the royal couple. Three other chariots behind the royal couple are occupied by escorting courtiers and officers. Inscriptions indicate that the scene once decorated one of the walls of the jubilee temple at Karnak. Future excavations at the East Karnak concession may determine its former position.

that is depicted, lasted for many days and involved many temple visits.

As the excavations continue they can be expected to reveal more of the fate of Akhenaten's structures. Our one-kilometer concession should, however, yield information of an even broader scope. For example, investigation of the urban settlement of the latter part of the first millennium B.C. could occupy us for years to come. One is not often given an opportunity to excavate a large section of a royal city. What was the ecological picture here? What was the basis of the city's economy? How was the city planned? These and many related questions come easily to mind.

Already, during the 1978 season, we have begun to see the answers to some of our questions. For example, we have found that the colonnade and the decorated temple wall extended along the west side of the temple courtyard. The scenes here also depict processions of the king and queen en route from the palace to the temple. Also seen are priests and courtiers pouring libations.

There is some indication, as we proceed northward along the west side of the temple, that we may be approaching a site where a pylon once stood. The exact north-to-south width of the temple court still eludes us, although our magnetometer seems to have picked up traces of the north wall at a point 90 meters away from the south side of the court.

Whatever else may be learned at Karnak, particular importance will attach to any fresh information about Akhenaten. The reformer Pharaoh is perhaps the best known and possibly the most attractive of all ancient rulers. This is probably because he is seen principally as the first champion of monotheism. Because he worshiped only one god Akhenaten has been made out to be a forerunner of Moses, Christ and Mohammed. Actually the spiritual and ethical content of Hebrew religion and nascent Christianity are entirely lacking in Akhenaten's program, just as his religion's solar aspects are equally foreign to the teachings of both Moses and Christ. Akhenaten's iconoclasm was distantly echoed in the rise of Islam, but the closest spiritual ally of his sun cult was the Roman emperor Aurelian's short-lived worship of "Sol Invictus" in the third century A.D.

The Pharaoh's espousal of a strikingly modern style of art does not diminish his artistic reputation; he seems, indeed, to be one of us. Whether or not our assessment of the man is correct, there can be no doubt that his achievement as a reformer working from the top is unique in early times. There is irony in his fame, because Akhenaten's actions made little more than a ripple in the stream of Egypt's long ancient history.

Fast Running Tracks

On a springy new indoor track at Harvard University runners can run faster than they can on standard tracks. The design of the track was arrived at through a close analysis of the mechanics of human running

by Thomas A. McMahon and Peter R. Greene

In October of last year Harvard University opened a new indoor sports facility housing a six-lane 220-yard running track. The track has a supporting substructure consisting primarily of wood and a synthetic surface covering. Most people find running on the track a pleasant and unusual experience. It feels particularly springy and therefore is comfortable to run on, and members of the Harvard track team have sustained considerably fewer injuries since they began practicing on the track. What is most remarkable, however, is that an analysis of the 1977–78 records of Harvard runners and their competitors shows that the track substantially enhances a runner's performance, reducing the time of, say, a well-run mile by several seconds. By all estimations the new track is fast.

One of the most important parameters of track design is compliance, and it is mainly in this respect that the new track differs from other indoor tracks. Just how compliant—or, alternatively, how stiff—should a track be? In 1976, when the new track was being designed, the Harvard track coach, Bill McCurdy, and the Harvard Planning Office sought our advice on this question. At that time there was no information available concerning the effect of a given track surface on running speed and comfort. It is intuitively clear, however, that running on a compliant surface such as grass is less conducive to injury than running on a hard surface such as asphalt. Indeed, if comfort were the only consideration, all tracks would be extremely springy, perhaps as springy as a diving board. Intuition also suggests, however, that on a springy track the time spent rebounding from the surface is increased, so that a runner is slowed down. Hence if a running track is to be fast, its compliance must be limited.

One might therefore suppose the hardest track surfaces are the fastest, but that is not the case. A compliant surface acts as a spring, and we found that if the stiffness of the spring is closely tuned to the mechanical properties of the human runner, the runner's speed can be increased. In other words, there is a specific intermediate track compliance at which running speed is optimized. At that optimum compliance the runner stepping down onto the track stores elastic energy in its surface, much as a pole vaulter stores elastic energy in bending a fiberglass pole, which is recovered as the pole propels him upward. A track whose compliance is in the theoretically optimum range can be called a tuned track.

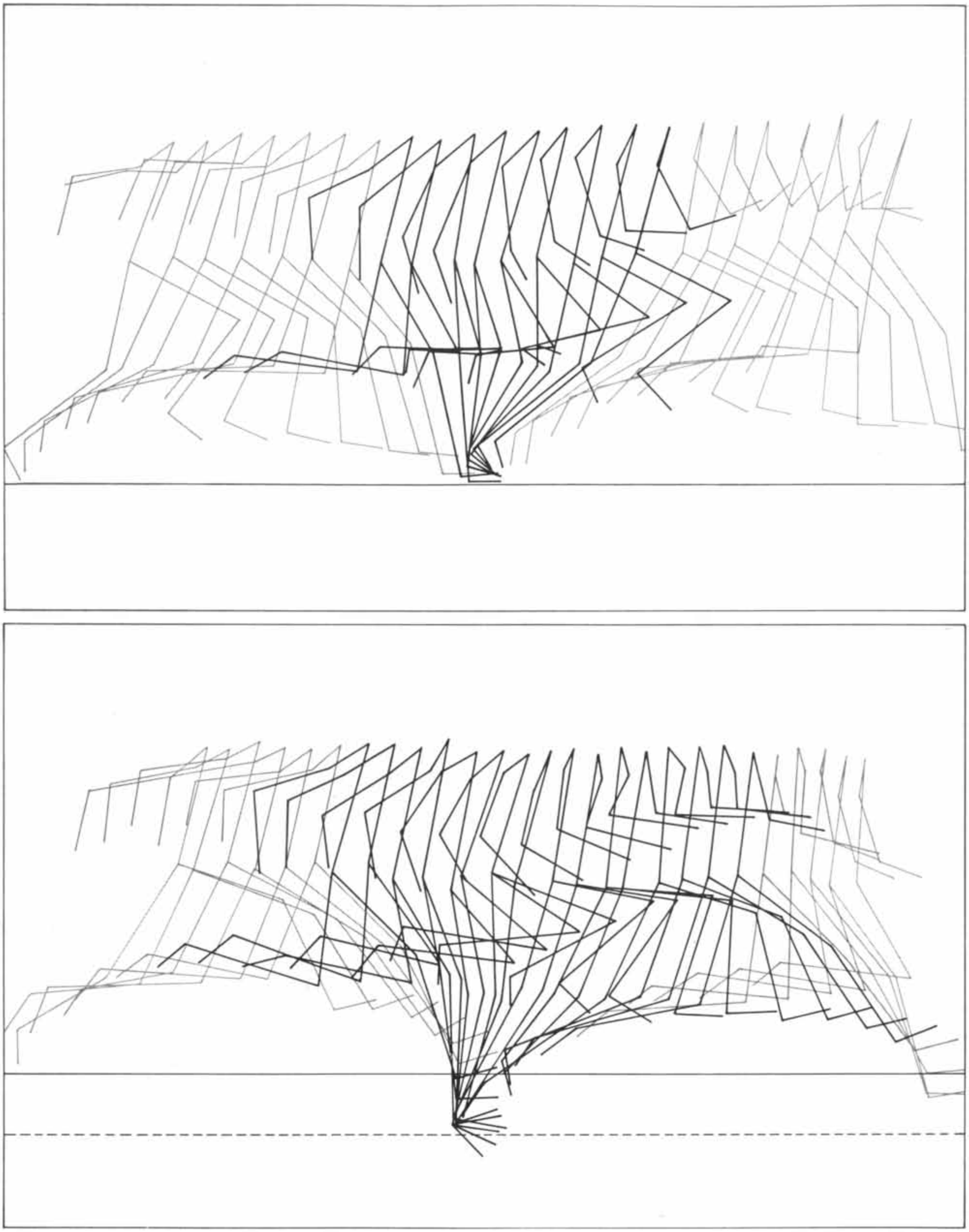
A tuned track is special only in that its properties are particularly compatible with those of the runner. Hence our first step in designing such a track was to develop a model of the mechanics of running, one that was complex enough to be realistic but simple enough to be mathematically manageable. Running speed is determined by several parameters. With the physiological simplifications introduced in the model it was possible to derive mathematical expressions for those parameters as functions of track stiffness. In this way we were able to predict the effect various track compliances would have on running speed. Our final step was to test the model predictions with runners and experimental tracks. The ultimate test was provided by the new Harvard track, whose wood substructure is designed to achieve a compliance in the range we found to be optimum. The results of these tests, which are discussed below, are in good agreement with the theoretical predictions.

Running is essentially a series of bounds. As the runner's foot strikes the running surface the antigravity muscles that support his skeleton contract and ultimately reverse the downward velocity of his body. To understand how our model was devised and why the tuned track works, it is necessary to understand how the physiological properties of these muscles and the reflexes that control them determine the functioning of the runner as a mechanical system.

Consider first an isolated muscle, removed from an animal and placed in an apparatus that measures its force at a constant length. With its blood supply cut off, a muscle from a mammal such as a rat will quickly fatigue and die, but in a suitably oxygenated bath a muscle from a small amphibian such as a frog will remain alive for hours or even days. A muscle that is not being stimulated to contract is said to be resting. When the force developed in the resting muscle is plotted against the length of the muscle, the force-length relation curves upward, that is, the force increases with length. The slope dF/dx of the force-length curve is the stiffness of the muscle, and the curve shows that it too increases with length. (Resting muscle is stiffer at greater lengths for the same reason a nylon stocking feels stiffer as it is stretched. As the muscle is lengthened more of the collagen fibers in the connective tissue associated with it become taut and begin bearing load.)

If a resting muscle is given a small electric shock, either directly or through the nerve that supplies it, the force in the muscle rises above the resting level and then quickly drops. This momentary rise in force, called a twitch, is the basic event in muscle contraction. In a sustained activity such as running, a train of twitches can merge at an elevated level of force; in this state the muscle is said to be tetanized. The force-length curve for tetanized muscle shows that, as in resting muscle, force increases with length. The same property is exhibited by a mechanical system: a coiled spring. It was this fact that suggested to us a model of running in which the muscles would be represented by springs.

The difference in force between tetanized muscle and resting muscle is termed developed tension. An important phenomenon having to do with developed tension is observed when tetanized muscle is placed in another type of apparatus: one in which the muscle is allowed to shorten and pick up a weight so that its shortening velocity can be determined. This experiment reveals that the shortening velocity does not increase throughout the shortening period; rather, after a brief starting period the mus-

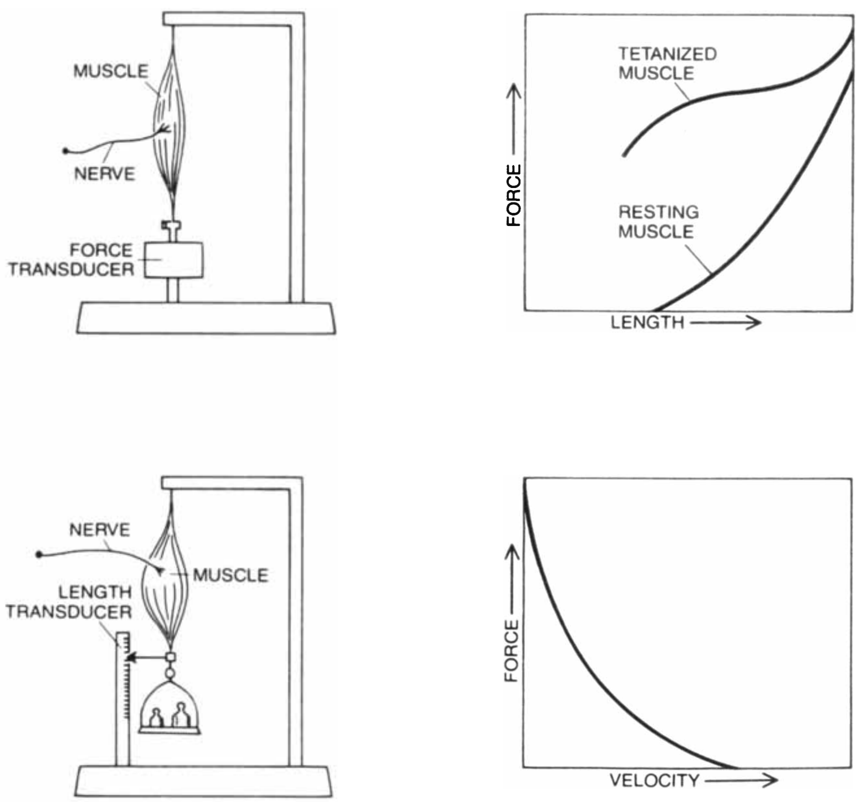


COMPUTER SEQUENCES showing running positions are obtained by digitizing the points marking a runner's major limb joints in a motion picture of running and then connecting those points on a digital plotter. In the sequences shown here the points mark the runner's right hip, shoulder, ear, elbow, wrist, knees, ankles and big toes. The same runner is shown on a hard, or stiff, surface (*top*) and on a soft, or springy, one (*bottom*). Running speed can be viewed as the ratio of the runner's step length (the distance the body travels while one foot is on the ground) to his ground-contact time (the time the foot is on the ground). The sequences show that a runner's step length and ground-contact time are both increased on a soft surface, with the net result that his running speed is decreased. A very hard surface, however, is not the fastest. The authors found that there is a range of intermediate track stiffnesses at which running speed is enhanced. The computer analysis for this illustration was performed in the Gait Analysis Laboratory of the Children's Hospital Medical Center in Boston.

cle shortens at a constant speed. When the shortening velocity is measured with different weights, it becomes apparent that muscle shortens more rapidly when it is working against lighter weights. It is as if a damping element—a dashpot, or shock absorber—were subtracting some of the developed tension. When the damping phenomenon was first discovered some 50 years ago, it was suggested that something like a mechanical dashpot was actually present in muscle, but it is now clear that the damping effect is a property of the force-generating mechanism itself, specifically of the interaction of actin and myosin, the contractile proteins of muscle.

Hence an isolated muscle shortening against a constant load behaves like a damped spring, or, more precisely, like a stretched spring acting in parallel with a dashpot. In the body, however, the functioning of the muscles is controlled by the nervous system. It is conceivable that under such conditions the spring-and-dashpot system might not apply. What we found is that with certain elaborations the model derived from the inherent properties of isolated muscles also describes muscles and reflexes as they function in the feedback control system of the body. (It should be noted that a mathematically linear spring, which has constant stiffness at any length, is utilized in the model, even though an isolated muscle acts as a mathematically nonlinear spring, which has variable stiffness. Recent experiments concerning reflexes, which we shall discuss, serve to justify this simplification.)

Muscle fibers receive their commands, or electrochemical stimuli, directly from the specialized nerve cells in the spinal cord called alpha motoneurons. The traffic of impulses along the axon, or long fiber, of an alpha motoneuron is efferent: it moves outward from the spinal cord and the rest of the central nervous system. Information comes back to the central nervous system along afferent pathways whose nerve-cell bodies are found in the dorsal-root ganglion: a swelling of the peripheral nerve just outside the spinal cord. The fibers of these nerve cells terminate in receptors that are specialized to respond most effectively to certain types of stimuli. Receptors in the loco-



MUSCLE REMOVED FROM THE BODY of a frog and held at constant length in an apparatus that measures force (*top*) develops more force at greater lengths, whether it is resting (engaged in minimal electrochemical activity) or tetanized (engaged in sustained electrochemical activity). A mechanical device that develops more force at greater lengths is a coiled spring. When the muscle is allowed to shorten and pick up a weight so that its shortening velocity can be measured (*bottom*), it is discovered that if the amount of force developed in the muscle (the weight lifted) is decreased, the shortening velocity is increased. The mechanical device that creates such a damping effect is a dashpot, or shock absorber. In the authors' mechanical model they represented muscles employed in running as spring connected in parallel with dashpot.

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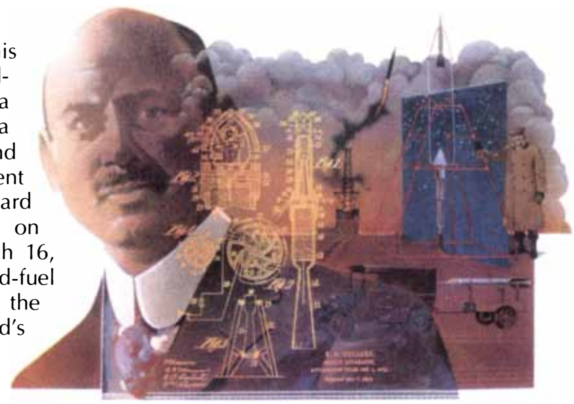

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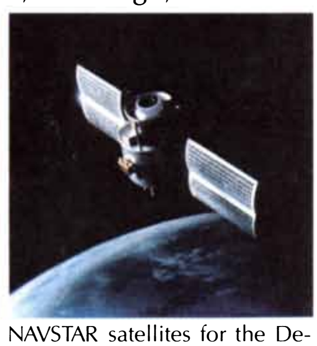

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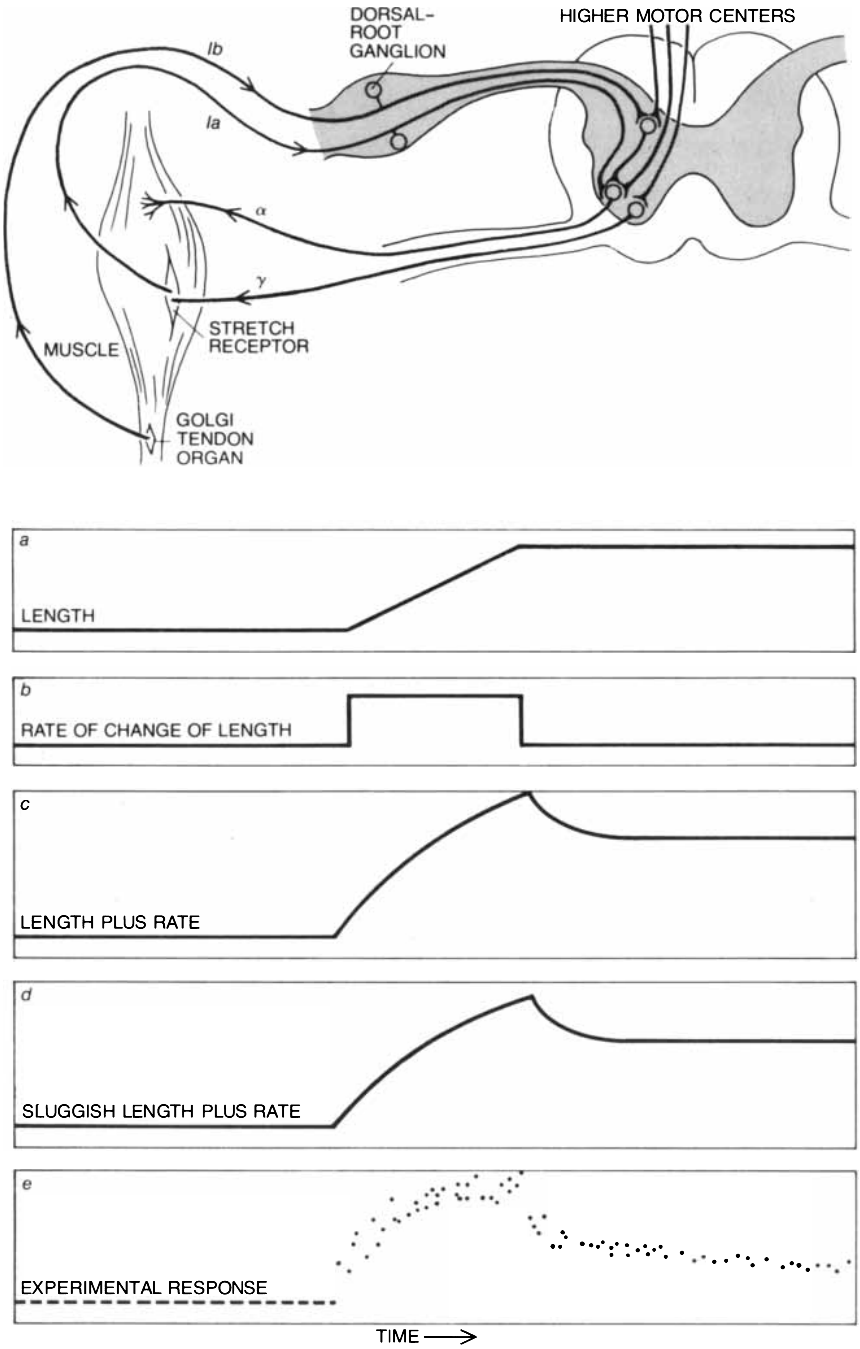

MUSCLES IN THE BODY are regulated by the feedback-control system of the reflexes: commands in the form of electrochemical impulses are sent to the muscles along the axon, or long fiber, of the specialized nerve cells in the spinal cord called alpha motoneurons; information about muscle activity is sent back to the central nervous system by stimulus-sensitive receptors. Impulses from the receptors travel along the fibers of nerve cells found in the part of the peripheral nervous system known as the dorsal-root ganglion. These pathways can be divided into two types: the *Ia* pathways innervate stretch receptors (*shown greatly enlarged here*), which are primarily sensitive to changes in muscle length, and the *Ib* pathways innervate the receptors called Golgi tendon organs (*also shown greatly enlarged*), which are primarily sensitive to changes in muscle force. The stretch receptors also act as muscles, innervated by the nerve cells called gamma motoneurons. In addition the stretch receptors are rate sensitive, that is, they are responsive to the rates of change in their stimuli. The rate sensitivity of the reflexes is another way the muscle system is damped. The graphs in the lower part of the illustration show how this phenomenon affects the stretch receptors called spindle organs. When a spindle organ is steadily lengthened starting from a resting position, the magnitude of its response is proportional not to the sum (*c*) of the "ramp" function representing the change of length (*a*) and the step function representing the change of rate (*b*) but to a damped, or sluggish, version of the sum (*d, e*). These findings suggest that dashpot introduced into the model of running to represent the force-velocity relation of muscle also serves to represent the rate sensitivity of reflexes. Graphs are adapted from work of Tristan D. M. Roberts of University of Glasgow.

motor system provide the central nervous system with the information that makes smooth movement possible. In control engineering the route from a receptor to the central nervous system over afferent pathways and from the central nervous system to an effector organ (such as a muscle) over efferent pathways is called a feedback loop; in physiology it is called a reflex arc.

For example, when a physician strikes the large tendon below a patient's kneecap with a hammer, he is testing the muscle-control system known as the stretch reflex. When the hammer strikes the tendon, the quadriceps group of muscles is stretched momentarily. As the muscles lengthen, stretch receptors in them (spindles) also lengthen and transmit a burst of impulses. This information travels along an afferent pathway to the quadriceps alpha motoneurons, eliciting the kick that tells the physician the patient's neuromuscular wiring is in good condition.

Two groups of afferent pathways designated *Ia* and *Ib* are the most important ones in the muscle-control system. The *Ia* pathways innervate the stretch receptors. Since stretch receptors are connected in parallel with muscles, they are primarily sensitive to muscle length. For example, in the stretch-reflex test an increase in the length of the quadriceps muscles sends information along an afferent *Ia* pathway. The *Ib* pathways innervate the receptors known as Golgi tendon organs, which are mainly sensitive to muscle force.

Stretch receptors respond to dynamic stimuli as well as static ones: they are sensitive to the rates of change in the strength of stimuli as well as to the changes themselves. In mechanical terms the stretch receptors encode and send back to the spinal cord not only position information but also velocity information.

Consider a spindle-organ receptor that is being steadily lengthened. The rate of change in length begins at zero, rises to a constant level and then falls back to zero when the lengthening stops. Experimental results show that the magnitude of the spindle response is proportional not to the sum of the "ramp" function representing the change in length and the step function representing the rate of change in length but to a sluggish version of the sum. The sluggishness is due partly to a property of all muscles, including spindles, known as series elasticity, and partly to the dashpot property of the receptors. In other words the sluggishness is an intrinsic property of the rate sensitivity of the reflex.

