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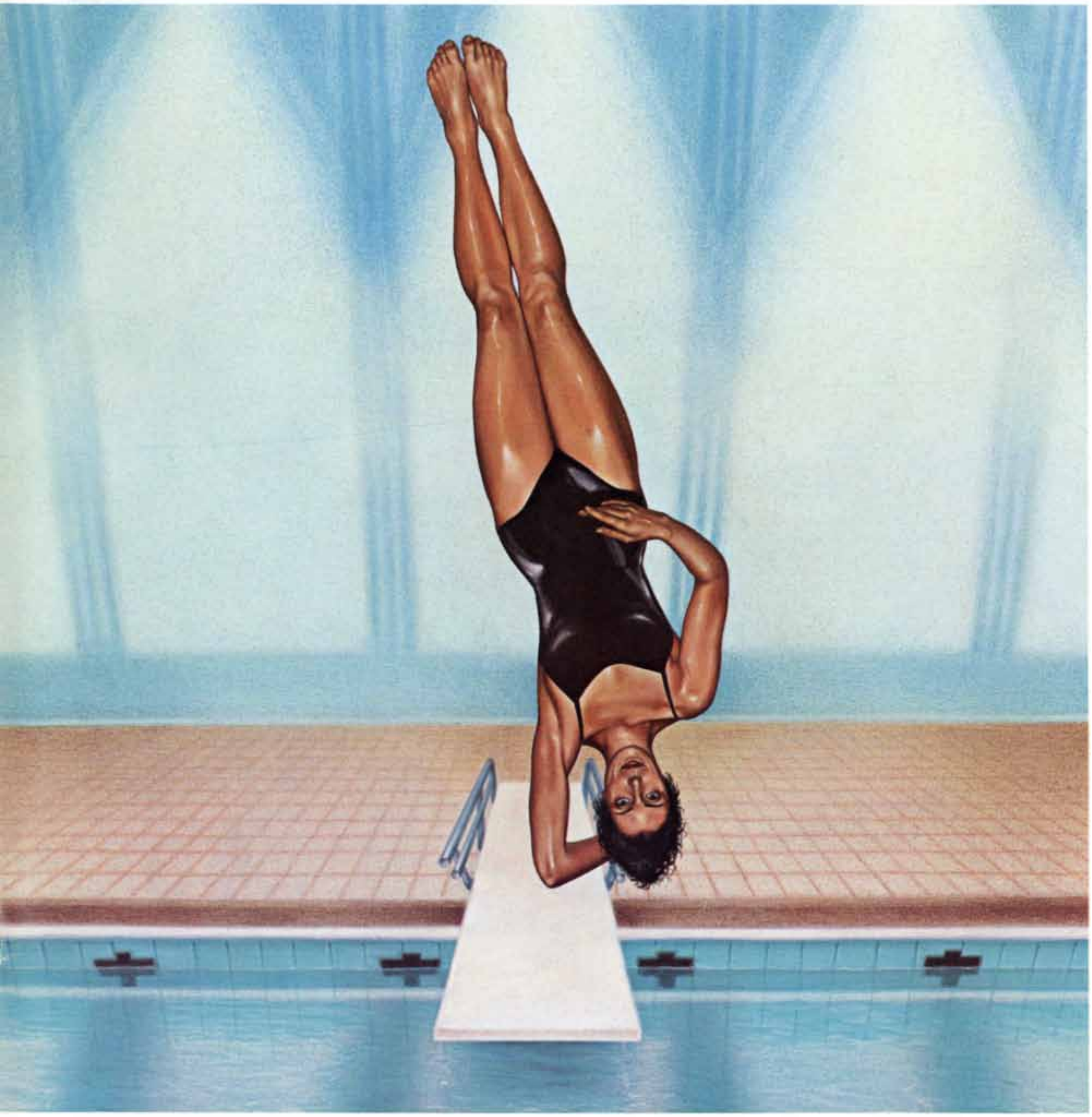