The spindle organ is itself composed of muscle cells and is separately innervated by the nerve cells called gamma motoneurons. Hence the length at which

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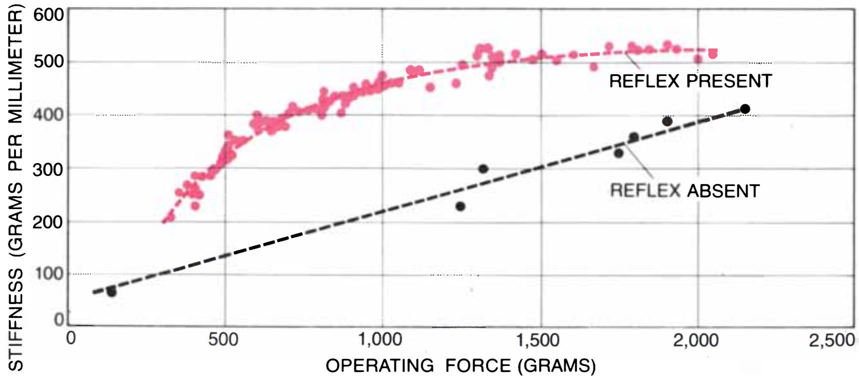
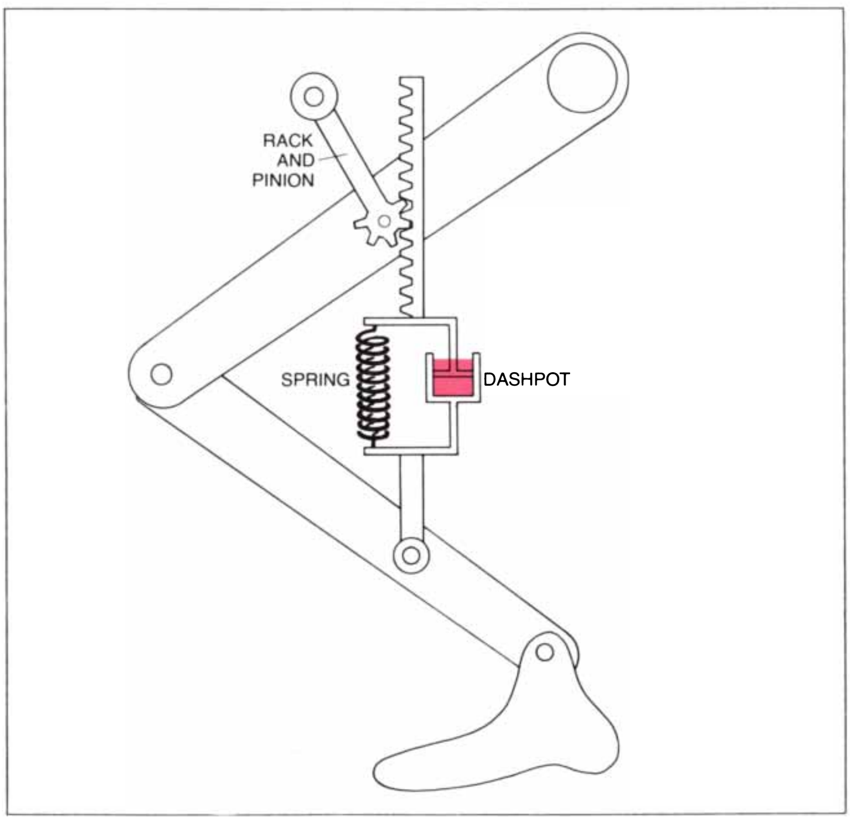


STIFFNESS OF AN ISOLATED MUSCLE (the change in the force developed by the muscle when it is stretched, divided by its change in length) increases as the muscle is stretched. Recent results indicate that in the body the reflexes maintain the stiffness of an actively contracting muscle at an almost constant level. J. A. Hoffer and S. Andreassen of the University of Alberta measured the increase in the stiffness of the cat soleus muscle (a plantar-flexor muscle in the ankle) as a function of force. When the pathways leading from the receptors back to the central nervous system were severed, the stiffness rose in proportion to the force exerted by the muscle (*broken black line*). With those pathways intact, however, the muscle stiffness was higher. (A closed-loop negative-feedback control system is always stiffer than an open-loop one.) After rising with low forces the stiffness reached a plateau at moderate and high forces (*broken color curve*). These findings suggest that spring, which has constant stiffness, is a suitable representation of the muscles involved in running, particularly in moderate-to-large range of forces.



MODEL OF THE MUSCLES AND REFLEXES involved in running consists of a rack-and-pinion element connected in series with a damped spring. The dashpot damping effect is created by a piston moving in a cylinder containing a viscous fluid such as oil (*color*). In the model the rack and pinion represents the role of movement commands from higher motor centers, the spring represents the muscle stiffness (assumed to be constant) and the dashpot represents both the force-velocity relation of muscle and the rate sensitivity of the reflexes. In other words, the setting up of leg positions is modeled by the motion of the rack and pinion, but the reaction to external force disturbances, such as the impact of the track on the contact leg, is modeled by the deflection of the damped spring. Hence the leg and hip positions at the beginning and end of the ground-contact phase, which determine step length, depend only on the movement of the rack and pinion, whereas the body motion during that phase, which determines ground-contact time, depends only on the deflection of the damped spring. With these simplifications, once runner's inherent spring stiffness and damping constants have been determined experimentally, effect of track stiffness on ground-contact time and step length can be calculated.

it sends a given intermediate frequency of impulses to the spinal cord can be changed by input from the higher motor centers. That makes the spindle organ a specialized type of strain gauge: a length-reporting device that converts mechanical stretch into nerve impulses, which in this case can be recalibrated to accommodate large-scale changes such as a change in the position of the body.

Consider again the stretch-reflex arc, where the final response to an imposed lengthening of muscle was the patient's kick reaction. Because the imposed muscle lengthening ultimately produced this muscle shortening, the reflex arc is a negative-feedback control system. Both the length and the rate of change of the length of the quadriceps muscles are reported along the *Ia* pathway as negative-feedback signals. Considering the mass of the leg, one can correctly predict that the normal overall response to the hammer blow will be a heavily damped, decaying oscillation of the knee angle, with the velocity feedback from the muscle giving rise to the damping effect. If the stretch receptor were sensitive only to muscle length, there would be no feedback damping, and in the absence of friction the oscillation would continue indefinitely.

What is the control function of the Golgi tendon organs, the group of receptors sensitive to muscle force? For many years it was believed their only role was to turn off the alpha-motoneuron activity and cause a muscle to relax whenever a critical muscle force, which might be capable of injuring the muscle, was exceeded. Newer evidence shows, however, that feedback from the Golgi tendon organs may also help to modify the stretch reflex in such a way that muscle stiffness, rather than muscle force or length, is the controlled property. J. A. Hoffer and S. Andreassen of the University of Alberta measured the increase in the overall stiffness of the plantar-flexor muscles in the ankle of the cat as a function of muscle force. In their first set of experiments the afferent pathways carrying information from the muscle spindles and Golgi tendon organs were intact. At low forces stiffness rose with force, but at moderate and large forces it reached a plateau. In their second set of experiments the afferent pathways were severed: the stiffness of the same muscles was always lower (because a closed-loop negative-feedback control system is always stiffer than an uncontrolled system), but it continued to increase no matter how much force was applied. In other words, through the regulation of the muscle spindles and Golgi tendon organs, muscle stiffness at all forces except very low ones was moderately independent of muscle force.

We were able to get similar results with the reflexes controlling the antigravity muscles of the human leg. In our experiments weight lifters bearing

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loads of up to twice their body weight on their shoulders executed small bouncing motions on a long plank. The subjects kept their knees bent to the extent they would in running. Knowing the total mass of the subject and the weight (and therefore the force exerted on the muscles), the effective mass of the plank and the natural frequency of vibration, we could use a simple mathematical procedure to calculate the stiffness of the subjects. We found that at knee-flexion angles in the range appropriate for running, the controlled, or reflex, stiffness is virtually independent of load and consequently of muscle force.

The observation that the reflexes maintain muscle stiffness at an almost constant level turns out to have considerable practical value. Remember that the problem with using a mathematically linear spring to represent the muscles involved in running was that the spring has constant stiffness and the muscles do not. The results of the experiments imply that the change in muscle stiffness with muscle force observed in experiments with isolated muscles can be ignored. Actually during the first quarter or so of the ground-contact period in a running step the reflexes have not had time to act, and so the intrinsic properties of the muscles alone determine the stiffness and damping of the leg. In the second half of the contact period, however, the stiffness and damping are almost certainly under reflex control and therefore are reasonably well represented by a damped linear spring.

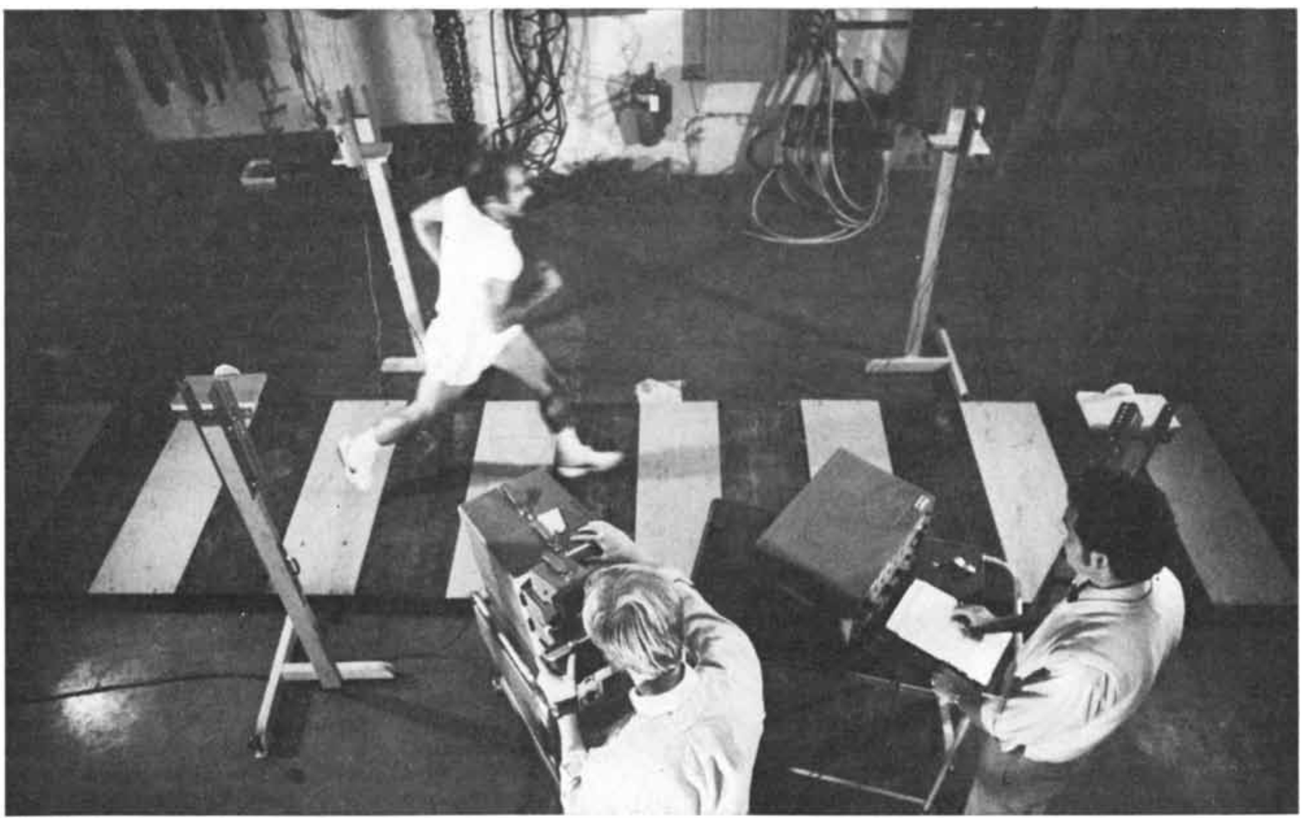
We are now able to complete our model of the mechanics of running. We shall view the muscles and reflexes of the leg as a system consisting of a rack-and-pinion element acting in series with a damped spring [*see bottom illustration on page 154*]. The rack-and-pinion element is included to emphasize the role of movement commands descending from higher motor centers; the spring represents the assumed constant stiffness of the muscles and reflexes, and the dashpot damping mechanism represents the intrinsic force-velocity property of the muscles and the rate sensitivity of the reflexes. In other words, the setting up of leg positions is modeled by the motion of the rack and pinion, and the effect of external force disturbances such as the impact of the track on the runner's leg is modeled by the deflection of the damped spring. As we shall now show, the simplifications introduced by the model make it possible to calculate a runner's speed on a track of arbitrary compliance with only a few items of information: the runner's mass, the length of his leg, his spring stiffness and his step length and top running speed on a hard surface.

What value of track compliance—if any—will optimize running speed? For our purposes the most useful way to measure running speed is as the ratio of step length (the distance the body moves forward while one foot is on the ground) to ground-contact time (the time the foot is on the ground). On a tuned track the ground-contact time should be minimized and the step length should be maximized. In the model it is primarily the runner's mass and the motion of the damped spring that determine the body motion during the ground-contact phase and therefore the ground-contact time; it is the motion of the rack-and-pinion element that determines the leg and hip positions at the beginning and end of the ground-contact phase and therefore the step length.

Consider first the relation of track stiffness to ground-contact time. To derive an expression for ground-contact time as a function of track stiffness it is necessary to assign to a runner a spring stiffness and also to determine the extent to which the combined effects of the force-velocity relation and the velocity feedback from the reflexes act to damp his spring. We observed that once a runner's muscles have guided his foot into contact with the ground their most important role is to contract as forcefully and as soon as they can in order to reverse the downward velocity of the body. For this reason we chose to make the somewhat arbitrary assumption that the rack and pinion cannot be disturbed by external forces while the foot is on the ground, so that the ground-contact time on a hard surface depends entirely on the runner's mass and the properties of the damped spring. Hence the numerical values denoting the runner's spring stiffness and damping can be derived from the measurement of his ground-contact time when he is running on a hard surface. (The matter is complicated by the fact that a runner's spring stiffness is affected by his effort. Muscle strength varies greatly among runners, and the stronger a runner is, the more muscle fibers he can recruit in parallel and the stiffer his spring is. For this reason we chose to determine a runner's spring stiffness by measuring his ground-contact time as he was running at top speed on a hard surface.)

Once a runner's stiffness and damping constants have been determined it is a straightforward matter to calculate how his ground-contact time is changed on tracks of various stiffnesses. This result was the most important in predicting the effect of track stiffness on running speed. It can be assumed the runner is tuned to the track so that he rebounds from it in half a period of the lowest natural mode of vibration. As intuition suggests, the calculations show that the ground-contact time on soft surfaces is long. If there were no damping element in the spring of human muscle, the ground-contact time would decrease continuously from that value as track compliance decreases, reaching a minimum at the compliance of infinitely hard surfaces. In that case a running surface such as concrete would be the fastest. Our findings show, however, that the ground-contact time does not decrease over the entire range of compliances. Since the runner is a damped system, his ground-contact time reaches a minimum at an intermediate compliance; at a track stiffness between two and four times greater than the runner's the ground-contact time is shorter than it is on harder surfaces. Therefore on tracks of precisely the right stiffness enhanced speeds should be possible.

To check these results we built several test tracks, ranging from wood tracks with an adjustable compliance to pillows or large foam-rubber blocks laid end to end. Test subjects were not given any information concerning our expectations. They were simply instructed to run at top speed, first on an experimental track and then on the concrete



MODEL RESULTS WERE TESTED with runners on tracks of various degrees of stiffness. In the experimental setup shown here a force platform under one of the panels of the track (not visible) records the beginning and end of a ground-contact phase. The results are plotted on the oscilloscope shown at the bottom of the photograph. Running speed is recorded with the electronic timer at the lower right and the two pairs of timing lights arranged on each side of the track. (The lights are placed at the level of the runner's neck to avoid the triggering of false timing readings by the runner's arms and legs.) The running trials were also recorded on high-speed motion-picture film.

RUNNING FILMS show that whether a runner is on a fairly stiff wood track (*top*) or on a soft pillow track (*bottom*) the trajectory of his head is nearly level. Therefore for the purposes of the model it can be assumed that the hip follows a level path no matter what surface runner is on. Assumption simplifies calculation of effect of track stiffness on the step length (*see bottom illustration on opposite page*).

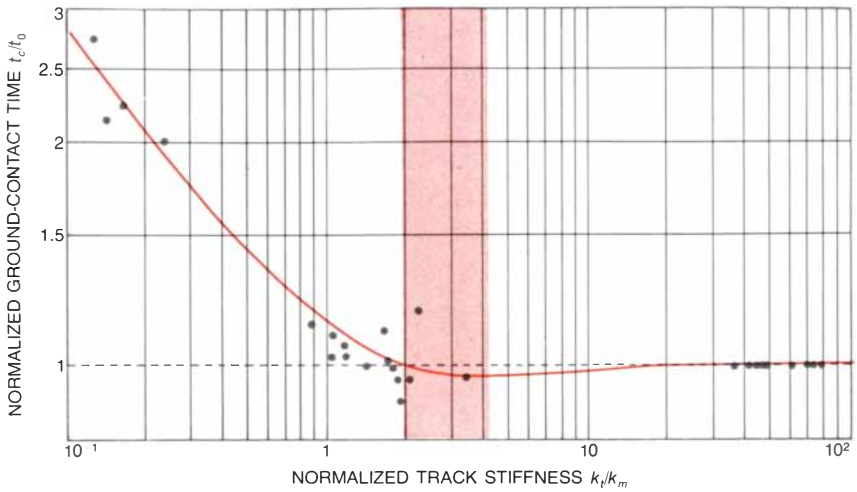
floor beside it. The trials were recorded with motion-picture cameras in order to measure the ground-contact time. Photoelectric timers and a precision force platform were also used. On all the tracks the measurements agreed well with the model predictions.

Running speed is not entirely determined by ground-contact time, however; step length is also an important factor. Remember that step length is the distance traveled while the foot is on the ground, as opposed to the distance between footprints, which is stride length. We noticed that as our subjects ran on the more compliant experimental tracks, such as the one consisting of foam-rubber blocks, their step length was greater. The explanation of this phenomenon has to do with the position of the contact leg at the beginning and the end of the contact phase. At those points the leg is fully extended, and it can be assumed there are no loads acting on the spring, that is, the geometry of the leg as it strikes the ground depends solely on the rack-and-pinion element.

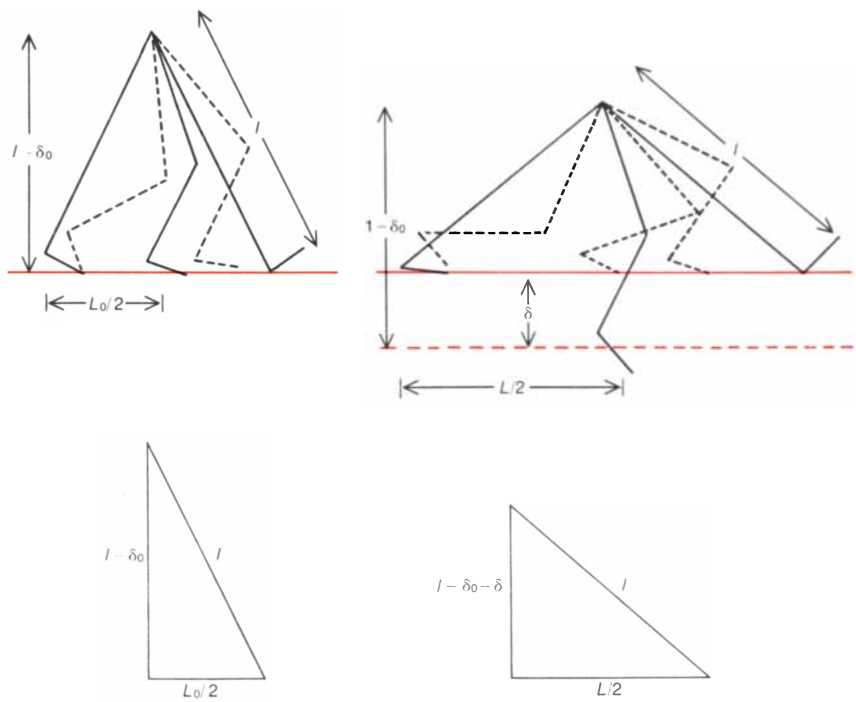
For our investigations of the rack-and-pinion motion we made another assumption based on a feature we observed in the running films. No matter how hard or soft the running surface was, the trajectory of each runner's head was nearly level, as if his postural controllers were trying to give the accelera-tion-sensing mechanism of the inner ear a smooth ride. In any case it is certain that at the frequency in question, with the modest value of the acceleration due to gravity and the short time between footfalls, the vertical motion of the body's center of mass cannot be great. Hence we chose to assume that the hip follows a level path whether the runner is on a hard surface or a soft one.

The step length on a track of arbitrary compliance can be calculated as follows. In each running step one of the runner's legs makes contact with the ground as the other swings over the running surface. As the swing leg moves forward it stays above the undeflected surface of the track, whether the track is hard or soft. On a hard track the contact leg also stays above the surface. On a soft track, however, the contact leg sinks below the surface. Therefore it is necessary to visualize the runner moving across a hypothetical surface a distance δ below the undeflected one, where δ is the average track deflection over a complete stride cycle. (The stride cycle includes not only the ground-contact phase but also the aerial phase; if the runner were standing motionless on the compliant track, he would be standing in a well of depth δ.)

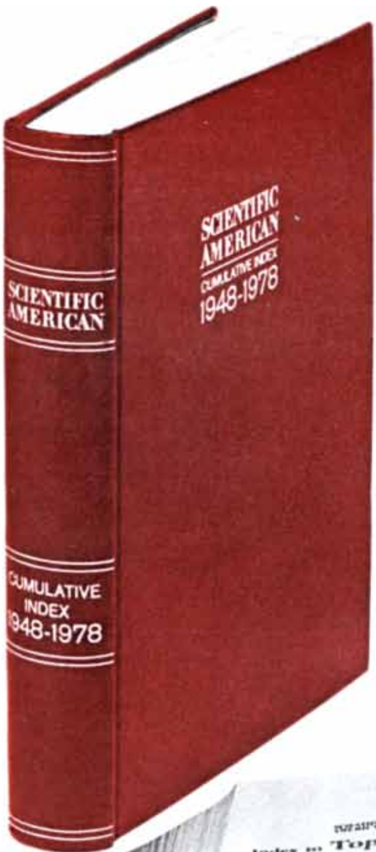
At the beginning (and end) of the contact phase the runner's contact leg is fully extended, and we shall call the full hip-to-heel length l. At mid-stance,



GROUND-CONTACT TIME can be derived from the model as a function of track stiffness. In this graph of the function, normalized, or dimensionless, values of each parameter have been used so that theoretical results (*curve*) can be compared with experimental findings for many runners (*black dots*). Ground-contact time has been normalized by dividing the time on a compliant surface t_c by the time on a hard surface t_0; track stiffness has been normalized by dividing the track stiffness k_t by the runner's stiffness k_m. Because of the damping of human muscle ground-contact time does not decrease continuously as track stiffness increases but reaches minimum at stiffnesses between two and four times that of average athelete (*color*).

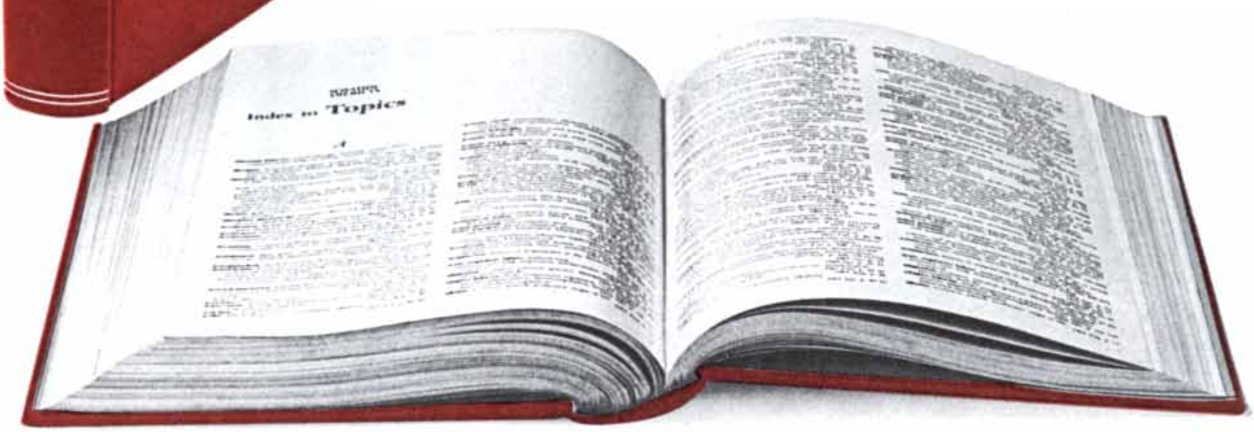


STEP LENGTH IS LONGER on a compliant surface (*right*) than on a hard one (*left*) because the bending angle of the hip joint is greater, as is shown by these schematic representations of a runner on the two surfaces. At the beginning and end of either running step the contact leg (*solid black line*) is fully extended, with length l. After heel contact (*leg position farthest to the right*) the contact leg moves back (to the left) as the swing leg moves forward. At mid-stance, when the body has traveled a distance of half a step length, the contact leg is flexed, that is, shortened by a distance of δ_0, which is taken to be independent of the track compliance. Hence on a hard surface, which has step length L_0, the distance from the hip to the track surface is $l - \delta_0$. On a compliant surface, however, the flexed contact leg sinks below the undeflected track surface (*solid color line*). It is as if the runner were moving across a hypothetical surface (*broken color line*) a distance δ below the undeflected surface, where δ depends on the compliance of the track and the mass of the runner. Therefore the distance from the hip to the undeflected surface on a compliant track is $l - \delta_0 - \delta$. The right triangles below each figure in the illustration show how these factors result in a greater step length L on a compliant surface. Since the distance δ is equal to the runner's weight divided by the track stiffness, and since L_0 and l can be measured directly, the step length on a track of arbitrary stiffness can be calculated by applying Pythagorean theorem to the two triangles (*see illustration on page 162*).



An advance announcement of the new SCIENTIFIC AMERICAN CUMULATIVE INDEX MAY 1948-JUNE 1978

This November the Editors of SCIENTIFIC AMERICAN will publish a Cumulative Index to the 362 issues of the magazine from May 1948 through June 1978. This new Index embraces all the issues published under the present editorial direction, recording 30 momentous years of intellectual history.



An encyclopedia of science

For libraries, scholars, scientists, engineers and all who have an active concern in the work of science the Index will prove a productive research and reference tool. It will multiply many times the value and the usefulness of the collected issues of the magazine. Indeed, the Index will transform these issues into an encyclopedia of the work of science in the last three decades.

The Index consists of these eight independent parts:

Index to Topics
A rotated key word index that offers access to the subject matter of all articles and Science and the Citizen items (*see facing page*).

Index to Proper Names
The names of all persons mentioned in the articles or Science and the Citizen items and of places and institutions featured in a primary role.

Listing of Tables of Contents
A chronological listing of the contents of all 362 issues that permits ready identification, by titles and authors, of the articles cited in the two foregoing indexes.

Index to Authors
An alphabetical listing of all authors of articles.

Index to Titles
An alphabetical listing of all articles by the first key word in the title and by the other key words in the title.

Index to Book Reviews
A listing of the longer book reviews in three parts: authors of books reviewed, titles of the books and reviewers.

Index to Mathematical Games
A listing of the puzzles, games and diversions presented in this department since its inception in January 1957, under the editorship of Martin Gardner.

Index to The Amateur Scientist
A listing of the projects, experiments and demonstrations presented in this department from April 1952 through February 1976 under the editorship of the late C. L. Stong and from July 1977 through June 1978 under the editorship of Jearl Walker.

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How the Index to Topics provides direct access to subject matter of 362 issues of SCIENTIFIC AMERICAN...and how to use it.

The Index to Topics is a rotated key-word index. That is: The topics cited in a given article are entered together in a cluster:

DNA, genetics, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

Each of these "key words" takes its turn as the first term in the cluster in its entry and re-entry down through the alphabet of the Index to Topics:

DNA, genetics, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

genetics, DNA, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

molecular structure, DNA, genetics, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

x-ray crystallography, DNA, genetics, molecular structure, DNA double helix resolved 1954 Oct. p. 54-61 [5]

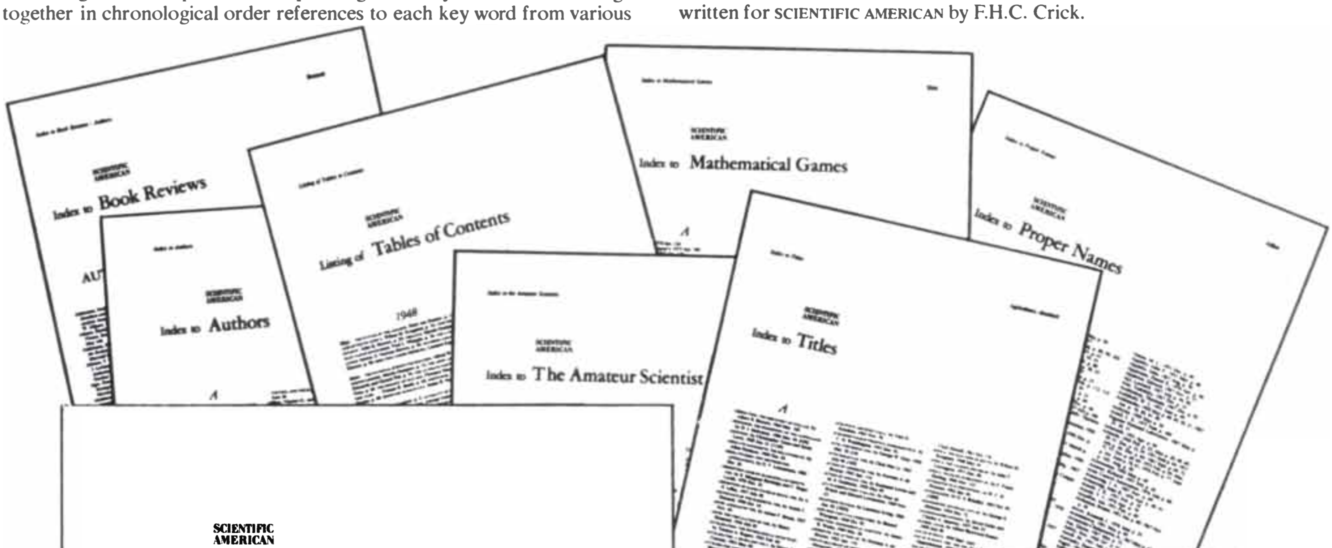
In most cases, a secondary citation, highlighting some aspect of the article, rides along with the rotating primary citations (In the example above: DNA double helix resolved). Each entry serves, therefore, as a "miniabstract" of the original. The alphabetical sequencing of the key words, in turn, brings together in chronological order references to each key word from various issues of the magazine. A portion of the grouping of clusters for "x-ray crystallography" follows:

x-ray crystallography, DNA, genetics, molecular structure, DNA double helix resolved 1954 Oct. p. 54-61 [5]
amino acids, myoglobin, proteins, 3-D structure of protein molecule 1961 Dec. p. 96-110 [121]
crystal structure, solid state, semiconductors 1962 Dec. p. 39-48 [249]
Bragg's law, crystal structure, diffraction, fourier series 1968 July p. 58-70 [325]
photoelectric effect, x-ray absorption 1976 Apr. p. 96-103

Articles are referenced by first and last page numbers. Thus, the entry for x-ray crystallography informs the reader that first appearance of the term is in the October 1954 issue, pages 54-61. Reference to the Listing of Tables of Contents discloses that the article is "The Structure of the Hereditary Material" by F.H.C. Crick.

References to about one-third of the articles close with a bracketed number. This is the offprint number and identifies articles republished as offprints. Thus, the Crick article in the example is identified as Offprint #5.

Reference to the Index to Authors will disclose, as well, all of the articles written for SCIENTIFIC AMERICAN by F.H.C. Crick.




SCIENTIFIC AMERICAN CUMULATIVE INDEX MAY 1948-JUNE 1978

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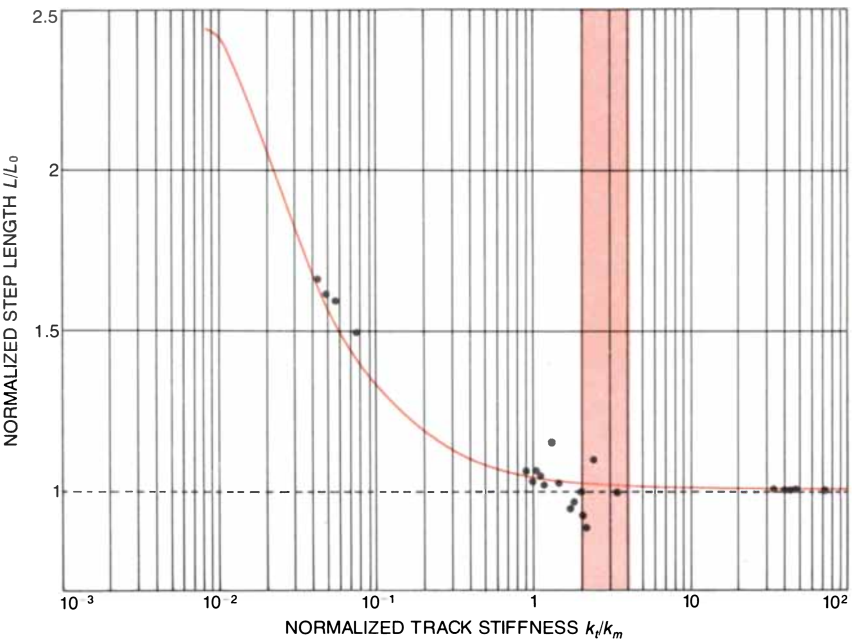


MODEL PREDICTIONS of the effect of track stiffness on step length (*curve*) are in close agreement with experimental findings (*black dots*). Step length is greatest on softer surfaces, where ground-contact time is also greatest. In the range of stiffnesses where ground-contact time is minimized and therefore optimum with respect to running speed (*color*) step length is still slightly increased over its hard-surface value. Hence in that range, and particularly in the low end of the range, running speed is enhanced. (In the graph step length has been normalized by dividing step length L on a surface of arbitrary stiffness by step length L_0 on a hard surface; track stiffness has been normalized by dividing track stiffness k_t by runner's stiffness k_m.)

when a distance of half a step has been traveled, the contact leg is flexed, shortened by, say, a length of δ_0 on a hard track, so that the distance between the hip and the hard-track surface is $l - \delta_0$. Assuming that the hip follows a level path, this situation is described by a right triangle with hypotenuse l and sides $l - \delta_0$ and $L_0/2$, where L_0 is the step length on a hard surface. On a compliant track, however, the comparable triangle has sides l, $L/2$ and $l - \delta_0 - \delta$, where L is the step length and $l - \delta_0 - \delta$ is the distance from the hip to the undeflected track surface. The average deflection δ is determined by two measurable quantities: the runner's body weight and the track stiffness. The leg length l and the step length on a hard track L_0 can be measured directly. Hence by applying the Pythagorean theorem to the two triangles it is a simple matter to calculate what a runner's step length will be on a track of arbitrary stiffness.

We found that the model predictions agreed well with our experimental measurements of step length on compliant surfaces. Just as we had calculated, the foam-rubber blocks increased a subject's step length by approximately 50 percent, partly compensating for the more than 100 percent increase in ground-contact time with the same surface. The net effect was that the runners were slowed to only about 70 percent of their hard-surface speed; if their step length had stayed constant on the foam rubber, they would have been slowed to about 50 percent of that speed.

Thus step length is most increased (a desirable effect) in the range of track compliances where ground-contact time is increased (an undesirable effect). It turns out, however, that in the range of compliances that are optimum with respect to ground-contact time, step length is still slightly increased over its hard-surface value. Therefore in this range of compliances—at a stiffness slightly more than twice the stiffness of the runner—the two factors determining running speed come together in an optimum way. Our model results showed that on tracks in this range of compliances the combined effect of decreased ground-contact time and increased step length should lead to a speed enhancement of between 2 and 3 percent.

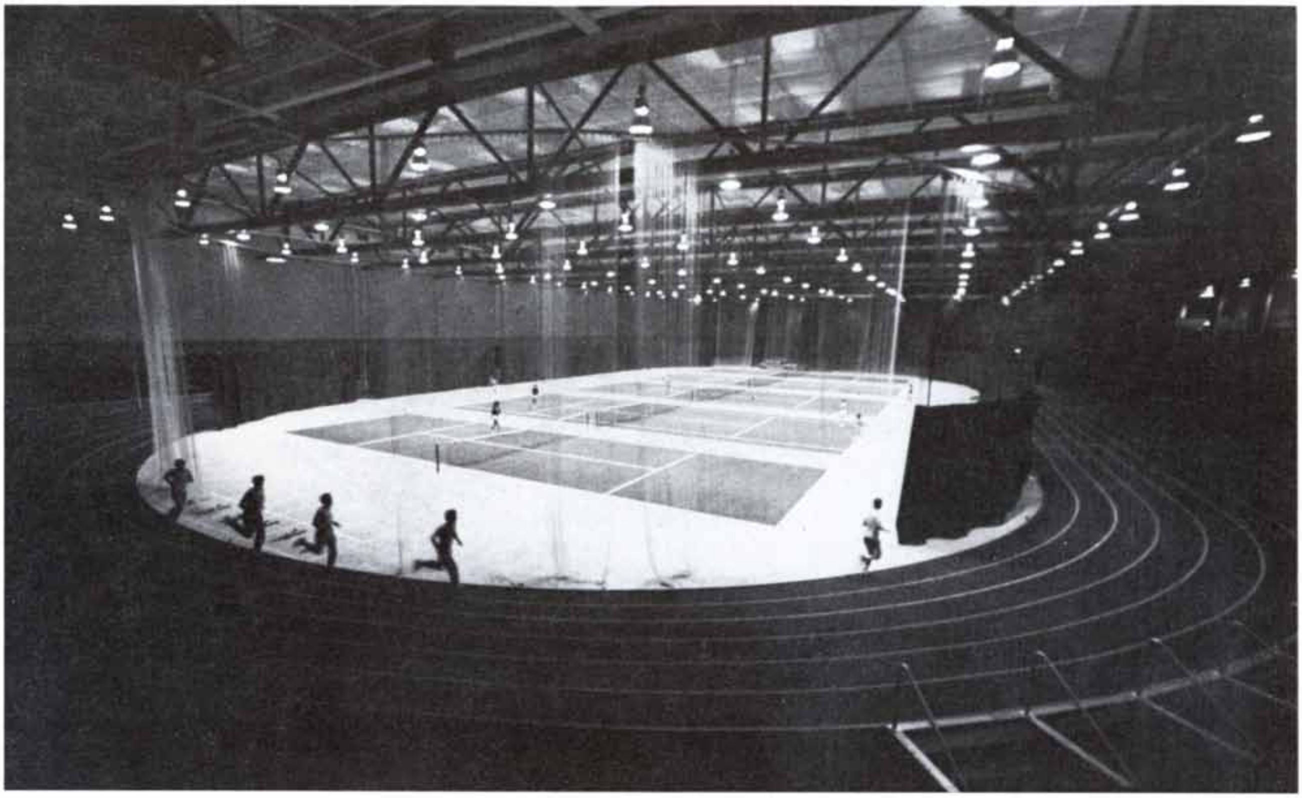
At the end of the 1977–78 track season, the first season the track was in service, we compared the overall performance of members of the Harvard track team on the new track with their performance at the Intercollegiate Amateur Athletic Association of America championships held at Princeton University and the Heptagonal championships held at Cornell University. The Princeton and Cornell tracks are almost identical with the new Harvard track in size, but both of those tracks have a hard substructure with a synthetic top surface. (The Harvard track is also the only one of the three with banked turns. There is disagreement over the value of this feature of track design: banked turns increase the comfort and safety of running at high speeds, but they work to the disadvantage of runners moving at speeds lower than those for which the banking was designed: a fast quarter-mile.)

The analysis of the track records leaves little doubt about the effects of the tuned track. Although the two meets away from Harvard were championships, where runners are challenged to make their best showing, every Harvard runner except one ran his best time of the year on the new Harvard track. The runners' average speed advantage on the new track was 2.91 percent, which is in close agreement with the predictions derived from our model. In the preceding year the team ran an average .26 percent slower at home (on a cinder track) than they did away, and so it seems unlikely that these statistics reflect a home advantage. Moreover, similar statistics on 11 of the top runners from four other institutions show that they experienced the same kind of improvement, running an average of 2.12 percent faster on the new Harvard track than they did at the championships.

In the same season an individual Harvard runner's best time on the new track was an average of 3.87 percent faster than his best time off it and an average 2.04 percent faster than his best time of the preceding season. In terms of competition, however, the real advantage of a properly tuned track is probably not its speed enhancement; after all, the opposing teams run faster on it too. It is the comfort and safety of a tuned track that gives the home team an edge, enabling them to train much harder than they could on an ordinary track. A coach who can train ambitiously without fear of injuring his runners during practice can build a better team. Far fewer runners have been injured on the new track, although the Harvard team trained very hard last year.

In view of the discussion so far it may come as a surprise that no one expects a world record to be set on the Harvard track. That is because the International Amateur Athletic Federation does not recognize records for indoor running. Indoor tracks must usually be fitted into existing structures and so there is little standardization of design; for example, the length of such tracks and the radii of their turns vary greatly. Hence official world records can be set only on outdoor tracks.

No outdoor track of the optimum mechanical design has yet been built. If such a track is built, we predict that the world record for the mile could be improved by as much as seven seconds. The opportunity stands as a challenge.



INDOOR TRACK AND TENNIS FACILITY at Harvard University opened in October of last year. Its six-lane 220-yard track features banked turns, a polyurethane top surface and a substructure made primarily of wood. The substructure is designed to convey a stiffness between two and three times the stiffness of an average athlete. Stiffness is in the low end of the range authors found to be optimum with respect to running speed. Facility was designed and built by T.A.C., Inc., and the Turner Construction Company of Boston.

		1977–78 SEASON			1976–77 SEASON		
EVENT	RUNNER	AVERAGE TIME AT HOME/ NUMBER OF MEETS	AVERAGE TIME AWAY/ NUMBER OF MEETS	SPEED ADVANTAGE AT HOME (PERCENT)	AVERAGE TIME AT HOME/ NUMBER OF MEETS	AVERAGE TIME AWAY/ NUMBER OF MEETS	SPEED ADVANTAGE AT HOME (PERCENT)
	EICHNER	9:05.56/4	9:32.5/1	4.9	9:29.0/3	9:28.0/2	−0.2
	MEYER	9:18.7/6	9:36.5/2	3.2			
TWO MILE	FITZSIMMONS				9:02.5/2	9:12.5/4	1.8
	DUNN				9:20.7/1	9:28.3/3	1.4
	SHEEHAN				9:25.2/1	9:33.4/1	1.4
	EICHNER	4:13.4/3			4:21.35/2	4:17.93/3	−1.3
ONE MILE	McNULTY	4:11.56/7	4:08.74/2	−1.1			
	CAMPBELL				4:15.0/2	4:12.5/3	−1.0
	FINN				4:26.4/1	4:24.8/3	−0.6
	CHAFEE	2:15.95/2			2:15.3/1	2:15.4/2	
1,000 YARDS	DOLSON	2:14.58/5	2:18.1/1	2.6	2:16.0/1	2:15.5/1	
	CAMPBELL				2:15.3/1	2:13.78/4	−1.1
	CHAFEE	1:54.92/6	1:56.43/2	1.3			
880 YARDS	DOLSON	1:55.14/2	1:57.33/1	1.9			
	SELLERS	1:57.94/6	2.01.1/1	2.7			
600 YARDS	SCHMIDT				1:13.8/2	1:13.4/4	−0.6
	SELLERS				1:19.3/2	1:17.4/1	−2.5
	LAMPPA	50.46/7	51.7/1	2.5			
440 YARDS	NICODEMUS	50.36/7	53.3/1	5.8			
	SCHMIDT	48.93/2	51.5/1	5.3			
				AVERAGE 2.91%			AVERAGE −0.26%

HARVARD TEAM'S TRACK RECORDS for the first season on the new track (*color*) show that the track substantially enhances running performance. Each Harvard runner's performance on the new track is compared with his performance at the Intercollegiate Athletic Association of America and the Heptagonal meets, which were run on standard tracks. The new track conveyed an average speed advantage of nearly 3 percent. Further analysis of these statistics shows the probability is about 93 percent that any given individual will run faster on the new track. Similar statistics are given for preceding year (*white*), when Harvard team's home meets were run on cinder track.

Gaseous Nebulas

These spectacular clouds within our galaxy are sites of star formation. Radio spectroscopy indicates, among other things, that the clouds belong to much larger systems of gas and dust

by Eric J. Chaisson

Astrophysicists generally agree on the broad outlines of a theory of star formation. Briefly, a star is born as follows. In the beginning a cool, diffuse cloud of gas and dust fills a huge region of interstellar space. Within the cloud a few atoms happen to come together, at first by accident. Provided that their combined gravitational force is greater than any countervailing forces, they begin to attract other atoms in the vicinity. In time the continuing action of gravity forms a dense concentration of matter and proceeds to compress it further. Frictional heating then causes the temperature of the gravitationally compressed gas to rise. After a few million years the gas reaches a critical temperature of about 10 million degrees Kelvin, at which point hydrogen nuclei begin to fuse in the core of the nascent star. The release of enormous amounts of thermonuclear energy from the "burning" hydrogen halts the gravitational collapse of the star, which thereafter radiates energy from its surface into space in the form of electromagnetic waves, including those of visible light.

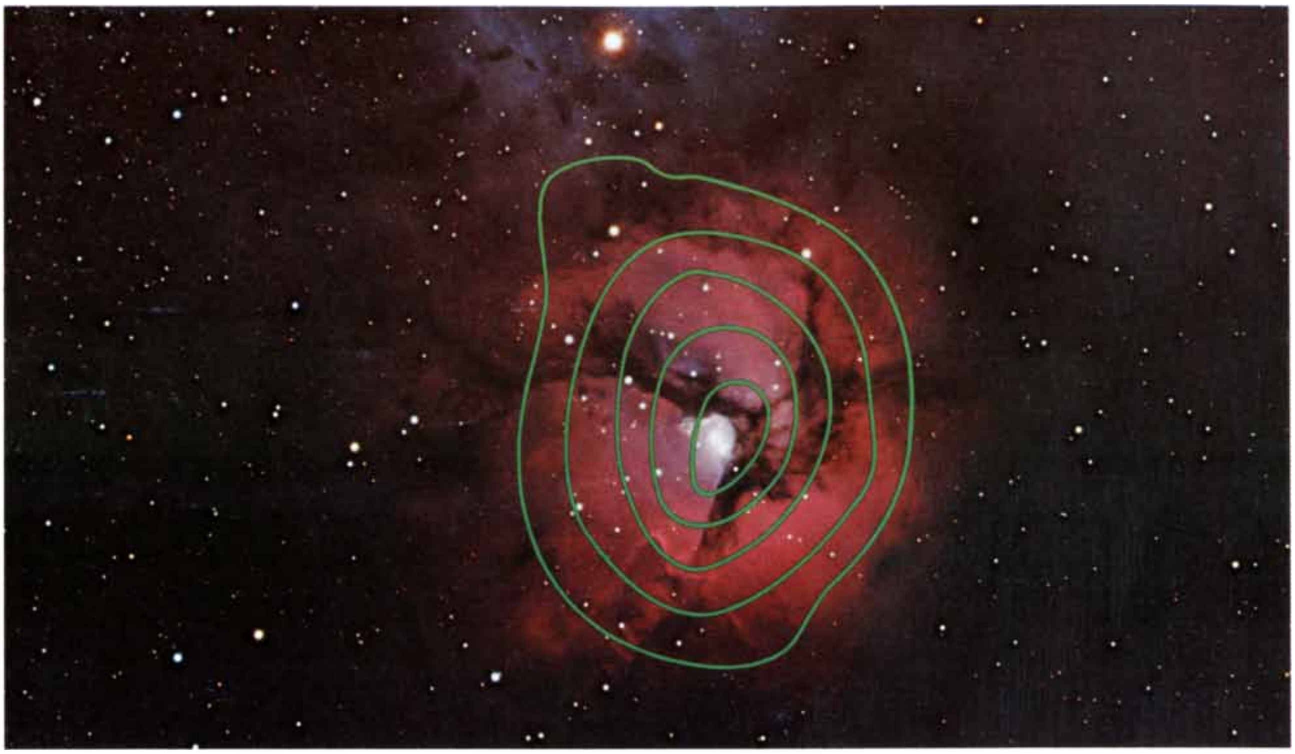
In spite of the almost universal acceptance of the foregoing scenario, it has until recently received little observational support. A few years ago a number of astronomical observatories undertook programs designed to examine regions of space thought to be conducive to star formation. Attention was directed initially toward the gaseous nebulas and later toward their surrounding interstellar environment. These visually spectacular parts of the galaxy are rich in gas and dust, and they are known to contain comparatively young stars (some no more than a few million years old). Yet places where such young stars and even more primitive protostars coexist often tend to be quite dusty and hence dark; they are hidden either partly or totally from the view of astronomers working with optical telescopes, because of the efficient scattering of light waves by the intervening dust. Fortunately radio waves penetrate such interstellar debris far more readily, making them superior to light waves for probing the interior of either partly obscured gaseous nebulas or totally obscured dark galactic clouds. I shall review here some interesting radio-wave observations made in recent years of a representative selection of gaseous nebulas and their interstellar environments. Such investigations may well furnish the key to a surer understanding of the process of star formation.

A gaseous nebula is a more or less spherical volume of plasma, or ionized gas, surrounding a very hot star or cluster of stars, each of which has an effective surface temperature in excess of 30,000 degrees K. Such blue-white stars are much hotter than our own star, the sun, which has a surface temperature of only about 6,000 degrees. Hot stars of the former type emit copious amounts of ultraviolet radiation, which is capable of interacting with the surrounding matter. Of all the photons of electromagnetic radiation emitted by such a star only an ultraviolet, or comparatively high-frequency, photon has more energy than that necessary to bind an electron to its parent nucleus. As a result the absorption of ultraviolet radiation by neutral, or un-ionized, atoms causes electrons to be stripped from their nuclei, creating a near-perfect plasma around the central star or stars. The energy released by the interaction of an ultraviolet photon and an atom is imparted as kinetic energy to the liberated electron, which is then free to wander about in the ionized gas. The behavior of these unbound electrons, called photoelectrons, is critical to the observation of the nebula. They can manifest their presence in three different ways.

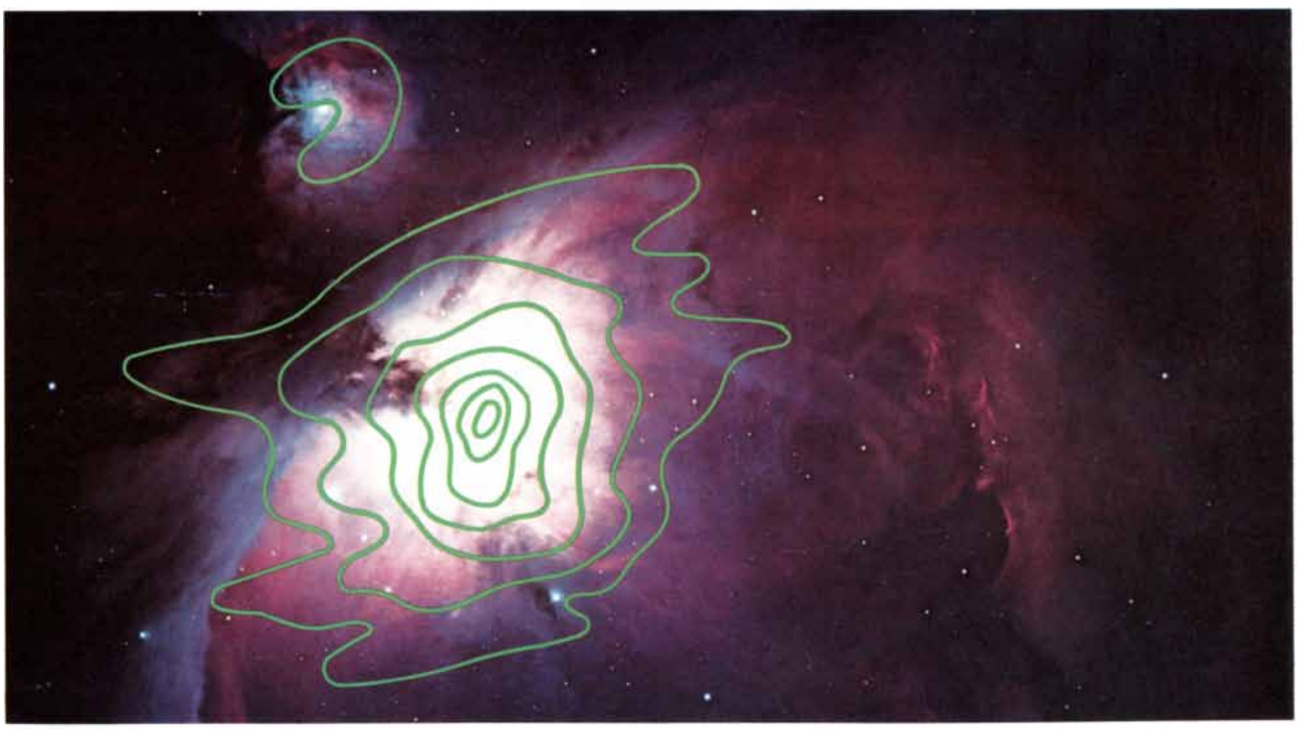
First, after several hundred years of wandering, a free electron eventually comes close enough to a nucleus (usually a hydrogen nucleus, or single proton) to be recaptured, making a neutral atom again. As the process of recombination begins, the electron generally enters the bound atomic system in an upper, excited state, decaying to lower energy levels at an average rate of about one level per second, thereby reaching the ground state, or lowest energy level, rather quickly. During the successive stages of recombination photons are emitted at specific frequencies characteristic of the atom's structure. Low-level transitions (those involving the first few principal quantum states of the atom) are responsible for the familiar hydrogen and helium emission lines that appear in optical spectrograms of stellar objects. Transitions between higher adjacent energy levels of the same elements give rise to longer radio waves, which can also escape the nebula and be analyzed spectroscopically.

Second, unbound electrons often collide with atoms of trace elements, such as singly or doubly ionized oxygen or singly ionized sulfur, that have very low energy levels. (The more abundant hydrogen and helium ions do not have comparably low-lying energy levels.) This collisional process can be sufficiently violent to transfer energy from the free electron to the ion, thereby populating some ionic energy states just above the ground level. In principle collisions can also depopulate the excited levels of an ion, but in general collisions are fairly rare in the tenuous interstellar environment, and as a result once an ion has been excited collisionally to a higher level it is much more likely to relax radiatively to the ground level by emitting a low-energy photon capable of escaping the nebula. Such transitions, which are said to be forbidden because their spectral lines cannot be detected in the much denser gases encountered in terrestrial laboratories, are responsible in part for the visually spectacular colors of the gaseous nebulas; singly ionized oxygen emits forbidden lines in the violet part of the visible spectrum, doubly ionized oxygen in the green, singly ionized sulfur in the red and so on.

Finally, inelastic, or energy-transferring, collisions among the free electrons themselves can rapidly (on the order of minutes) distribute the electrons' initial-



TRIFID NEBULA, designated M20 in the Messier catalogue of extended celestial objects, is represented here in two ways. The photographic image, made with the four-meter reflecting telescope at the Kitt Peak National Observatory, records the various wavelengths of visible light emitted by the nebula as a result of the recombination of free electrons with different atoms in the volume of ionized gas surrounding the central exciting star. The green contours, drawn from data obtained with the 37-meter radio antenna at the Haystack Observatory, show the distribution of radio waves emitted by the nebula at a frequency of eight gigahertz. In this case the constant-intensity contours increase uniformly inward toward the known position of the central star, coinciding closely with the shape of the visible nebula.



GREAT NEBULA IN ORION (M42) is similarly represented in both optical and radio form. In this case, however, the map of radio intensity shows that substantial parts of the nebular gas are hidden from the view of astronomers working with optical telescopes. The radio map of M42 is more detailed than the one of M20, because for this observation the Haystack antenna was operated at a frequency of 24 gigahertz, and the higher frequency yielded a better angular resolution. New stars are almost certainly being born in or near both of these representative gaseous nebulas. In all the astronomical photographs accompanying this article north is at top and east is at left.

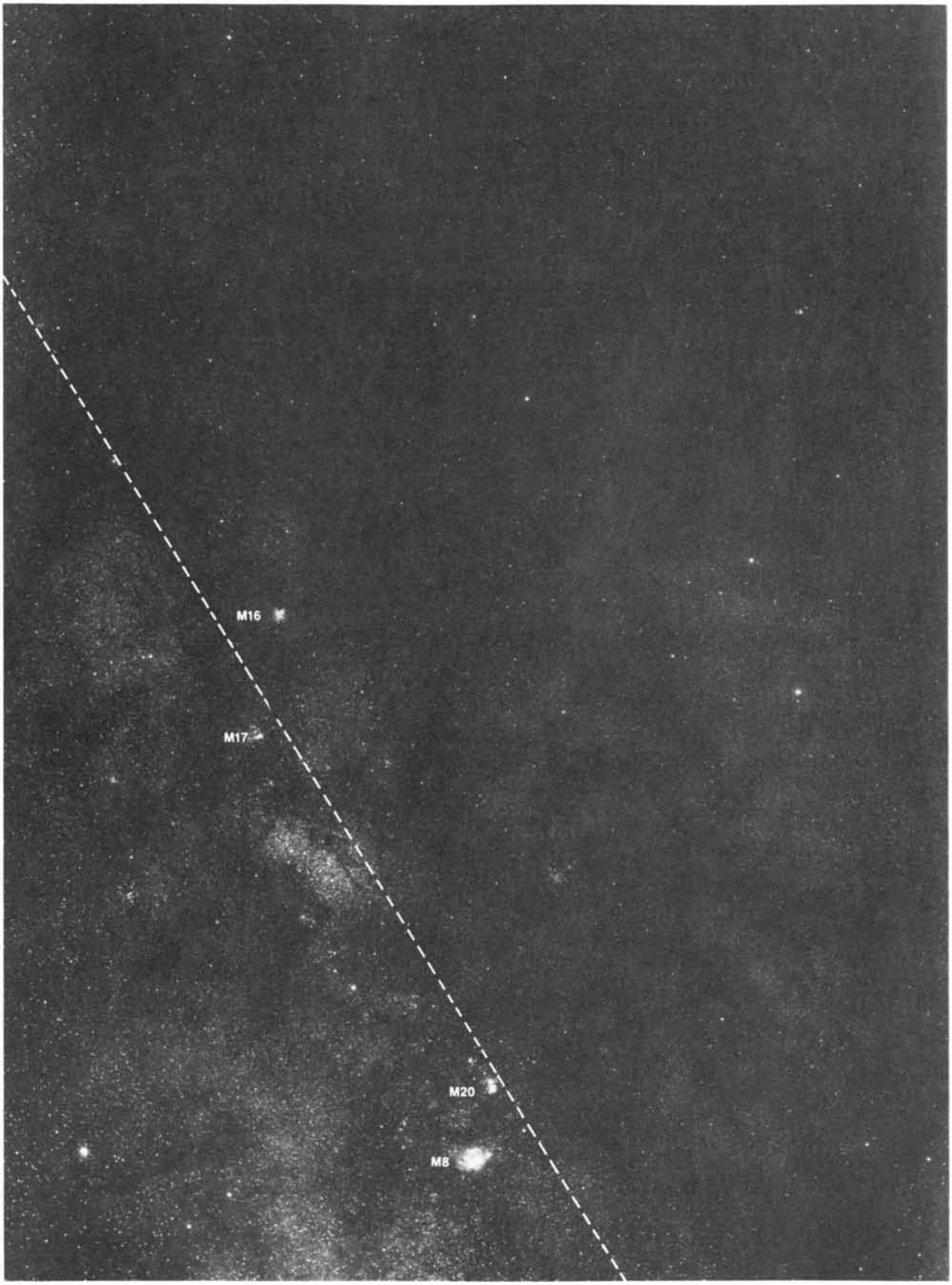
ly gained energy throughout the region of ionized gas, establishing a thermodynamic state, called a Maxwellian distribution, that is characterized by a mean nebular temperature of about 10,000 degrees. (This gas temperature is actually a measure of the electrons' average velocity in the nebula.) In this way the thermal structure of the nebula is generally maintained in a steady-state equilibrium between heating by photoionization and cooling by recombination and collisional processes that generate low-energy radiation capable of escaping the nebula. It is of more than passing significance that it is the trace ions (those at least 1,000 times less abundant than hydrogen and helium) that serve to control the nebula thermostatically, maintaining the nebular temperature generally between 5,000 and 15,000 degrees.

In addition to the thermal equilibrium established among the various heating and cooling mechanisms gaseous nebulas are characterized by an ionization equilibrium. Since the time it usually takes for an electron to recombine (a few hundred years) is small compared with the lifetime of a typical nebula (about 10 million years), the number of recombinations per unit of volume equals the corresponding number of ionizations. There are two distinct physical processes competing here. On the one hand, the rate at which an ultraviolet photon interacts with a nearby neutral element depends solely on the element's atomic properties and the number of sufficiently energetic photons, and it is independent of the thermodynamic properties of the gas. On the other hand, the rate of radiative recombination of an electron with an ion is a sensitive function of the temperature and density of the nebular gas.

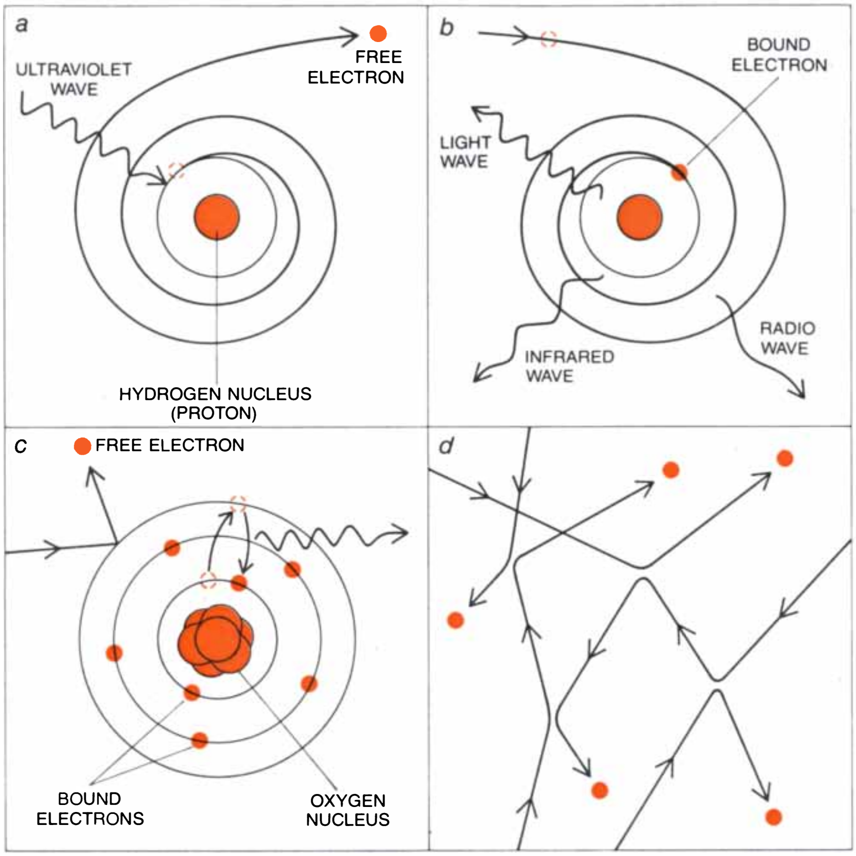
To a first approximation, solving the equations of ionization equilibrium is remarkably simple. The solution, which specifies the ionization structure and geometry of a nebula, demands that the flux of stellar radiation become diluted at some distance from the central exciting star, partly because some ultraviolet photons are continually being used to ionize new elements (predominantly hydrogen) as the ionized zone, quickly at first and then slowly, expands into the surrounding neutral region. Some 10,000 years or less after the birth of the central exciting star or stars the size and shape of the nebula reach a virtual steady state, becoming almost completely ionized within a well-defined region and remaining almost entirely neutral beyond it. Such regions are sometimes called Strömgren spheres, after the astronomer Bengt Strömgren, who was the first to solve the equations of ionization equilibrium.

Stars of different spectral types have characteristic Strömgren radii. The calculation of the nebular radius is com-

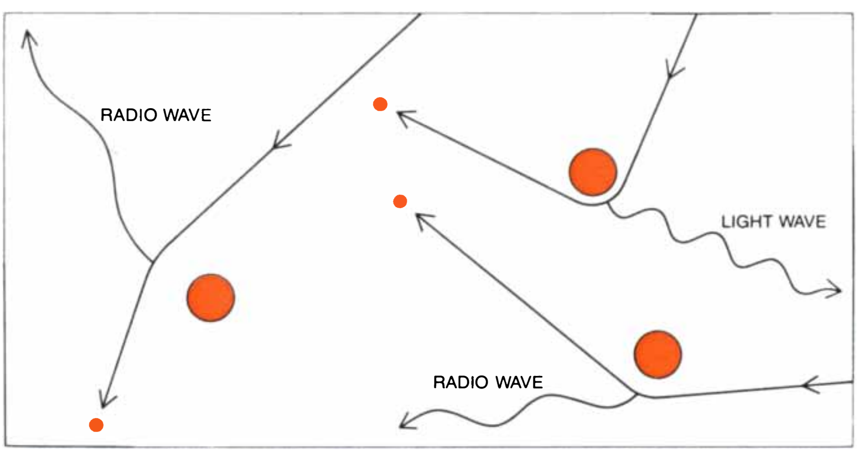
NEBULA-RICH REGION of our galaxy is seen in the wide-angle black-and-white photograph at the right, made with a three-inch sky-patrol camera at Harvard University's southern observing station at Bloemfontein in South Africa. The view is toward the center of the galaxy, northeast of the constellation Sagittarius; the broken white line indicates the central plane



of the galaxy. The photograph extends over an extraordinarily large angular section of the sky, measuring 26 degrees in declination (vertically) and 19 degrees in right ascension (horizontally). It contains several notable nebulas, including the three shown in color at the left. Reading from top to bottom they are M16, the Eagle Nebula; M17, the Omega Nebula; M8, the Lagoon Nebula. (M20, also indicated in the wide-angle view, is reproduced in color elsewhere in this article.) Color photographs were all made with Kitt Peak four-meter telescope.



FREE ELECTRONS can interact with other particles in the ionized nebular gas in three principal ways once they have been individually liberated from the single-proton nuclei of hydrogen atoms by the action of ultraviolet radiation from a central star (*a*). First, a free electron can simply be recaptured by a proton, forming a new hydrogen atom (*b*); as the electron cascades to the lowest energy level of the atom some of the electron's kinetic energy is emitted in the form of electromagnetic radiation at characteristic wavelengths (first at low-frequency radio wavelengths, then at medium-frequency infrared wavelengths and finally at high-frequency optical wavelengths). Second, a free electron can transfer some of its kinetic energy by colliding with certain atoms such as singly ionized oxygen (*c*); the collision excites an electron within the ion to a higher energy state, from which it can then return to its normal energy state, emitting energy in the form of visible light. Third, free electrons can interact among themselves, establishing a fairly uniform nebular-gas temperature of about 10,000 degrees Kelvin (*d*).



RADIATION IS ALSO EMITTED from a gaseous nebula when free electrons pass near protons or other positively charged nuclei without combining with them. In a particularly close encounter of this type the electron loses a considerable amount of energy, emitting a photon of high-frequency optical radiation in the process. Most electrons are hardly deflected at all, however, and they emit comparatively low-frequency radio waves. The net result of a large number of such grazing encounters is a continuous spectrum of radiation, the radio-frequency portion of which is transmitted through space completely unattenuated by interstellar debris. Radiation produced by this mechanism is referred to as bremsstrahlung, or "braking radiation."

paratively insensitive to the assumed temperature of the nebula, since the ionized region is thermostatically controlled by the collision rate of the photoelectrons with the trace ions. The density of the nebula, however, can be expected to vary by more than an order of magnitude from an average value of 300 ions per cubic centimeter. For example, very diffuse nebulas (those with a density of about 10 ions per cubic centimeter) can extend some 20 light-years from a very hot star. Even larger nebulas can exist when several hot stars (or a full-fledged cluster of stars) collectively provide a large flux of ultraviolet photons.

In spite of the complete ionization of interstellar regions near hot stars, any star or cluster of stars can produce only a finite number of ultraviolet photons, and therefore it can ionize only a finite volume of matter. Of course, if there is a lack of neutral material capable of becoming ionized near a hot star, then the size of such a "density-bounded" nebula becomes limited by the amount of neutral material present, and its generally irregular shape depends on the geometrical distribution of the interstellar material in the neighborhood of the star. In recent years, however, astronomers have come to realize that most nebulas are embedded in much larger and more massive clouds of neutral atoms and molecules that envelope the "radiation-bounded" nebulas. Such nebulas often have some symmetry about their exciting sources. The equations of ionization equilibrium further specify that the thickness of the transition region between the hot, completely ionized gas within the nebula and the cold, predominantly neutral gas outside it is extremely sharp compared with the overall dimensions of the nebula. Nevertheless, it is within this transition zone, measured in light-hours rather than light-years, that the temperature and degree of ionization of the gas drop drastically, typically by several orders of magnitude.

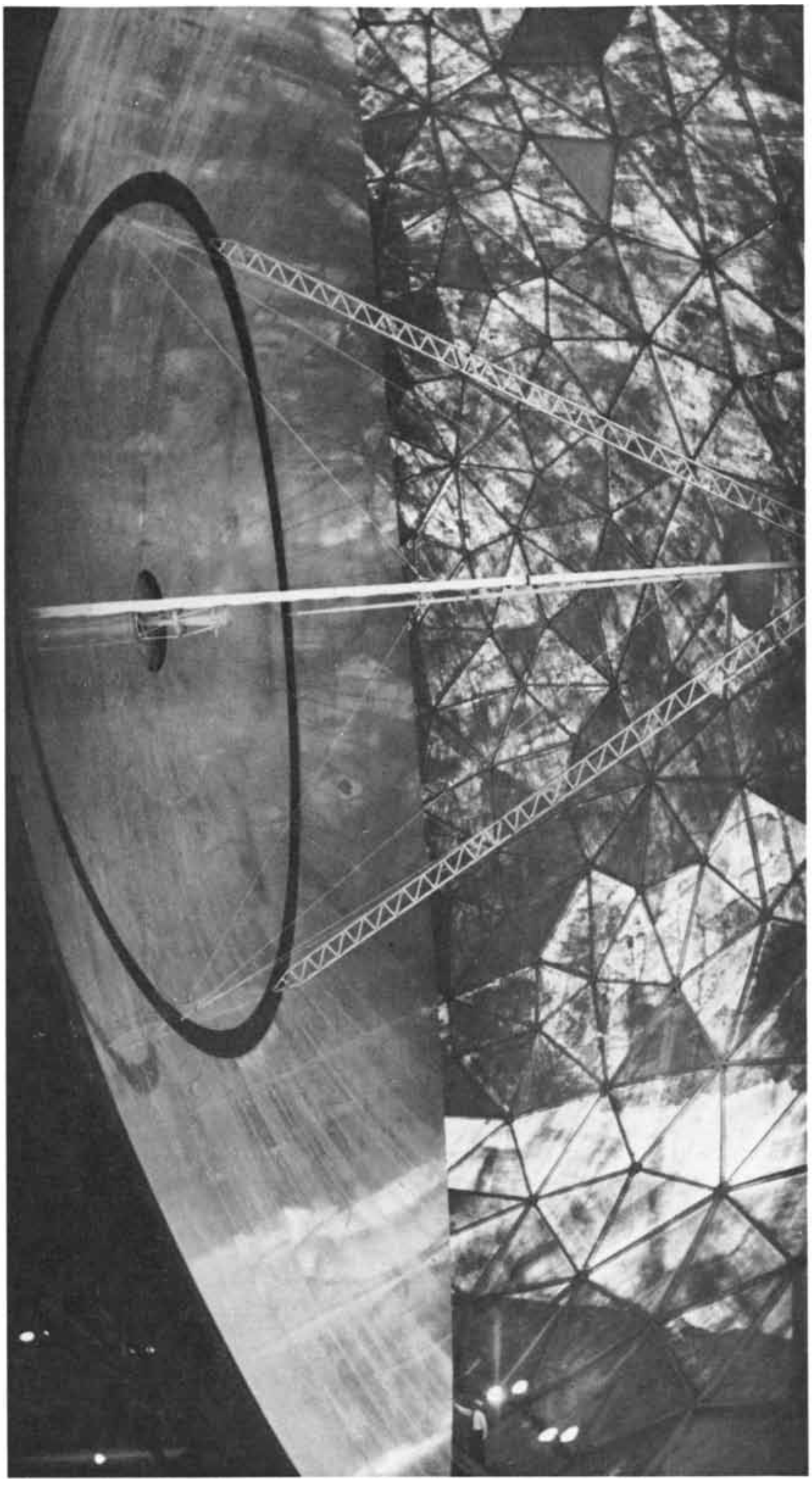
A gaseous nebula, then, is a hot region of almost complete interior ionization separated by an exceedingly thin transition layer from a cold, predominantly neutral interstellar cloud. Information about gaseous nebulas accumulates solely by virtue of the detection of electromagnetic radiation emitted and absorbed by electrons, ions and neutral atoms. The astrophysicist categorizes these electromagnetic data according to four fundamental parameters, namely direction, frequency, intensity and polarization, in order to characterize the physical and chemical state of the gas in terms of temperature, density, composition and velocity.

To take a typical example, consider a region of space to the northeast of the constellation Sagittarius. A wide-angle photograph of this part of the sky encompasses the central plane of our galaxy [*see illustration on preceding page*].

A careful examination of the black-and-white positive print reveals a mottled appearance, signifying an uneven distribution of stars. The apparent irregularity is the product of visual obscuration, blemishing an otherwise uniform distribution of stars. The obscuration is particularly evident along the galactic plane itself, where the accumulation of dust and other forms of interstellar debris is quite pronounced. Indeed, such a large degree of obscuration prevents one from seeing farther than about 10,000 light-years in this direction; accordingly there is no possibility of using optical telescopes to study the nucleus of the galaxy, which lies in the same direction some 30,000 light-years away from the solar system.

Embedded in this vast sea of interstellar gas and dust are several gaseous nebulas, four of which are shown in color in the accompanying illustrations. These are some of the visually most striking nebulas observable anywhere in the sky. Their Messier numbers (given to them by Charles Messier, the 18th-century French astronomer who first catalogued them), together with their popular names, are M8, the Lagoon Nebula; M16, the Eagle Nebula; M17, the Omega Nebula, and M20, the Trifid Nebula. A careful look at these individual nebulas shows additional obscuration, often directly across the face of the photographic image. This widespread scattering of light by interstellar dust helps to make analysis of the optical data difficult. In fact, some of the most energetic nebulas are entirely invisible, in particular those located toward the galactic center.

How then can one confidently obtain a true delineation of the gas in a nebula? For that one must rely on the fact that nebulas emit radio waves that are completely unattenuated by interstellar dust. Consider again the role of the free electrons. During the several hundred years that they wait for recombination with a nucleus unbound electrons lose some of their kinetic energy through inelastic collisions with other charged particles. In a typical electron-ion encounter the lighter electron is decelerated on entering the electrostatic field of the ion, which is usually a proton. A grazing interaction of this type does not lead to recombination, because either the approach velocity or the separation at impact is too great for capture. To conserve energy the small amount of kinetic energy lost by the electron is emitted as a comparatively low-frequency radio wave, the phenomenon known as bremsstrahlung, from the German for "braking radiation." In spite of the infrequency of individual encounters the ensemble of about 10^{58} electrons in a typical nebula is endowed with a continuous array of approach velocities and impact separations, ensur-



HAYSTACK RADIO ANTENNA is employed by the author and his colleagues at Harvard to detect radio waves from gaseous nebulas. The facility, which is managed by the Massachusetts Institute of Technology for the Northeast Radio Observatory Corporation, is on a hill in Westford, Mass. It is enclosed within a large geodesic dome to protect it against the New England winter. In this "fish eye" photograph, made from inside the dome, the 37-meter primary antenna surface is at the left. The primary surface (which is extremely smooth, approximating a mathematically perfect parabola to within half a millimeter across its entire surface) serves to focus cosmic radio waves toward a smaller secondary surface (*right*), which in turn reflects the signals back to a sensitive receiver at the center of the primary dish. The operating range of the Haystack antenna is normally between one and 25 gigahertz, although it has been used to detect higher-frequency radio signals. Man at bottom center gives an indication of scale.

ing the continuous emission of radio waves capable of escaping the nebula.

The weak bremsstrahlung emission provides a powerful means of delineating the true distribution of nebular gas with a large radio telescope. Consider, for example, a map of the radio waves emitted from M20, the Trifid Nebula [*see top illustration on page 165*]. This radiation was sampled at the microwave frequency of eight gigahertz (eight billion cycles per second) by the Haystack antenna of the Northeast Radio Observatory Corporation, a consortium of northeastern universities. The effective angular resolution of the telescope in this case was nearly four minutes of arc. The radio map demonstrates that with the exception of the trisecting lanes of obscuring material the optical image of M20 is a reasonably good representation of the extent of the ionized gas. This, however, is a rare circumstance.

The Great Nebula in Orion (M42) provides a better example of how substantial parts of nebular gas can be visually hidden [*see bottom illustration on page 165*]. The map of radio intensity observed in the direction of M42 is more detailed because at the 24-gigahertz operating frequency of this observation the angular response was about one minute of arc. The resolution is still poor compared with that obtained with optical telescopes, but it is the best currently attainable with a large radio telescope. Two or more radio telescopes can work synchronously to form an interferometer capable of better resolution, but these arrangements are sensitive to only a small fraction of the nebular gas.

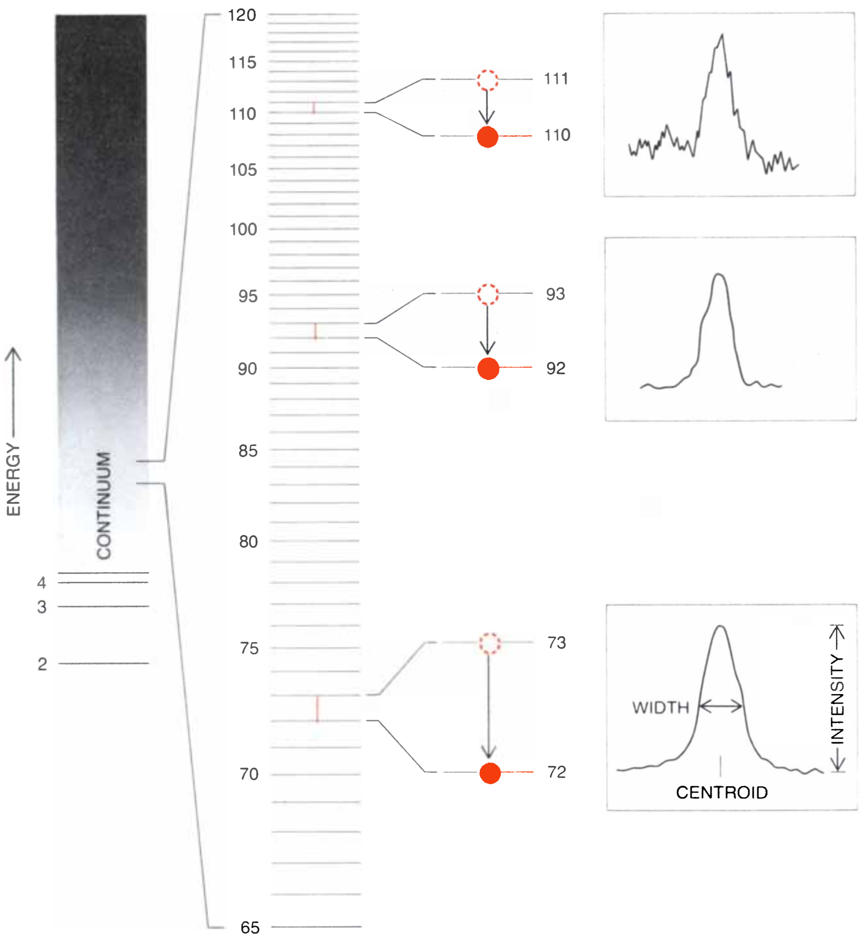
Comparatively high-resolution radio maps such as that for M42 can be used in conjunction with optical studies to make a more quantitative statement about the intervening obscuration. The radio waves, completely unattenuated by the intervening dust, can be scaled several orders of magnitude in frequency to predict the true intensity of the optical radiation. The difference between the predicted (unattenuated) and observed (attenuated) values of the optical intensity yields a measure of the obscuration.

This procedure was recently accomplished by comparing the radio map of M42 that I made with the Haystack instrument with an optical map of M42 made by M. A. Dopita of the University of Manchester at the high-altitude Pic-du-Midi Observatory in the Pyrenees. The resulting distribution of foreground obscuration can be presented silhouetted against the glowing gas of M42 [*see bottom illustration on page 172*]. As one might expect, the dark tongue of dust to the east of the core of the nebula can be recognized as the region of heaviest obscuration.

Similar studies have shown that major parts of some nebulas, notably M17, are completely invisible. Indeed, hundreds of gaseous nebulas hidden to optical astronomers have been uncovered in recent years by radio-astronomical techniques.

In addition to providing a measure of the degree of obscuration, radio maps of continuous nebular radiation can yield a wealth of information about the thermodynamic state of the ionized gas. For example, the total intensity of the radio waves emitted obviously depends on the number of electrons encountering ions within a given volume of space. A mathematical description of the bremsstrahlung process can then be inverted to determine the electron density or the ion density, given the observed radio intensity. If the distance to the nebula is known, its physical size can be calculated from its apparent size; the mass of the nebula can then be determined from its known volume and density. Estimates of the distance, the Strömgren radius, the density and the mass for the five nebulas prominent in this article are listed in the table on page 178. The densities and masses given depend somewhat on a theoretical model, yet they satisfactorily represent the gross properties of the hundreds of nebulas distributed throughout the galaxy. By comparing the observed size of a nebula with its theoretical Strömgren radius one can even infer the spectral type of the central exciting star or stars. In this way the energetics of the nebula can be studied without ever having to see the central exciting star.

Eventually the free electrons recombine with protons and occasionally with more complex nuclei in the nebular gas. Quantum physics predicts that captured electrons can have only discrete energies, corresponding to the atomic energy levels described above. As the bound electrons seek the lowest energy level the successive downward transitions re-



QUANTUM-MECHANICAL PICTURE of a hydrogen atom consists of a set of discrete energy levels the atom's single electron is allowed to occupy. Electron transitions between the lowest energy levels, represented at the left, give rise to the emission of visible light. Transitions between the higher, more closely spaced energy levels, shown greatly enlarged at the middle, are accompanied by the emission of radiation at radio-wave frequencies. Three such transitions are indicated in color, along with actual tracings of their corresponding radio recombination lines (*right*), recorded from the direction of the nebula M20. The tracings for the 111-to-110 and 73-to-72 transitions were made with the aid of the 43-meter antenna of the National Radio Astronomy Observatory (NRAO). The tracing for the 93-to-92 transition was made with the Haystack antenna. Radio recombination features of this type can be fully characterized by three measurements: their intensity, their width and the frequency of their centroid.

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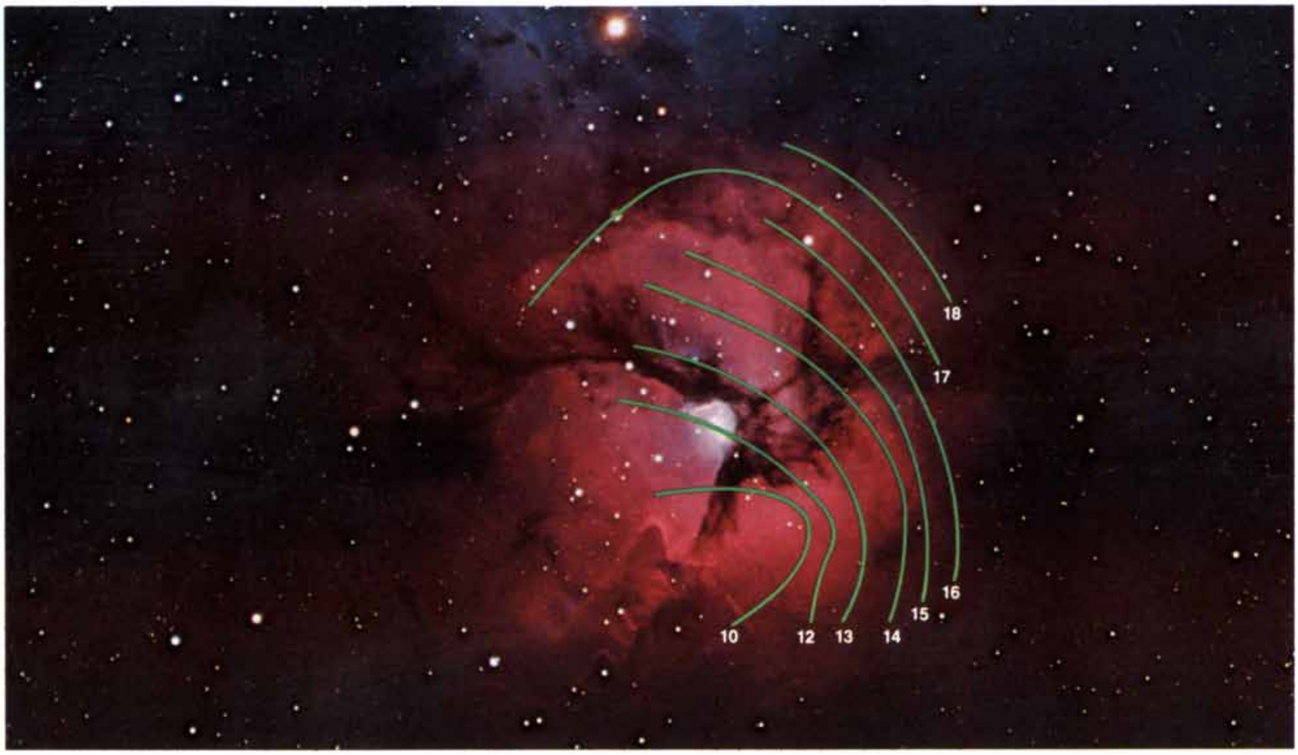
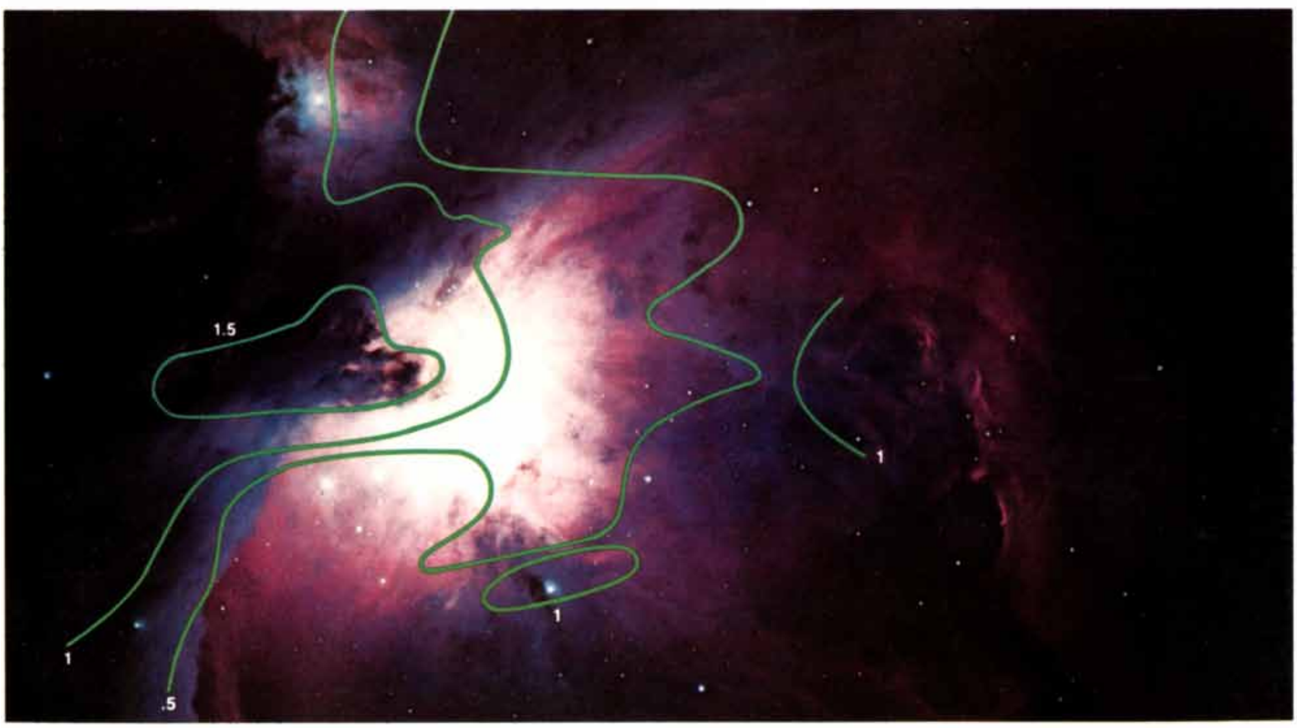


SLOW ROTATION OF NEBULA is suggested in the case of M20 by this map of the velocity distribution of the ionized gas, obtained by analyzing the centroids of a number of radio recombination lines. The contours show the varying Doppler shifts of different parts of the nebula, measured in kilometers per second with respect to a frame of reference based on a local group of stars near the sun. The resulting kinematic map, superposed on the same Kitt Peak photograph of M20 reproduced at the top of page 165, suggests that the nebula is rotating on an axis oriented 45 degrees east of north with a period of several million years. Alternative interpretations are also possible.



ATTENUATION OF LIGHT from a nebula by interstellar dust and other forms of galactic debris can be plotted in the form of a contour map. In the case of M42, shown here, the dust appears to be concentrated in the dark region to the east of the core of the nebula. Visible light from the zone within the magnitude contour marked 1.5 is diminished by about 80 percent; light from within the 1-magnitude contour is about 60 percent less than it would be in the absence of the dust, and light from within the .5-magnitude contour is about 40 percent less. It is not known whether the dust is physically mixed with the nebular gas or whether it is in the form of foreground clouds unrelated to the nebula. The striking asymmetry of the visible nebula and the nonuniform distribution of the nearby stars were the first clues that the ionized volume of the gaseous nebula is only a small part of a much larger aggregation of neutral interstellar matter.

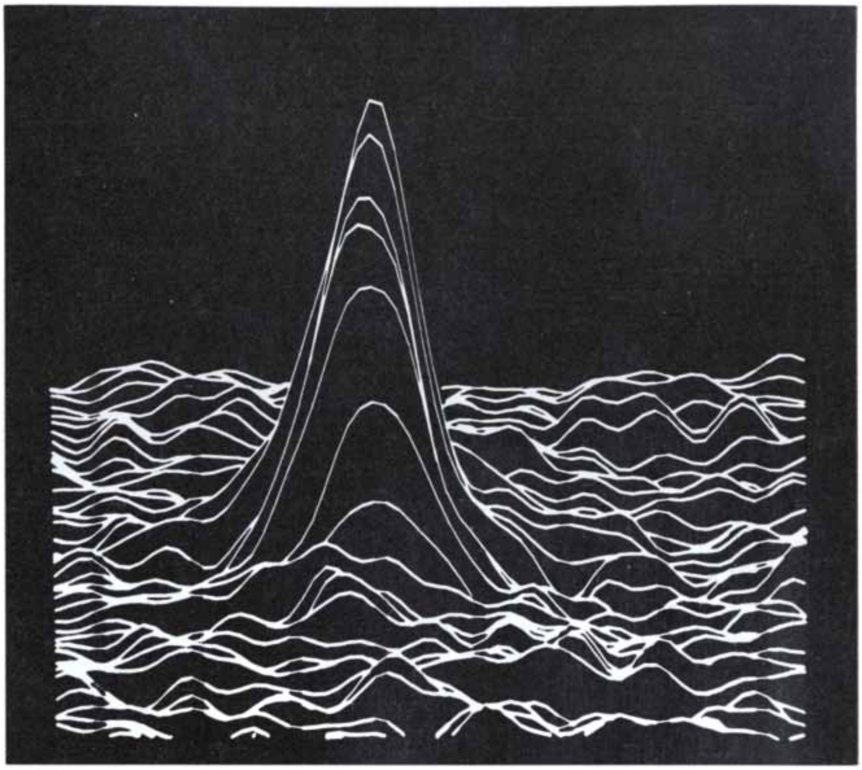
lease precise, quantized packets of radiation (photons), giving rise to clearly defined spectral lines that are superposed at precise frequencies on the spectrum of continuous radiation. The study of these spectral features enables astronomers to examine any single nebular atomic species to the exclusion of all others. Such spectroscopic analyses of nebulas continue to provide more accurate experimental data with which to build more realistic models of nebulas and of their interstellar environment.

The downward cascade of an electron within the quantized ladder of bound energy levels leads first to the emission of radio waves from levels high within the atom, then to infrared radiation and finally to visible light. The frequency of the emission shifts because the energy difference between adjacent atomic levels gets smaller with increasing distance from the central nucleus. For example, the permitted visible lines of hydrogen and helium seen with an optical spectroscope are actually recombination lines involving electron transitions between the very lowest energy levels of an atom. Their intensities are often confused by scattering, much as the continuum radiation of starlight is.

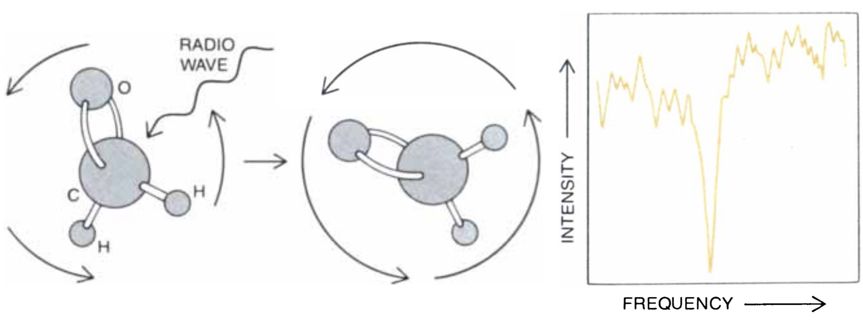
Infrared spectrometers are only now being constructed to observe lower-frequency recombination lines from electron transitions between atomic levels higher than about level five. Radio-frequency spectrometers attached to large radio telescopes, however, can easily detect very-low-frequency recombination lines from electron transitions between energy levels higher than about level 30. In fact, radio recombination lines are now routinely observed from gaseous nebulas at frequencies ranging from about 300 megahertz to 100 gigahertz. At the lowest frequencies electrons cascade between exceedingly high atomic levels, sometimes approaching level 300, enabling radio astronomers to study the largest atoms ever observed spectroscopically. These giant atoms have a diameter of about five thousandths of a millimeter and cannot be studied in terrestrial laboratories because in the comparatively dense conditions of even a laboratory "vacuum" collisions depopulate the electrons from the highly excited atomic levels before they have a chance to radiate.

Consider the typical appearance of a radio-frequency spectral line emitted as nebular electrons cascade from level 111 to level 110 in the hydrogen atom [*see illustration on page 170*]. This observation was made toward M20 with the multichannel spectrometer attached to the 140-foot radio telescope of the National Radio Astronomy Observatory in Green Bank, W.Va. Bell-shaped lines of this type are specified mathematically by their intensity, their width and the frequency of their centroid. Of course, such spectral features arise not from a single atom but from large numbers of electrons undergoing a particular transition within the nebular volume sampled by the telescope.

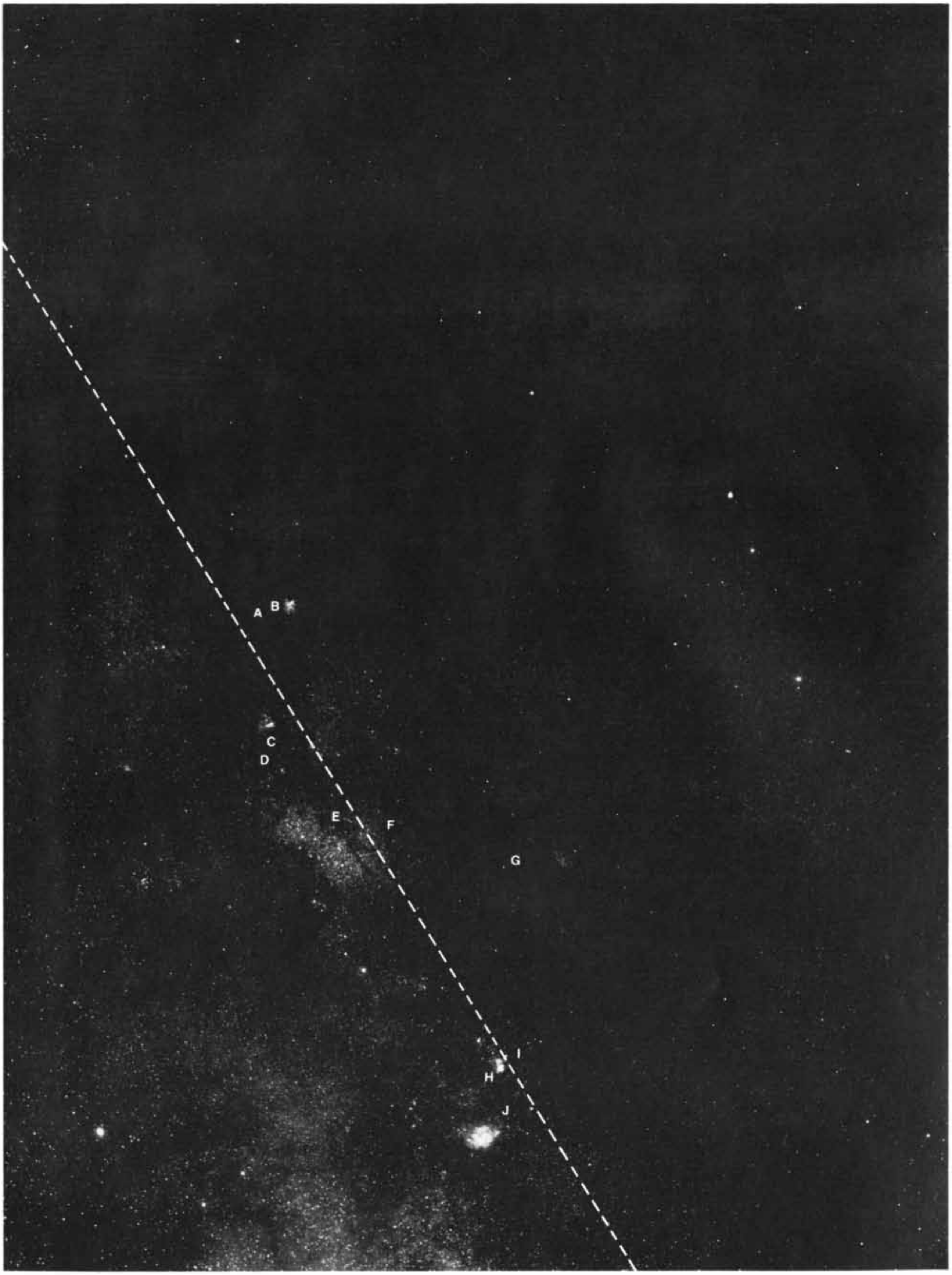
Spectral lines can generally yield a great deal of information about the emitting or absorbing gas, whether it is a laboratory sample or a cosmic sample. My Harvard colleagues and I at the Haystack Observatory use radio recombination lines to extract physical, chemical and kinematic information from the measurements of spectral features of different elements at a variety of different locations. For example, we have constructed a contour diagram of gas velocities across M20 [*see top illustration on opposite page*]. This map was made from observations of a radio recombination line at many locations distributed across the nebula. The central frequency of the spectral line was converted to a radial velocity on the basis of the Dopp-



PROFILE OF INTENSITY OF RADIO WAVES from M42 is derived from the same data as the contour map of the nebula shown in the bottom illustration on page 165. In this case, however, the radio-intensity distribution is viewed from the perspective of a 30-degree elevation. Maps of this type, displayed on a large television screen at the Haystack Observatory, emphasize the greater radio intensity at the center of the nebula and demonstrate how gaseous nebulas and other strong radio sources rise up out of the "noise" of the galactic background radiation.



FORMALDEHYDE MOLECULES in interstellar space rotate at specific quantized rates according to their energy content. Changes in the rotational configuration of such a molecule are accompanied by the emission or absorption of radio-frequency radiation, which can be detected on the earth in the form of a characteristic spectral feature such as the one shown at the right. In the pair of diagrams at the left a photon of comparatively low-frequency radio radiation emitted by a nebula is shown being absorbed by a molecule of formaldehyde (H_2CO) in a foreground cloud, causing the formaldehyde molecule to rotate faster. The particular spectral feature illustrated was recorded for M20 by the 43-meter radio antenna at the NRAO.



RECENT RADIO OBSERVATIONS of formaldehyde in the region of space lying in the general direction of the galactic center delineate a vast cloud of neutral molecules that apparently engulfs many nebulas, including M8, M16, M17 and M20. This wide-angle photograph is the same as the one shown on page 167. Letters give the location of measurements of formaldehyde line (*see graphs on opposite page*).

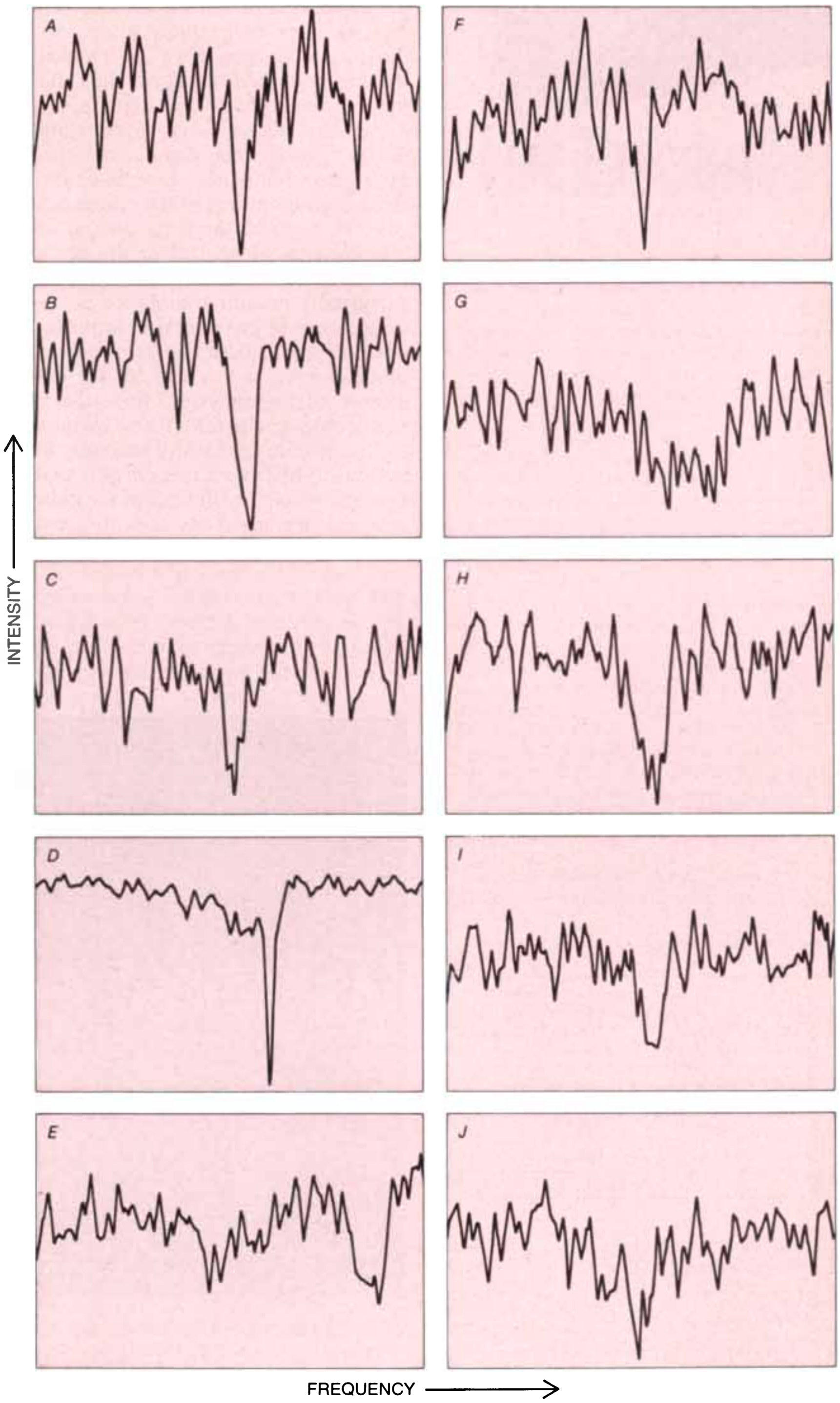
ler effect, according to which the frequency shift of radiation can be used to interpret motion of approach or recession. It should be emphasized that Doppler motion is only line-of-sight motion; transverse motion cannot be studied for distant objects.

A close examination of the gas-velocity map suggests that this nebula is rotating on an axis oriented approximately 45 degrees east of north. If that is the case, then given the distance to M20 the apparent velocity gradient implies a solid-body rotation period of a few million years. That is pretty slow; in fact, the rotation period is longer than the suspected age of a dusty young nebula such as M20. Alternative interpretations are also possible; in particular, the observations may result from the differential expansion, or shearing, of the hot nebular gas against the cold surrounding environment. Future observations, made with instruments capable of a finer angular resolution, will be needed to unravel numerous ambiguities such as this one concerning the bulk dynamics of the nebular gas.

Careful analysis of a spectral line can provide much additional information about the physical conditions within a nebula. Consider the various mechanisms that can broaden a spectral line. Heat is one obvious source of line broadening, since each of the electrons undergoing a specific downward transition has an agitated random motion; some thermal motions are receding, others are approaching, but all serve to widen a spectral line because of the Doppler effect. Nonthermal, turbulent motions of bulk nebular matter on a scale that is small compared with the angular resolution of the telescope are another source of line broadening; microturbulent cells of gas have different motions and when they are averaged over the entire nebula, can measurably broaden or distort the spectral profile. Large-scale motions of the gas, particularly rotation, could also conceivably contribute to the broadening of an observed feature, although none has yet been observed unambiguously. In addition inelastic collisions of recombining atoms with the surrounding plasma, notably with the free electrons, can appreciably broaden a spectral line, particularly if the bound electrons undergoing recombination are far removed from their parent nuclei at the moment of collision.

Fortunately the mathematics of many of these line-broadening mechanisms can be formulated precisely so that one can accurately specify the dominant physical factors giving breadth to the spectral lines associated with particular recombination events. For example, thermal Doppler motions of individual atoms are obviously a function of the temperature of the gas: the hotter the gas, the greater the microscopic atomic motion and the wider the profile of the line. Similarly, a dense gas ensures more frequent collisions and therefore a wider spectral line.

The objective in analyzing the observed spectral features is to invert one's theoretical knowledge of the individual line-broadening mechanisms, disentangle the magnitude of the various contributions and extract meaningful information about the nebula. This task has been successfully done for several nebulas by observing many recombination lines of the same element at different frequencies, and sometimes of different elements at almost the same frequency. Values for gas temperature and density found in this way agree remarkably well with those obtained from analyses of the radio-frequency continuum radiation. The values for gas turbulence are usual-



TRACINGS of the formaldehyde absorption feature at the various locations indicated by the letters on the photograph on the opposite page show that the absorption is strongest in the dustiest regions, where the conditions are best suited for the formation and protection of fragile molecules. Tracings were obtained by the author and his colleagues with the NRAO antenna.

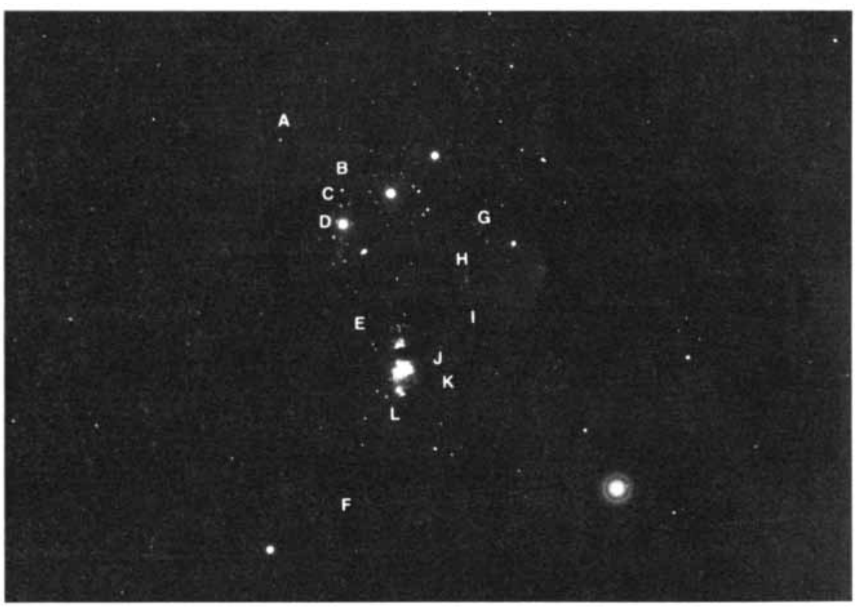
ly less than the anticipated 11-kilometer-per-second speed of sound in a tenuous gas at 10,000 degrees K. Some nebulas, however, notably those with large excitation requirements such as M17, show some evidence for supersonic turbulence, which can be regarded either as the product of nebular shock fronts or as the accumulated motion of individual subsonic cells maintained by high-velocity winds from several exciting stars.

Chemical abundances can also be determined from observations of radio recombination lines. In particular we have obtained values for the ratio of helium ions to hydrogen ions for several nebulas. The average value, about 9 percent, equals the cosmic helium-to-hydrogen abundance if, as is expected from considerations of the energetics of gaseous nebulas, there are no appreciable amounts of neutral or doubly ionized helium.

Actually helium-abundance determinations are of considerable importance not only for a better understanding of gaseous nebulas but also for the entire science of astrophysics. Since the proton-proton cycle that fuses helium in stellar interiors generally accounts for a helium-to-hydrogen ratio of less than 1 percent, given the lifetime of the galaxy, cosmologists generally seek to account for the production of another 8 or 9 percent helium in the early stages of the "big bang" that is believed to have created the universe. Objects for which the helium-to-hydrogen ratio is substantially less than the 10 percent cosmic abundance therefore present potential difficulties for many cosmological theories, since there is no way to destroy helium once it is formed. Thus measurements of the abundance of helium made with unscattered radio waves originating from a large number of galactic objects may ultimately have profound implications for an understanding of the nature of the universe itself.

In short, spectral-line intensities, widths and centroids can be mapped across nebulas. In this way angular variations in temperature, density, turbulence, composition and velocity have been documented for several nebulas in an attempt to learn more about the general properties of plasma near young stars.

The preceding discussion represents only a brief survey of a rather detailed set of physical parameters that can be extracted from spectroscopic studies of gaseous nebulas. There are, of course, a few critical assumptions inherent in the interpretation of nebular spectral lines. Nevertheless, the frontier of the subject is largely concerned with the fine measurement of spectral features of several elements in an attempt to assess the validity of these basic assumptions, and hence to accurately determine the nature of the interstellar plasma. In fact, investigators working in the field have reached the point where they quibble about whether a nebular gas temperature is 8,000 or 9,500 degrees K. and whether the gas density is 500 or 800 electrons per cubic centimeter. That is remarkable precision for galactic as-



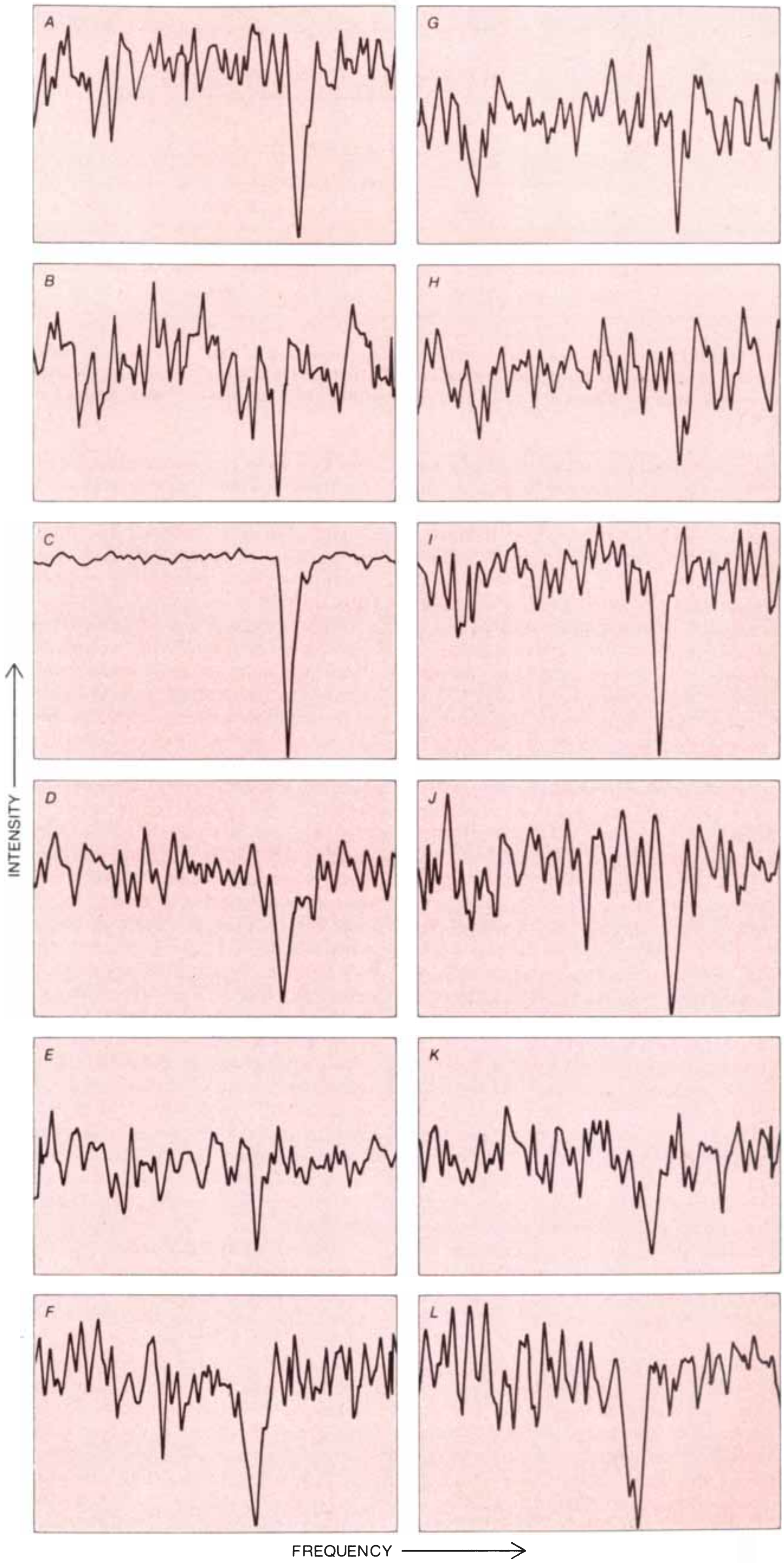
CONSTELLATION ORION also appears to be engulfed in a vast molecular cloud, according to measurements of the characteristic formaldehyde absorption feature at various locations in this region of the sky. The photograph, which measures 13 degrees by 19 degrees, was made with a three-inch sky-patrol camera at one of Harvard's northern observing stations in Massachusetts. The Orion nebula itself (M42) is the extended spot of nebulosity surrounding the middle star of the three vertically aligned stars at the center. In classical representations of the constellation these three stars correspond to Orion's sword, which hangs from his belt, defined by the row of three brighter stars just above it. Letters refer to the tracings on the opposite page.

tronomy. It is in marked contrast to many areas of astrophysics for which theoretical arguments, let alone observations, can be made no more accurate than an order of magnitude. It is indeed an indication of how well radio astronomers soon hope to achieve a full understanding of matter in one of its commonest nonterrestrial forms.

To gain a complete understanding of gaseous nebulas, however, one must also examine their surrounding interstellar environment, because it is there that galactic matter condenses to form hot stars in the first place. Until recently gaseous nebulas were thought to be among the most massive objects in the galaxy. Within the past few years, however, radio astronomers have uncovered evidence for huge, dense molecular clouds that dwarf gaseous nebulas in both size and mass. Many of these molecular clouds are in the spiral arms of the galaxy, regions that are rich in gas and dust but devoid of nebulas. Several of the more prominent clouds, however, are known to be intimately associated with gaseous nebulas. In fact, it is now widely assumed that molecular clouds play an important role in the prestellar evolutionary sequence of interstellar matter. Therefore a complete understanding of gaseous nebulas necessarily includes a description of their inhomogeneous galactic environment.

There are several ways to study neutral matter near a nebula. One observational technique used to estimate obscuration along the line of sight to a nebula was noted above. Additional evidence for interstellar debris can be gleaned by visually scanning the nonuniform star field adjacent to a nebula. Numerous dark areas often obscure partly or totally an otherwise uniform distribution of background stars. For example, a zone with a low star count nearly encompasses each visual nebula illustrated here; in particular, such zones are found to the south and west of M17 and also of M20. Such inhomogeneities in the distribution of stars, including the appearance of several small blotches of complete obscuration, become even more apparent on long-exposure photographs. Another discipline where there is considerable potential for the elucidation of neutral matter near nebulas is infrared astronomy. At present infrared studies clearly imply the presence of dust, although it is not known whether the dust is mixed with the nebular gas or external to it. Actually it is still virtually impossible to determine the precise physical relation between the dusty regions of obscuring matter and the ionized regions of nebular gas.

In any case there are obvious limitations to these methods. The comparison of optical and radio radiation can be made only for those few regions where radiation can be detected visually, star



SPECTRAL FEATURES characteristic of the absorption of radio waves by interstellar formaldehyde were recorded at the 12 locations denoted by the letters in the photograph of the constellation Orion on the opposite page. All the measurements coincide with dark clouds, which serve to protect the molecules against disruption by ultraviolet radiation from the nearby stars.

NAME OF NEBULA	MESSIER NUMBER	DISTANCE FROM EARTH (LIGHT-YEARS)	STRÖMGREN RADIUS (LIGHT-YEARS)	DENSITY (ELECTRONS PER CUBIC CENTIMETER)	MASS (MULTIPLES OF SOLAR MASS)	ELECTRON TEMPERATURE (DEGREES KELVIN)	VELOCITY OF TURBULENT GAS (KILOMETERS PER SECOND)	He^+/H^+ (PERCENT)
LAGOON	M8	3,500	4	400	60	7,500	9	9
EAGLE	M16	8,000	12	100	600	8,000	12	6
OMEGA	M17	7,000	5	800	300	8,700	17	10
TRIFID	M20	6,500	8	100	150	8,200	7	10
ORION	M42	1,500	1	2,000	10	9,000	10	9

PROPERTIES of the five representative nebulas discussed in this article are listed. The Strömgren radius, named after the astronomer Bengt Strömgren, measures the region of space within which the nebular gas is ionized by ultraviolet radiation from central star. Last column gives ratio of helium ions (He^+) to hydrogen ions (H^+) in the nebulas; average value (about 9 percent) equals cosmic He^+/H^+ ratio.

counts have only limited accuracy even for those workers eager to take on such laborious tasks and infrared astronomy so far lacks spectroscopic techniques and an adequate knowledge of the emission properties of dust particles. It appears that the observational technique currently best suited to addressing the problem of nebular environments is the radio-frequency spectroscopy of interstellar molecules.

Molecular astronomy is a new and rapidly developing interdisciplinary science. Within the past eight years more than 40 new molecular species and 100 new spectral lines have been detected by means of microwave and millimeter-wave spectroscopy. Some of these molecules, such as the hydroxyl radical (OH) and formaldehyde (H_2CO), absorb radiation from intense background radio sources. Others, such as carbon monoxide (CO), carbon monosulfide (CS), hydrogen cyanide (HCN) and methyl alcohol (CH_3OH), emit radiation of their own. Still others, such as water (H_2O) and silicon monoxide (SiO), emit intense radiation as a result of maserlike processes.

In spite of the novelty of molecular astronomy the presence of rather complex molecules in interstellar space is not very surprising. The basic physical and chemical properties of more than a million different molecules have been accumulating for years in laboratory studies, but not until recently did astrophysicists recognize that some molecules are virtually ubiquitous throughout the galaxy. Most of the chemical processes that serve to form molecules have been studied only under terrestrial conditions and hence are poorly understood in the interstellar environment, since the densities there are usually orders of magnitude less than the best vacuums achievable in terrestrial laboratories. Nevertheless, the notion that even simple molecules would be easily destroyed by interstellar radiation has now perished with the recognition that large amounts of dust not only provide suitable sites for the formation of molecules but also serve to protect molecules from the harsh radiation of interstellar space. Indeed, within the past few years it has become an observational fact that the abundance of all molecules is strongly correlated with interstellar regions of obscuration.

How can molecules be detected in the interstellar medium? One technique utilizes modifications in their electron configuration, in analogy with the electron transitions described above for atoms. These alterations, however, usually lead to high-frequency ultraviolet radiation that is scattered by interstellar debris and cannot be observed from the earth because it is completely blocked by the earth's atmosphere. Instead it is the bulk motion of the molecules themselves that generally gives rise to observable spectral lines. Molecules rotate end over end and vibrate like a coiled spring simply by virtue of their heat. They do so, however, at precise rates, according to the rules of quantum mechanics. Vibrational modes usually give rise to characteristic spectral lines in the relatively inaccessible domain of the infrared. On the other hand, a large variety of molecules, from simple diatomic inorganic molecules to complex polyatomic organic ones, rotate at specific frequencies capable of detection in the radio-frequency spectrum.

Several competing processes serve to excite molecules and thereby populate specific rotational states in much the same way that the high-level energy states of atoms are populated by radiative and collisional effects. The commonest sequence of events goes as follows. Local stellar sources of ultraviolet radiation heat the dust, which transfers energy through collisions to molecular hydrogen (H_2), the most abundant neutral molecular species, which in turn excites more complex molecules through collisions. The heat input then is primarily stellar radiation, whereas the dominant cooling mechanism is thought to result from the emission of radiation that accompanies transitions between high rotational-energy levels of carbon monoxide molecules. Dense molecular clouds, however, often become opaque to this carbon monoxide radiation, creating an imbalance in the heating-cooling competition. Lacking an effective cooling mechanism, certain parts of a cloud (the densest parts) may then begin to heat up. They are on their way to becoming stars.

The ubiquitous formaldehyde molecule serves to illustrate some of the foregoing considerations. By absorbing or emitting radiation this polyatomic molecular species can undergo a change in its rotation at the characteristic frequency (among others) of 4,830 megahertz. That frequency corresponds to a change in the molecule's rotational configuration nearly five billion times a second. Modern radio-frequency spectrometers can easily detect such radiation as an emission or absorption feature at a wavelength of about six centimeters, unscattered by interstellar debris and unattenuated by the earth's atmosphere.

Molecular lines of this type can be analyzed in much the same way that atomic lines are. Molecular-line profiles generally furnish valuable information about the temperature, the density, the composition and the motions of the molecular cloud. Furthermore, precise knowledge of the physics of the molecule under observation and of the rate of operation of the collisional scenario sketched above yields an estimate of the density of the dominant colliding species: neutral diatomic hydrogen. In this way the total density and mass of a molecular cloud can be inferred, provided that the extent of the cloud is fully delineated. In general molecular clouds are cold, dense and massive, in fact so massive that most of them dwarf their associated gaseous nebula.

In a dramatic illustration of just how large some molecular clouds can be I recently detected formaldehyde molecules at numerous locations between M16 and M8, a span of more than 11 degrees across the sky. (The full moon is only half a degree across.) The nearly constant velocity of these features suggests that there is a giant cloud of molecular matter extending from M16 to M17, from M17 to M20 and possibly from M20 to M8. It implies that each of these nebulas arose from what was, and for the most part might still be, a single incredibly vast interstellar cloud.

At the mean distance of the nebulas (some 7,000 light-years) the cloud would have a dimension of about 1,300 light-years, at least in the plane of the sky. It is surely not a homogeneous cloud, because formaldehyde can be detected only in those places that are particularly dark and obscuring; this in itself is a remarkable demonstration of the strong correlation between the abundance of molecules and the amount of dust. The mass of this vast cloud, which is still not completely delineated, could be more than 10 million times the mass of the sun. A similarly vast molecular cloud apparently engulfs the M42 nebula and much of the constellation Orion. Our recent observations in this part of the sky show again that wherever there is a dark region there is formaldehyde, and by implication there are other molecules as well.

It is evident that our galaxy is richly populated by an assortment of molecules, mainly associated with gaseous nebulas, although some infrared objects and dark clouds devoid of nebulas harbor substantial numbers of molecules. The small kinematic (motion) differences observed in the atomic (nebular) and molecular (interstellar) velocities are not surprising, because if nebulas indeed evolve through the collapse of a molecular condensation, they will do so predominantly at the cloud's periphery, 90 percent of the mass of the uniformly dense sphere being concentrated in its outer half. Thus it seems likely that most visible nebulas, particularly those objects considered here, represent ionized foreground fragments of larger molecular clouds.

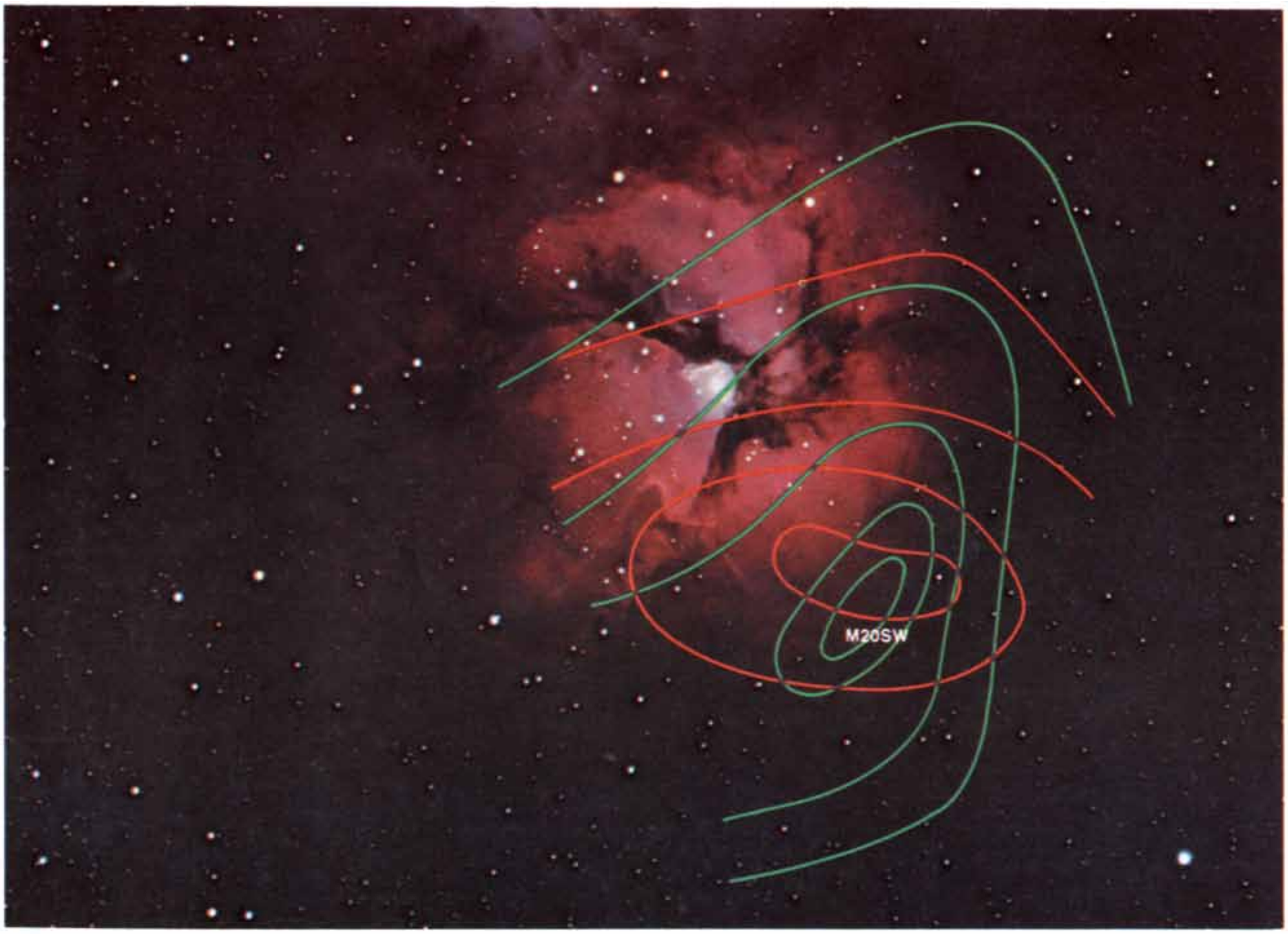
How closely do these observations match the broad scenario for star formation suggested at the beginning of this article? Consider once again the M20 complex as a representative example of a region potentially rich in newborn stars. A contour map of the concentration of formaldehyde near M20 appears to engulf this gaseous nebula from the south and west [*see illustration on next page*], mimicking the distribution of obscuration by dust. In fact, the peaks of molecular abundance coincide with a totally opaque dark blotch we have labeled M20SW. There are fewer molecules to the east and northeast of the blotch, where the density of background stars appears to be comparatively unobscured. Interestingly enough, the blue reflection nebula to the northeast of the M20 complex appears to hold enough dust to scatter starlight (much as sunlight is scattered in the earth's atmosphere to give the sky a blue tint) but not enough to protect the molecules from destruction by radiation.

The same illustration includes a map of the formaldehyde line width, which also peaks at M20SW. The common symmetry of the kinematic distribution and the molecular concentration suggests that the molecular condensation at M20SW may be in a state of gravitational collapse; at the periphery of the cloud narrower molecular features are observed because the motion of infalling material is primarily transverse to the line of sight, playing no role in the Doppler-effect broadening of the line profile. If this interpretation is correct, the M20 complex includes one of the first examples known to embody observational evidence for the interstellar evolutionary scenario I have outlined here.

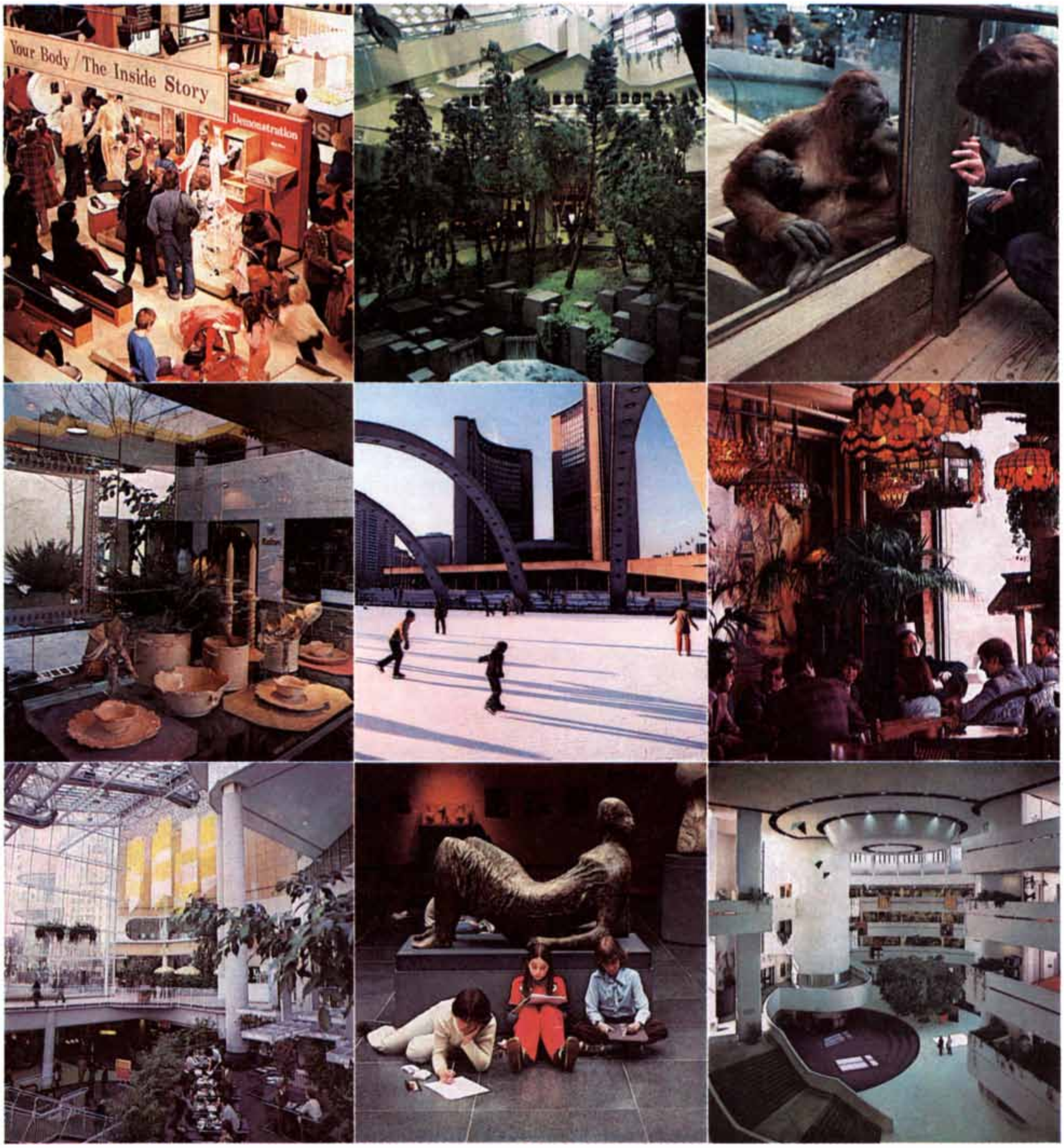
A review of our findings on the M20 complex appears to provide tentative evidence for the three principal phases of star formation. In the northwest of the complex the nebular velocity of about 18 kilometers per second deduced from the analysis of radio recombination lines meshes nicely with the velocity of the adjacent molecular cloud, thereby establishing the initial or quiescent phase for which the total density is probably not very high (perhaps 100 particles per cubic centimeter). The velocity of 18 kilometers per second can be viewed as a measure of the motion of the giant interstellar cloud prior to the formation of M20's exciting star. At certain locations, for example at M20-SW, the molecular cloud has probably reached a high enough density (greater than 1,000 particles per cubic centimeter) and mass (greater than 2,000 solar masses) to initiate gravitational collapse, the intermediate phase of star formation.

The M20 nebula itself represents the final phase of star formation. The outermost contour of our eight-gigahertz radio map of the nebula shows two irregularities that could be real. The first is an outer bulge to the northeast, where photographs show some ionization and where the molecular cloud is absent or at least tenuous. The second is an inner bulge at the nebular boundary closest to M20SW. It is easy to visualize a wave of ionization created by the action of stellar ultraviolet radiation propagating into the dense molecular region near M20SW. The shock front preceding the ionization of material would certainly compress the gas and probably contribute to the enhanced density in the molecular cloud near M20SW. It is even conceivable that such a shock wave could act as a triggering mechanism for rapid star formation at that location.

Future observations of the radio waves emitted by various atomic and molecular species, particularly observations with better spatial resolution, may make possible quantitative estimates of the degree of shocklike interaction of the hot, tenuous nebular gas with the cold, dense molecular matter. It may then be possible to identify an additional phase intermediate between the collapsing phase and the nebular phase, namely a small-scale fragmentation of the cloud into individual sites of star formation.



FORMALDEHYDE IS CONCENTRATED in the vicinity of a dark region to the southwest of the center of M20, the Trifid Nebula. The green contours, which indicate an increase in radio intensity in uniform steps from the outside to the inside, show that the formaldehyde concentration reaches a peak in the zone marked M20SW. The orange contours, which also increase in uniform steps from the outside to the inside, plot the velocity distribution of the formaldehyde in terms of the Doppler broadening of the characteristic formaldehyde absorption line. Since only line-of-sight motions produce such a Doppler effect, the greater broadening of the line at M20SW implies that the cloud may be in a state of gravitational collapse at that point. The data may thus constitute evidence of the impending birth of a star.



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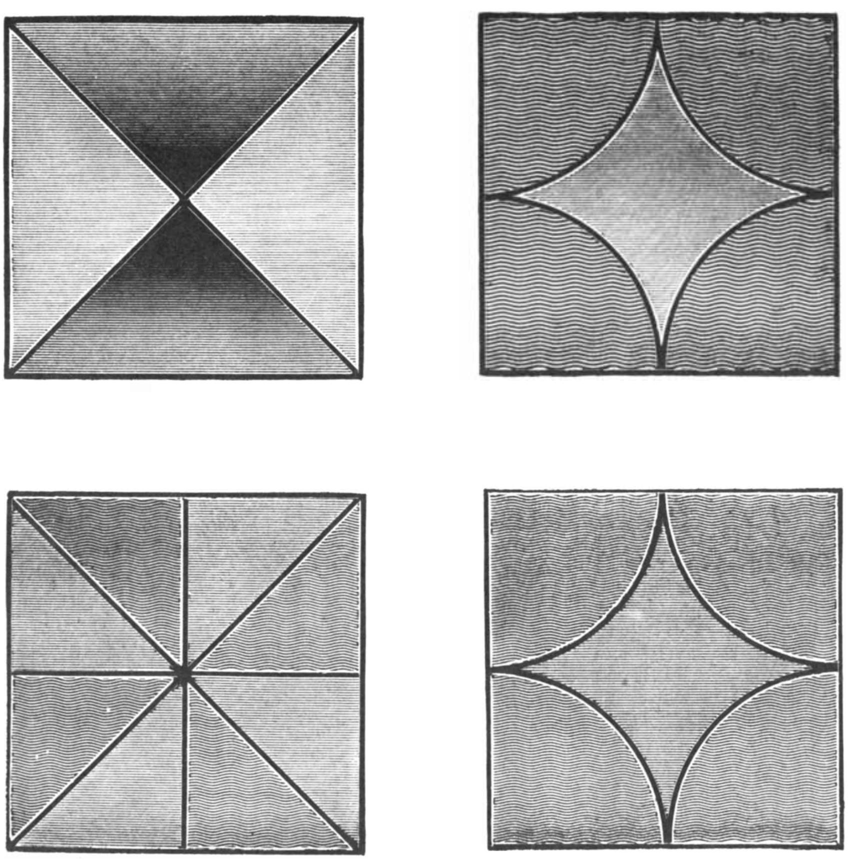
THE AMATEUR SCIENTIST

Moiré effects, the kaleidoscope and other Victorian diversions

by Jearl Walker

This month I shall discuss some classic visual toys that appeared in the 19th century. Although a few of the toys are still sold, most of them have fallen victim to newer entertainments. They are so diverting and instructive that they deserve a better fate.

One of the simplest of the visual toys involved what are now called moiré patterns, the shimmering effect one sees when certain regular patterns are laid one over the other so that in some places they are in step and in others they are out of step. A simple illustration of the effect can be seen with a haircomb. Hold the comb parallel to a mirror so that you can look through the teeth and see the image of the comb in the mirror. If the comb is the right distance from the mirror, some of the teeth in the image will coincide with the real teeth in your field of view. Other teeth will be exactly out of step with the real teeth. What you see is a periodic pattern along the comb's length. The pattern is darker where the teeth are out of step. If you move the comb parallel to the mirror, the periodic pattern of darkness (assuming the comb is dark) runs along the length of the comb in a wavelike motion.



Patterns that can give rise to moiré effects

This kind of motion was employed in illustrations published in the 19th century. A black-and-white illustration was drawn with many closely spaced parallel lines. The reader was told to place over the drawing a screen that was also covered with evenly spaced parallel lines. I am not sure what the screen was made of; it could have been glass or some kind of translucent paper. When the viewer slowly moved the screen over the drawing, the moiré pattern that developed between the screen and the drawing moved across the drawing, giving the illusion that objects in the drawing were moving.

Dover Publications has reproduced (under the title *The Magic Moving Picture Book*) a book that was originally published in London in 1898 as *The Motograph Moving Picture Book*. The transparent screen is acetate ruled with closely spaced lines. The pictures include geometric designs, a representation of an erupting volcano and a scene in which a fireman directs water at a fire. When you move the acetate over the picture of the fireman, for example, the moving moiré pattern makes the fire shimmer, the smoke rise and water on the street flow along the pavement. In other illustrations the moiré effect seems to make wheels turn and water flow past a ship.

You can easily duplicate the effect for yourself. Draw on a sheet of paper a geometric design consisting of many evenly spaced parallel lines. Then rule similar lines with comparable spacing on a sheet of transparent acetate. The acetate can be bought in an art-supply store, where you can find out what kinds of ink adhere well to acetate.

After the ink dries place the acetate on your picture and move it slowly across the picture with the lines in the acetate and the picture parallel. The pattern in the picture will wiggle and squirm. You can try several variations of the trick. Make the lines on the paper slightly more or less widely spaced than the lines on the acetate or make them wavy rather than straight. Try orienting the lines on the paper at angles different from the ones on the acetate and making composite figures consisting of areas with different orientations of lines. Finally, you can draw scenes in which only the appropriate areas show motion.

A related toy was marketed recently through "7-Eleven," the national food-store chain, to promote a beverage. The toy, now under patent application by Magic, Magic, Magic, Unlimited, consists of two plastic cups that are nested and can be rotated individually. The outer cup is clear plastic with an area of vertical black stripes. The opaque inner cup bears two superposed drawings consisting of vertical stripes the same width as those on the outer cup.

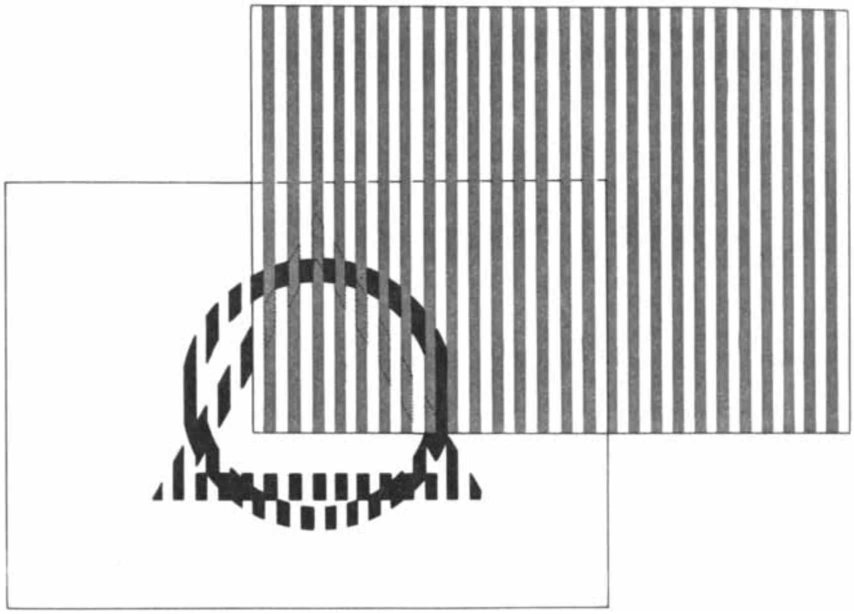
With one orientation of the inner cup

the black stripes block all the vertical segments of one of the drawings and expose all the segments of the other drawing. From a distance of a foot or so the viewer sees a nearly complete picture because the black stripes are apparently ignored and the viewer mentally completes the picture across the stripes. By rotating the inner cup the viewer can replace the exposed segments of one picture with those of the other. Slowly continuing the rotation alternates the exposure of the two pictures. On my cup a baseball player is either bending down to field a ball or is standing. When I rotate the inner cup, he appears to alternate between the two poses.

A large variety of changeable pictures were available in Victorian times. The simplest kind involved nothing more than a picture that had several slits through which segments of an alternate picture could be slipped. Motion was better suggested by the slipping slides developed for the "magic lantern," which today is called a slide projector. These consisted of a glass slide with a scene painted on it and a second slide that could be slipped in front of the first one. The second slide bore the element of the composite picture that was to be moved. When the slide was projected, the operator could slip the second slide over the first to give motion to the projection.

You can easily duplicate this system with most slide projectors. In the book *Making Victorian Kinetic Toys* Philip and Caroline Freeman Sayer suggest using the thin sheets of glass from the mounts for 35-millimeter slides. Buy a translucent paint that adheres to glass and does not degrade in the heat of a slide projector. Paint the fixed scene on one sheet of glass. You may want to trim the other sheet so that there is more room for sliding it. Attach to that sheet a convenient handle, such as a plastic toothpick, so that when both sheets have been inserted into the slide holder of the projector, you can move the second sheet by the handle.

One Victorian visual toy, the kaleidoscope, is still popular. It was invented (or at least patented) in 1816 by David Brewster, who is best remembered for his work in classical optics and particularly for the Brewster angle of the polarization of light by reflection. Although there are many variations on the kaleidoscope theme, the basic design is a tube containing two rectangular mirrors or pieces of shiny metal taped together at an angle of about 45 degrees with the taped edges running the length of the tube. At one end of the tube is a compartment containing bits of colored glass or other material. At the other end is a small hole through which the viewer peers. One can see a pie-shaped section of the bits of material at the other end and reflections of the same segment in the mirrors. When the tube is rotated, the symmetrical pattern shifts as the bits of material fall into different configurations.



Intermixed patterns

Designs for a homemade kaleidoscope are available in Carson I. A. Ritchie's excellent book *Making Scientific Toys*. Cut off the bottom of a fairly long plastic bottle with a narrow neck opening. The bottle will serve as the tube and the opening will be the aperture through which you will look. Inside the tube will be two rectangular mirrors with their edges at an angle of between 40 and 70 degrees. The bottle should be about a centimeter longer than the mirrors once they are fitted in.

Put the cutoff end of the bottle on a sheet of 1/8-inch Plexiglas, trace a circle on the Plexiglas around the circumference of the bottle and then with a jigsaw cut out the circle of Plexiglas. File the edge until the piece just fits inside the bottle.

Hinge the two mirrors together with strong reinforced tape. Put the Plexiglas piece on a table, stand the mirrors upright on it and fasten them to it by gluing some small wood blocks into the angle between them and the piece. The blocks will also fix the angle between the mirrors. Your results will be best if you have positioned the mirrors so that both edges of each touch the circumference of the circle. When the glue of the assembly has dried, push the assembly into the bottle (Plexiglas end last) as far as it will go. Now make another Plexiglas circle of the same size, but instead of leaving it transparent rub it with steel wool to make it translucent. This piece will be the end of the kaleidoscope.

To make a compartment for the bits of colored glass cut out a strip of stiff cardboard that is long enough to be fashioned into a ring to fit in the bottle between the two Plexiglas circles. The cardboard should not stick out of the end of the bottle. Glue the ring to the translucent piece of Plexiglas. Put into the ring a few bits of colored glass and slip the ring into the end of the bottle. You now have a kaleidoscope with a changeable display.

To investigate the effect of the angle between the mirrors you might prefer to work with a simpler arrangement. Hinge the two mirrors together and stand them upright on a geometric design drawn on a piece of paper. Look down into the trough formed by the mirrors to see the kaleidoscope design. How many pie-shaped sections do you see for a given angle between the mirrors? Try varying the angle from the smallest one you can achieve to one as close to 90 degrees as is possible, recording the number of images as a function of the angle. Do all the pie sections have the same angular width? In particular, is the pie section lying behind the hinge of the mirror the same size as the other sections?

One of the best kaleidoscopes I have found has a lens at the far end instead of a container. (I think the device is properly called a teleidoscope, but I am not certain.) The focal length of the lens is less than the length of the tube. When a fairly distant object is viewed with the device, the image size is reduced by the lens so that many such objects can be seen simultaneously. To me the effect is beautiful, since it is brighter and more colorful than the images in a standard kaleidoscope, where the bits of colored glass and the translucent backing reduce the intensity of the light. If I watch passing scenery with the device as I ride in a car, the constantly varying display is almost psychedelic.

You can make this kind of kaleidoscope out of a cheap lens, a cardboard tube and the usual two mirrors. Choose the lens and the tube so that the focal point is about halfway down the length of the tube. The opening at the viewing end of the tube should be small but should still be large enough for you to see all the image, including the reflections in the mirrors.

An enormously popular diversion in the late 19th century was viewing photographs in a stereoscope. In his book Ritchie gives plans for making replicas of the old stereoscopes. You can find old stereoscopes and stereo cards in antique shops, and you can buy replicas from Stereo Classics Studio, Inc., 145 Algonquin Parkway, Whippany, N.J. 07981. The commonest kind of stereoscope has two lenses, one for each eye, through which a viewer sees two pictures, one for each eye. The pictures are not identical but give slightly different perspectives of the same scene to match the perspectives each eye would see in the same setting. Hence when the pictures are fused by the stereoscope, they are seen in the original three dimensions.

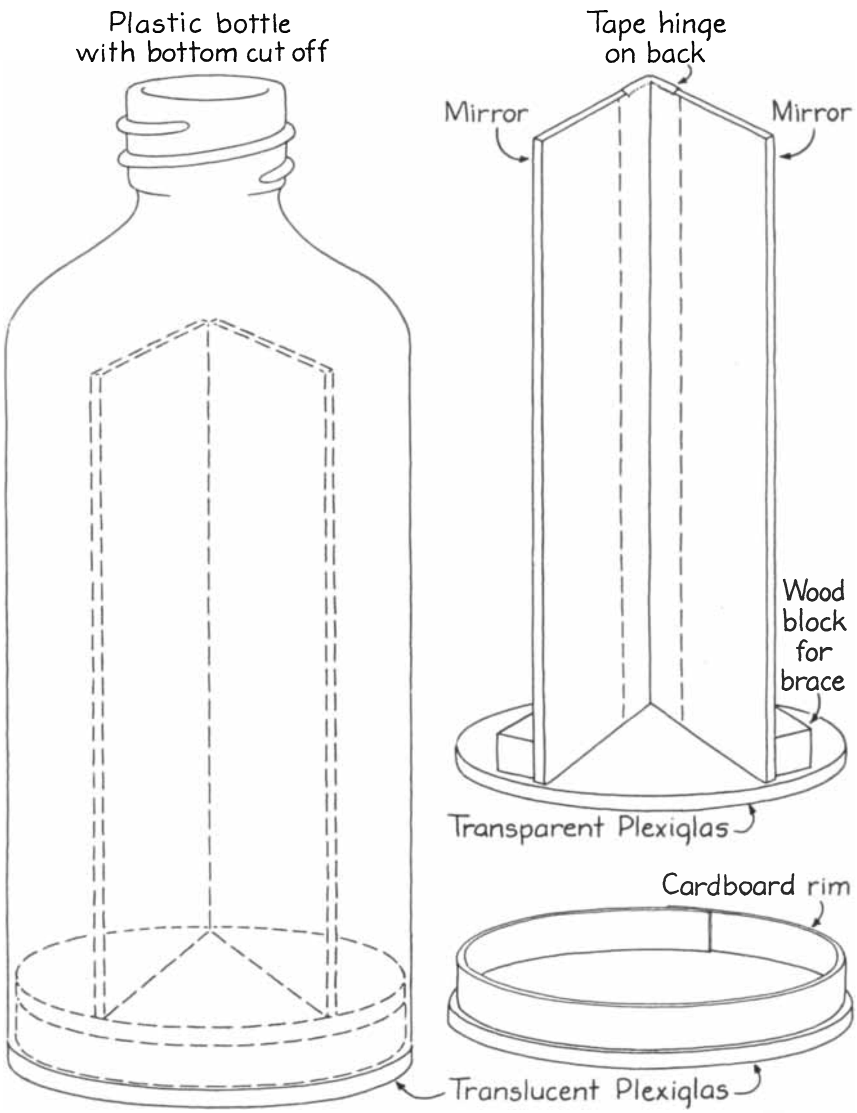
Budd Wentz describes a simple procedure for making a different type of stereoscope in his book *Ready-to-Make Photo & Scene Machines*. The viewer looks through a piece of cardboard resembling a Halloween mask. One purpose of the mask is to eliminate distractions so that the viewer can concentrate on details that help him in assigning depth to the objects in the picture.

In the center of the mask there is a length of stiff cardboard that has a flat mirror glued or taped to one side. The idea is to view one picture directly with one eye while viewing a reflection of the other picture in the mirror with the other eye. This system forces the eyes to converge, which in turn helps the viewer to assign depth to the pictures. As before, the two pictures show slightly different perspectives, but in addition one of them must be "flopped" (left and right reversed) so that it has the same orientation as the other one after reflection. If everything is done right, the viewer fuses the two images to get a single three-dimensional image. Wentz provides reproductions of some of the stereo cards that were popular with this type of device in the late 19th century and early 20th.

The standard stereoscope available in antique shops is different from Wentz's in that it has two wedge-shaped lenses to facilitate the merging of the different images seen by the viewer. Both pictures have the same orientation, since no reflection is involved. This kind of stereoscope was apparently developed in 1859 by Oliver Wendell Holmes, partly on the basis of earlier work by Brewster. Photographs were usually made with a camera that had two lenses, which were separated from each other by about the distance between the eyes of an average person. The focal lengths of the lenses in the camera and in the stereoscope were the same, so that the viewer saw the same perspective the camera did. The photographs could also be obtained with an ordinary camera by making one photograph and then moving the camera seven or eight centimeters to the side to make the other.

Thomas B. Greenslade, Jr., and Merritt W. Green III have published an account of their experiments with this type of stereoscope and their attempts at making photographs for it. You might like to follow up on some of their work either with an antique stereoscope or with a stereoscope you have made. If you make one, Ritchie suggests that you have an optician grind the lenses. His specifications for the lenses are "power approximately flat B 1/SPH + 5.50, lens cut on optical center, 8 base out E/E 47 pound blank." You might try to work with some wedge-shaped glass prisms instead.

Greenslade and Green were able to make their photographs with a Polaroid camera (Model 180) that had a lens with a focal length close to that of the antique stereoscope they had bought. In one experiment they wanted to ascertain how the lateral displacement of camera positions between successive photographs affected the quality of the three-dimensional illusion. Ideally the displacement should match the distance between the viewer's eyes, but depth appeared in the



Carson I. A. Ritchie's design for a homemade kaleidoscope pictures even when the camera displacement was more than or less than the ideal distance. With a large displacement, however, the objects in the photographs became "unreal" in proportion from front to rear because the larger separation gave them too much depth.

Greenslade and Green also found that stereo photographs could be made by rotating the camera through a small angle (they made it 7.7 degrees) between successive photographs. The rotation apparently altered the perspective enough for the viewer to be able to perceive depth when he made the two photographs fuse. You might want to experiment with a range of angles to see if the three-dimensional effect persists and if large angles give rise to distortions in the perceived view.

I had easy success with a Polaroid Model 104, making street-scene stereo photographs holding the camera by hand. Using a tripod to displace or rotate the camera would undoubtedly improve the quality of the pictures, but the three-dimensional illusion was readily apparent even with my casual efforts. I aligned the left side of the camera's field of view on an object and made one photograph. Then I rotated the camera five or 10 degrees to the left, aligned it so that the reference object was at the same height in the field of view and made the second photograph.

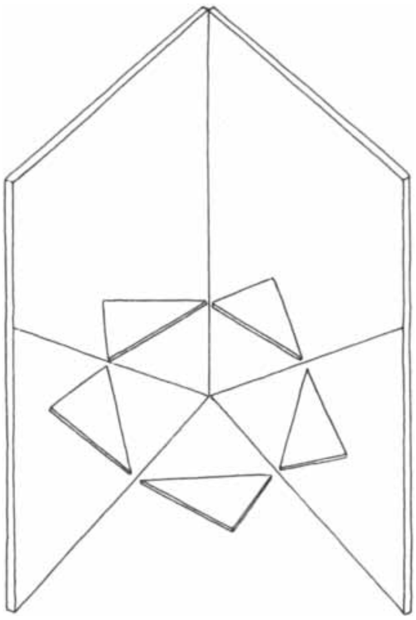
Next I trimmed the white edges off the photographs and put them in the stereoscope. As I viewed the pictures through the instrument I slid one of them across my field of view until it approached the correct position, whereupon the photographs suddenly snapped together into a single image with depth. Then I taped the pictures together and mounted them on stiff cardboard to keep them at the right spacing.

When the photographs were correctly positioned, my left eye saw more of the left side of the scene than my right eye did. This difference is automatic if you rotate or laterally displace the camera. Even if I photographed exactly the same scene without moving the camera between successive exposures, I could still get a reasonably good three-dimensional illusion by fiddling with the position of the photographs in my stereoscope. I find, however, that this does not work for everyone.

Making your own stereo cards is great fun. You could even use an old Polaroid snapshot if you have it duplicated, either by Polaroid or by making a photograph of it yourself. For new pairs of photographs the best type of scene to shoot is one with objects in both the foreground and the background.

You normally assign depth to a scene with the aid of several clues, among them the fact that you usually know the relative sizes of the objects you see and so can judge their distance partly by the relative angles they subtend in your field of view. Also of help are shadows and the converging geometry of things such as walls and roads as they are seen receding from you.

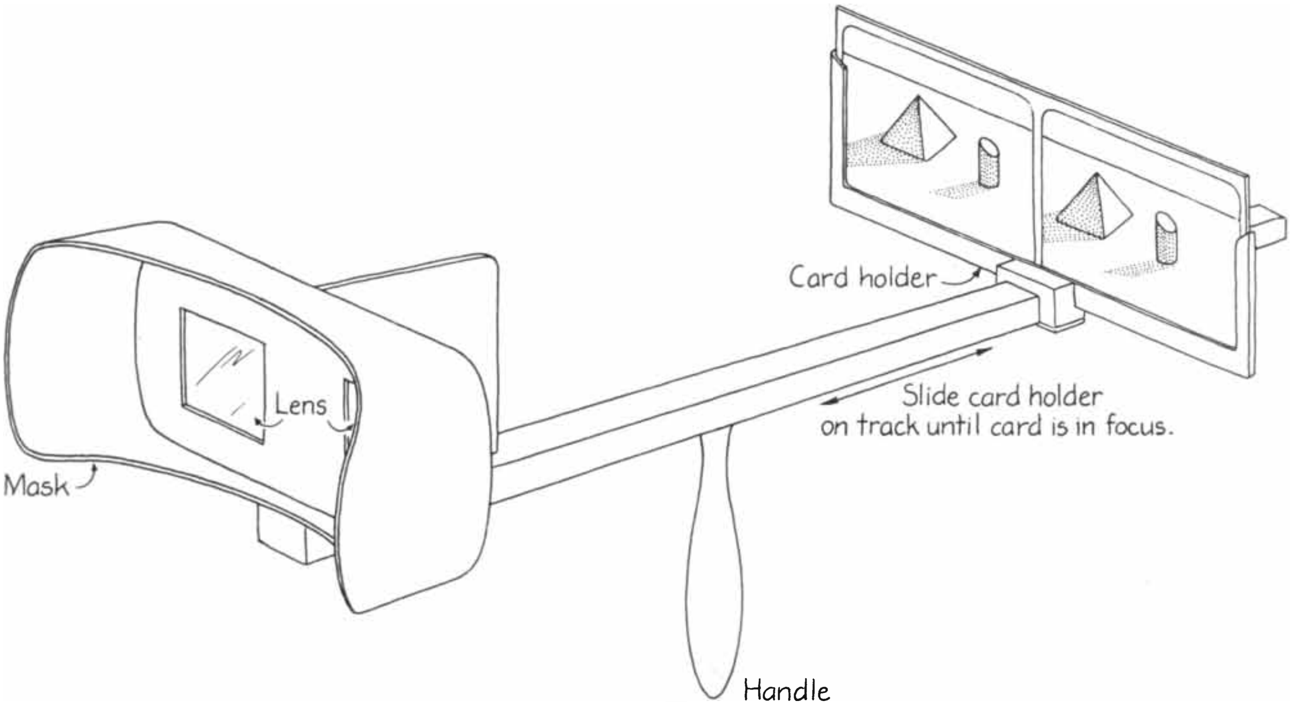
You also unconsciously sense the accommodation and convergence of your eyes as you view an object in a scene.



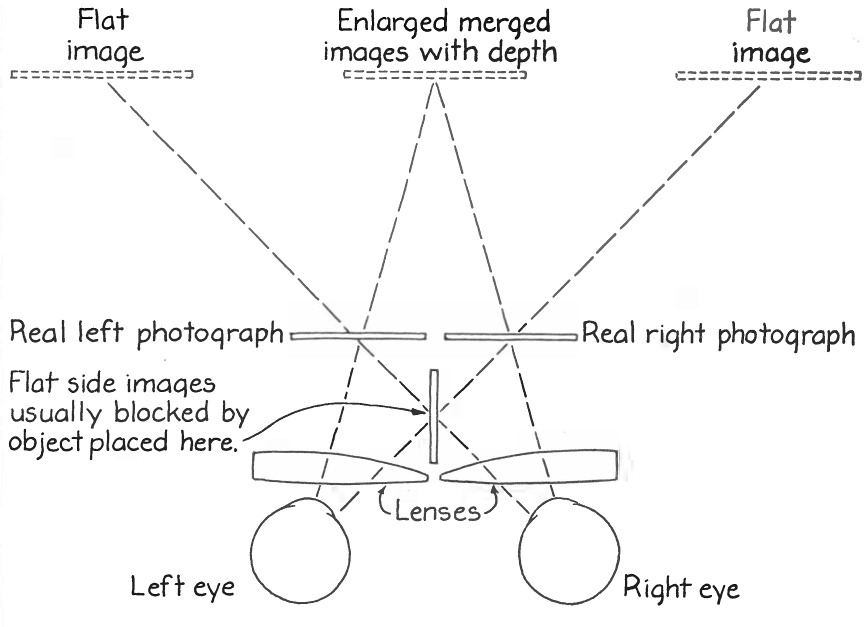
A multiple-reflection pattern

Accommodation reflects the amount of muscular stress that must be placed on the crystalline lens of the eye to alter its shape so that the image of the object is in focus on your retina. This clue to the depth does not depend on an interplay between the two eyes; it is monocular.

Convergence is a binocular clue, having to do with the angle between the optical axes of the eyes. The axis is an imaginary line running through the cen-



Components of a stereoscope



Optics of a stereoscope

ter of the lens and into the fovea, the pitlike depression on the retina where the photoreceptors are the most densely packed. Normal viewing involves moving the eyes to the left or the right until the image of the object falls on the fovea. For a distant object the optical axes from the two eyes are nearly parallel. For a nearby object they are at a significant angle. The muscle control necessary to make the optical axes converge on an object helps you to gauge the distance of the object.

Suppose you view a collection of objects that are at different distances. You will have a sense of their different depths even if you do not look at them individually because the positions of their images on the retina around the fovea will be different for the two eyes simply because of the separation of the eyes. The difference in position with respect to the fovea will be greater for a nearby object than for a distant one. Through this effect the brain can assign proper depths to the objects.

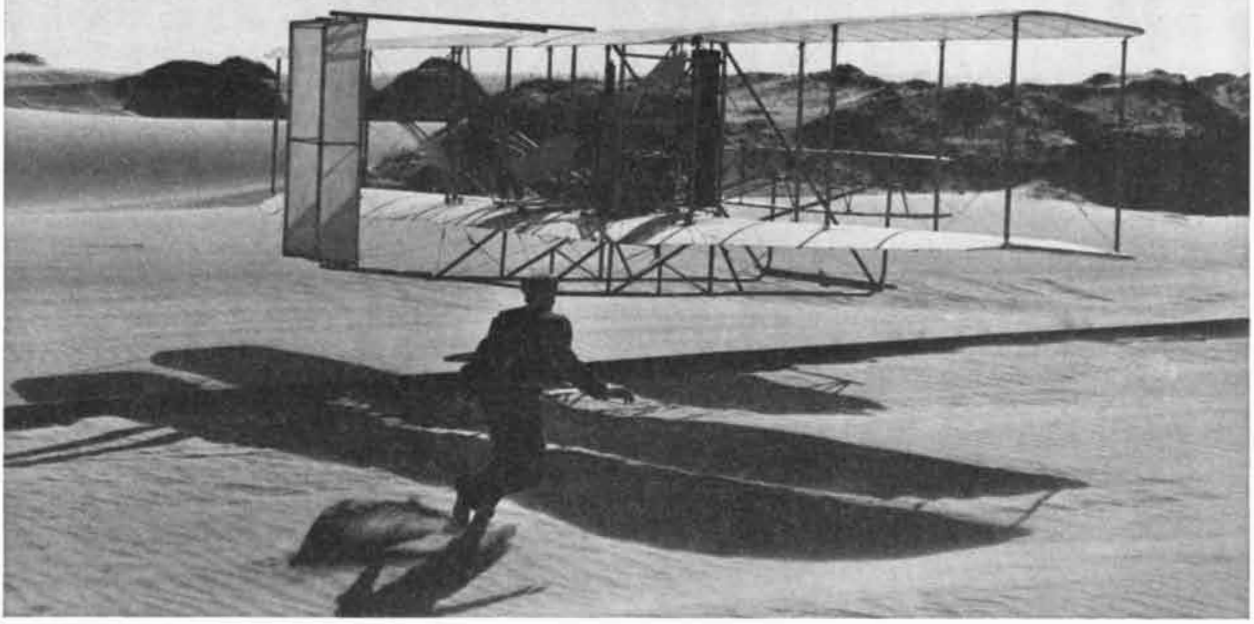
In re-creating depth from a two-dimensional photograph the problem is to trick the brain into ignoring the clues that suggest it is seeing a photograph. When you look at a photograph, both the focusing of each eye and the convergence between them tell you that you are looking at a photograph rather than a real scene. Two adjacent photographs are no better; your brain knows you are only looking at two adjacent photographs.

The stereoscope enables you to focus on the photographs while you are forcing your eyes to converge; the result is that the images occupy the same positions on the retinas they would occupy if you were viewing the real scene. This clue is so strong, at least for people who can see the three-dimensional illusion, that you are convinced there is depth in the fused pictures. The brain so wants to assign depth that the photographs in the stereoscope do not have to be exactly in their proper position. As they come close to the proper position the brain suddenly snaps their images together and immediately begins to assign depth. It apparently can do this to some degree even with photographs that are exact duplicates.

Although a stereoscope is a convenient means of getting the illusion, it is not strictly necessary. You can see depth in a stereo card alone by means of a simple trick. After focusing your eyes on an object about five feet away quickly slip a stereo card into your field of view. As you are focusing on it, try to maintain the same convergence of your eyes as you had for the object at five feet. With some practice this trick will enable you to merge two images from the stereo card into a single image having depth, just as you do with a stereoscope. I can actually create this three-dimensional illusion at will and without the trick by merely staring at a stereo card while deliberately adjusting the convergence of my eyes until the two images, one from each eye, merge.

With either the trick or the brute-force technique what you see is noticeably different from the illusion in the stereoscope. Without the instrument you see, on each side of the image with depth, an additional two-dimensional image of the scene in the stereo card. Greenslade and Green offer a demonstration to explain the two flat images. Focus your eyes on an object about five feet away, simultaneously holding two pencils vertically about 10 inches in front of your eyes and about three

On December 17, Orville and Wilbur fly. Be there.



Be at Kitty Hawk as the Wright Brothers conquer the sky.

Go along with them as their primitive flyer with its sputtering engine struggles aloft for the first time.

With their breathtaking flight of 12 seconds, Orville and Wilbur succeed where so many others have failed.

But the unlikeliest part of their story is what happens next.

On December 17th, the 75th Anniversary of the first powered flight, live the *human* side of their adventure with them.

"The Winds of Kitty Hawk," an original two-hour teleplay, will star Emmy Award-winner Michael Moriarty and David Huffman in a Charles Fries production.

You know how the story ends, but the incredible part is how it all began.

"The Winds of Kitty Hawk." The story of two very human heroes. An ITT Special on NBC-TV, Dec. 17 at 8 p.m. (ET), 7 p.m. (CT), 8 p.m. (PT).

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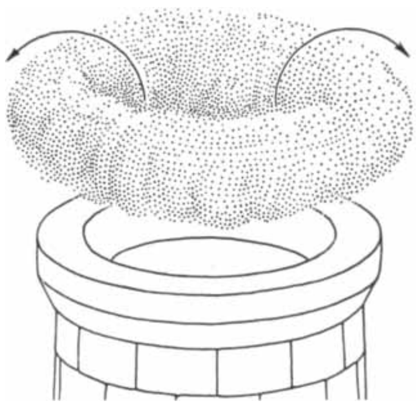


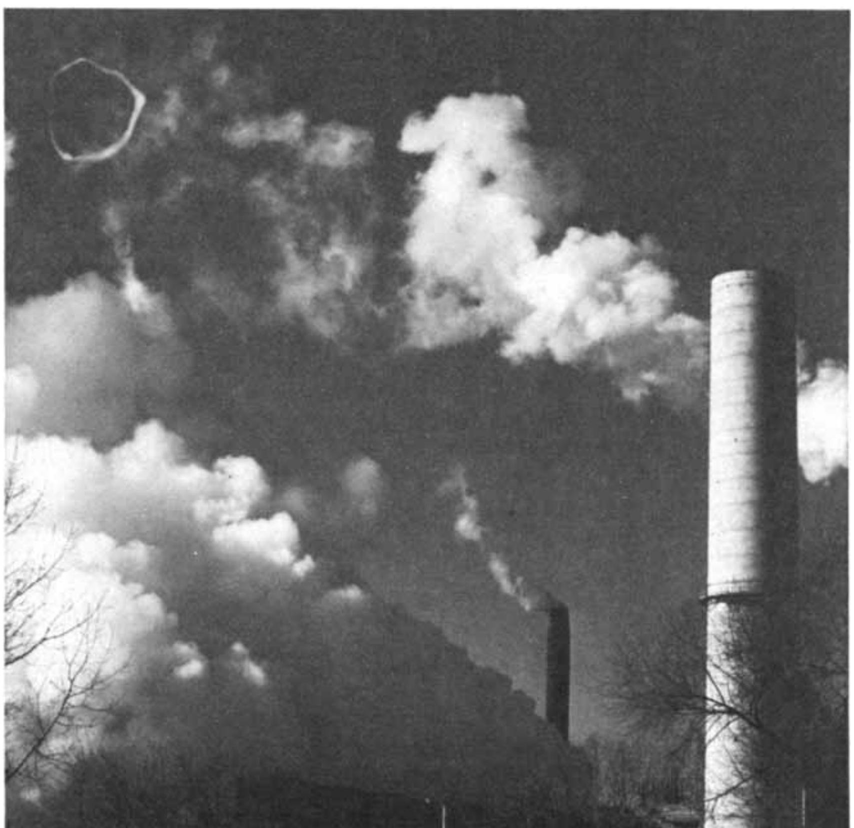
A smoke-ring vortex

inches apart. You will notice that you see not two pencil images but four, two with each eye. As you concentrate on the distant object, move the pencils closer together until the two inner images merge. It is this merging of images that forms the three-dimensional image when you view stereo cards through a stereoscope. With the pencils the two outer images are still present: the left image is the left pencil as seen by the right eye and the right image is the right pencil as seen by the left eye. In the stereoscope those two outer and distracting images are eliminated by the thin wall in the apparatus that is positioned between the eyes and perpendicular to the face.

In May I discussed the shape of smoke plumes from chimneys under various vertical temperature profiles. G. Frederick Stork of Chevy Chase, Md., has sent me a photograph of a rare occurrence: a smoke ring. Although he did not see the emergence of the ring, he and I believe it must have been blown from the chimney that appears in the foreground. As a puff of hot gas is sent through a circular opening the viscosity between the wall and the gases adjacent to the wall forces those gases to move slower than the gases in the center, causing the latter to curl around the former once they have emerged. The curling creates the ring structure. The stack must have somehow condensed water in the puff and so made the ring visible.

As many readers pointed out, I should make three corrections in my July article about chemical oscillations: (1) The oxidation of a chemical means that electrons are removed and reduction means that electrons are added, not vice versa. (2) A two-normal solution of sulfuric acid is equivalent to a one-molar solution, not the other way around. (3) In adding Tritox X-100 surfactant or "photoflo" in A. T. Winfree's oscillator use one microgram per liter.

Winfree still has samples of his chemical waves for which you can send. In-



G. Frederick Stork's photograph of a smokestack's smoke ring

formation on ordering these beautiful and inexpensive samples appears on page 156 of the July issue.

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SCIENCE/SCOPE

A bright, high-resolution, large screen liquid crystal projection system that can display dynamic tactical military situations in real time has been delivered to the U.S. Navy for evaluation. It can project virtually anything that can be displayed on a cathode ray tube either in raster scan or random scan mode. Typical applications include symbols, alphanumerics, geographical maps, and text. Its bright, clear display reduces requirements for specially controlled lighting during briefing sessions or command conferences.

The system uses a liquid crystal light valve developed by Hughes, and has a reliability never before achieved in large screen displays. Mean-time-between-failure is estimated at 5000 hours, and, as no consumables are required, this results in lower operating and maintenance costs. Other features are 1000 line resolution and 30 millisecond response time.

Television broadcasting direct from satellites to schools, hospitals, hotel and motel chains, and other institutional users may be one result of a new NASA program. Hughes will develop for NASA's Goddard Space Flight Center a low-cost, mass-producible 12-GHz receiver for TV reception from broadcast satellites. Objective: a smaller, less expensive receiver to sell for under $1000. Current ground terminals are in the 4-GHz frequency range, and cost between $20,000 and $30,000. The higher frequency range has already been approved by the FCC for domestic TV satellite systems.

Career growth opportunities exist at all levels at Hughes Support Systems in Los Angeles for a variety of engineers qualified by degree or extensive work experience. They include: design and development of automatic test systems for major Hughes radar, electro-optical, and laser programs; field engineering posts throughout the U.S. and the world offer travel, autonomy, and responsibility for the life cycle of Hughes electronic systems. Other positions include training customer personnel and publishing technical manuals (requiring people-oriented engineers with strong oral and written communications aptitudes). For immediate action, phone collect (213) 670-1515, ext. 5444. Or send your resume to Professional Employment, Hughes Aircraft Company, P.O. Box 90515, Los Angeles, CA 90009.

New product from Hughes: a new high-power amplifier, designed to operate in the earth terminal transmitters of commercial satellite communications systems using the new 12/14-GHz frequency (Ku-band). Designated Model 9225H-04, it provides 250 watts of CW output power at the 14.0- to 14.5-GHz satellite uplink frequency band. Upcoming programs that will use this frequency include SBS (Satellite Business Systems), Canada's Anik B and C, and Intelsat V. The amplifier features extensive monitoring capability, including the ability to switch all operational status indicators and control switches to a remote control. A full-year, unlimited-hour warranty is offered.

Creating a new world with electronics

HUGHES

HUGHES AIRCRAFT COMPANY

ANNUAL INDEX

The following index lists all the authors and articles that appeared in SCIENTIFIC AMERICAN *during 1978. Also indexed are "Mathematical Games" and "The Amateur Scientist."*

AUTHORS

The most powerful argument for our new receiver is not just power.

True, it's tempting to be swept up by our power.

150 watts per channel minimum RMS at 8 ohms, from 20Hz to 20kHz, with no more than 0.07% Total Harmonic Distortion, is nothing to sneeze at.

But raw power means nothing. What's important is how that power is delivered. In the case of the STR-V7, it's brought to you by Sony in a very classy package.

You get a combination of features and controls that are impressive on their own—but almost unheard of in a single machine.

To start with, we've built in a Dolby system, for decoding Dolbyized FM broadcasts.

The advantages of our tuner, though, need no decoding. They include a normal and narrow FM IF bandwidth selector. It makes life simple for people in areas where their signals are crowded together elbow to elbow.

In our preamp section, the V7 comes equipped with a special phono EQ circuitry. Thanks to Sony's high IQ, it allows for direct connection of a low-output, moving-coil cartridge phono source. Without calling for an external step-up transformer or pre-preamp.

When you're gifted with as much power as the V7, you need a way to keep track of it. This receiver keeps tabs with two power-output meters, monitoring the power being fed to the speakers. So overload can't result from oversight.

And all that power comes from our direct coupled DC power amp. And our power is stable, thanks to a high-efficiency, high regulation toroidal-coil transformer.

There's a lot more to the STR-V7 than power. This receiver takes the best that contemporary technology has to offer, and offers it in a single machine.

Other manufacturers may have the power to bring you power. But only Sony has the power to bring you more than just power.

SONY® AUDIO

ARTICLES

MATHEMATICAL GAMES

THE AMATEUR SCIENTIST

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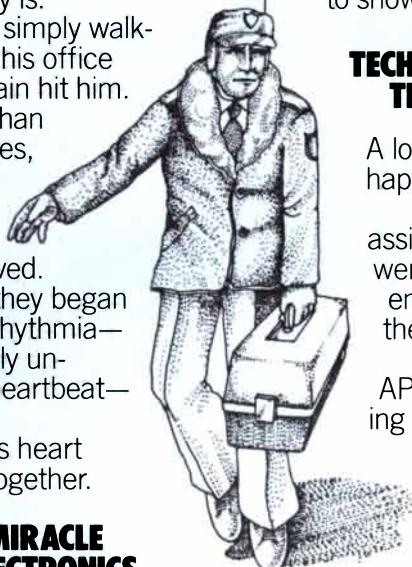
MOTOROLA HELPED BRING

His name isn't important.
His story is.
He was simply walking back to his office when the pain hit him.
In less than three minutes, an ambulance with two paramedics arrived.
But as they began to work, arrhythmia—erratic, wildly uncontrolled heartbeat—set in.
Then his heart stopped altogether.



A MIRACLE OF ELECTRONICS.

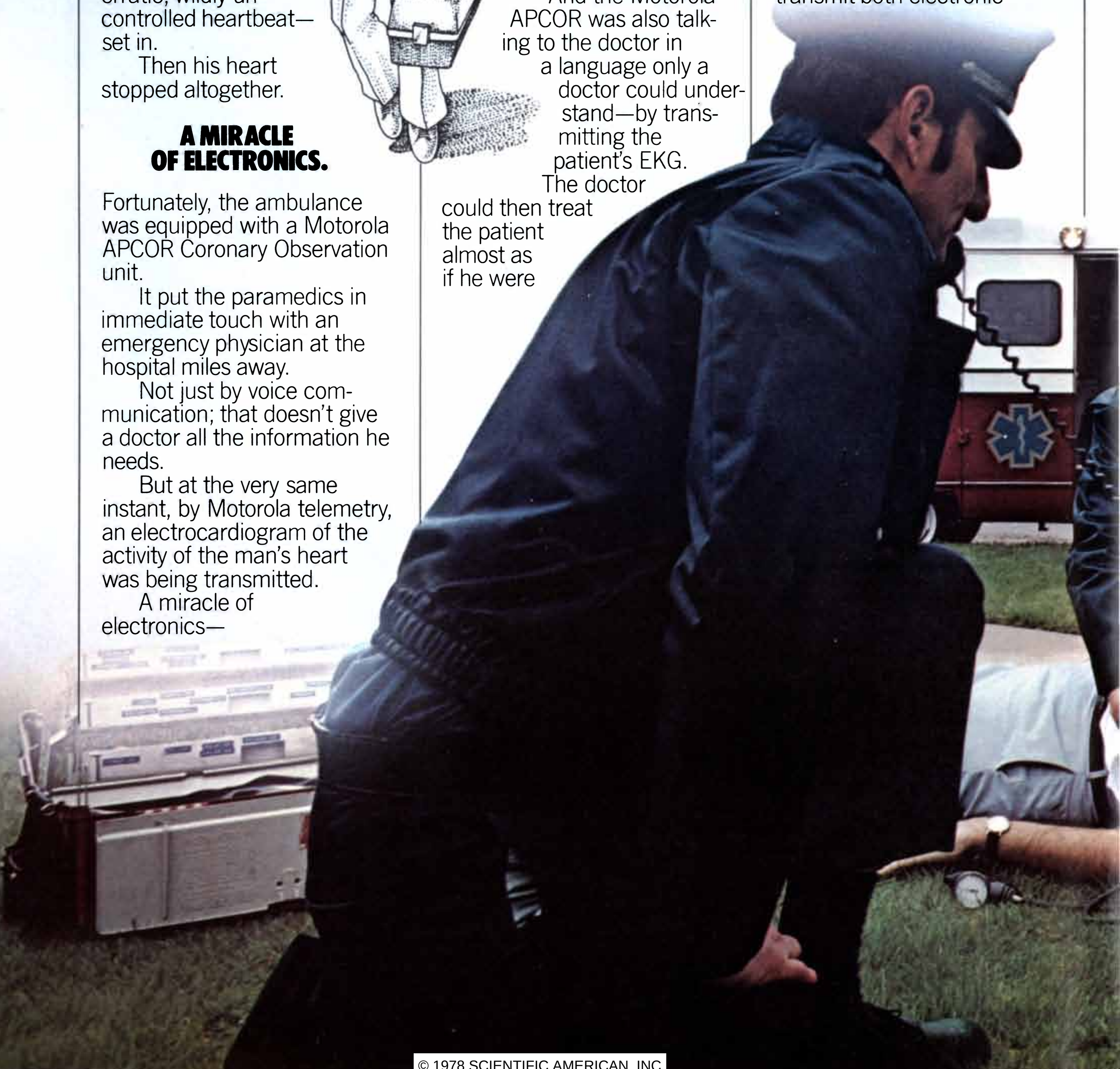
Fortunately, the ambulance was equipped with a Motorola APCOR Coronary Observation unit.
It put the paramedics in immediate touch with an emergency physician at the hospital miles away.
Not just by voice communication; that doesn't give a doctor all the information he needs.
But at the very same instant, by Motorola telemetry, an electrocardiogram of the activity of the man's heart was being transmitted.
A miracle of electronics—microelectronics—was about to show what it could do.

TECHNOLOGY DOES THE TALKING.

A lot of things were happening at once.
The medical assistants at the scene were talking to the emergency room at the hospital.
And the Motorola APCOR was also talking to the doctor in a language only a doctor could understand—by transmitting the patient's EKG.
The doctor could then treat the patient almost as if he were on the spot.
In a few minutes, the man's heart began to beat. He was once again on his way to being alive, in every sense of the word.

MICROCIRCUITS MAKE IT HAPPEN.

APCOR is made possible by Motorola microcircuits, tiny information processors that transmit both electronic

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