PHYSICS OF SOMERSAULTING

$2.00

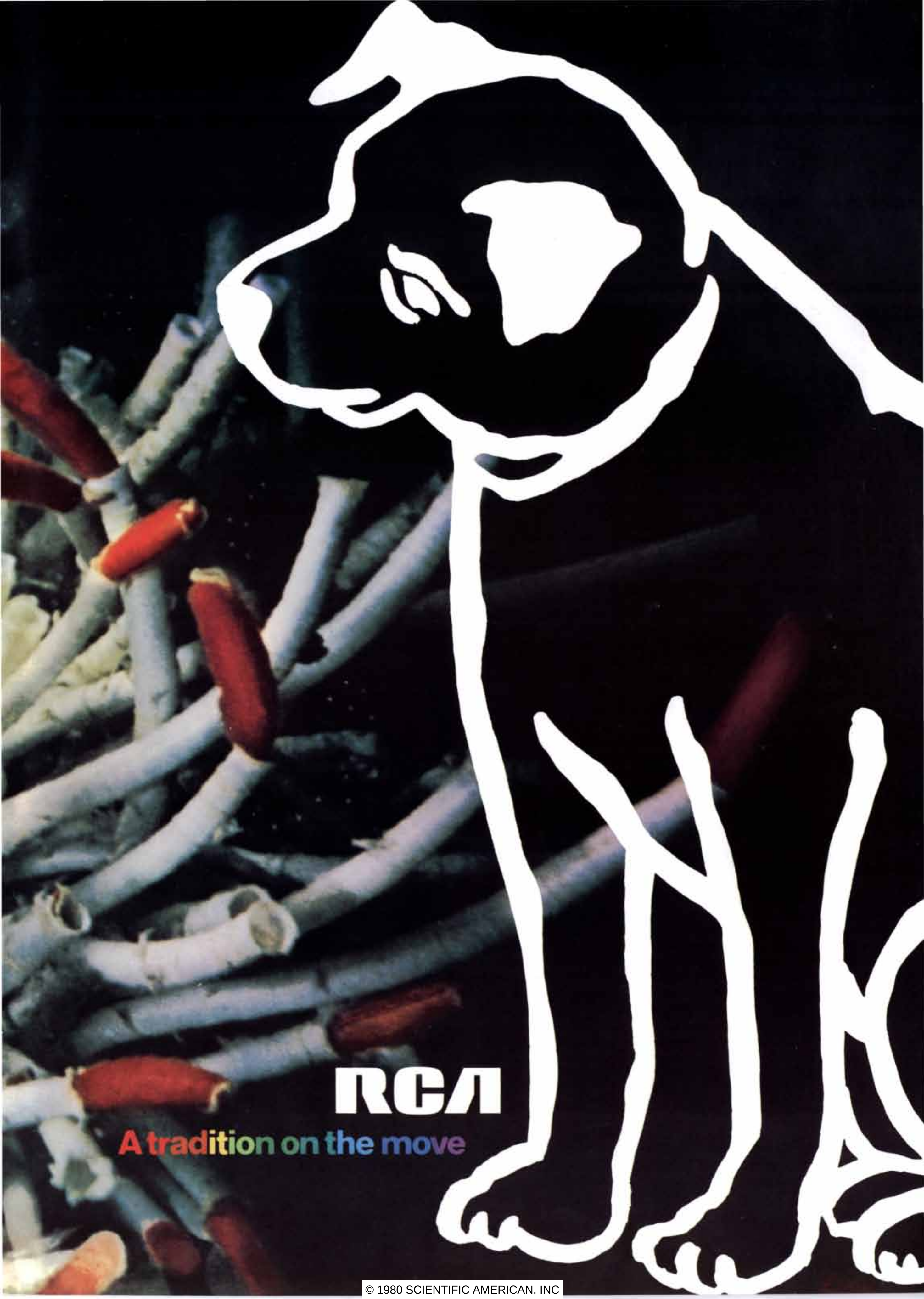
March 1980

A revolutionary RCA TV camera discovers new forms of life 9,000 feet beneath the Pacific.

Giant tube worms, more than 8 feet long, made their television debut on a National Geographic special thanks to a solid state RCA TV camera that has no tubes at all. This tiny TV camera, developed by RCA scientists and engineers, isn't much bigger than a home movie camera. It uses three image sensors, called CCD's (Charged-Couple Devices), in place of standard vidicon tubes.

The image sensors turn a visual image into thousands of electrical signals which are processed and displayed on a TV monitor as exceptionally clear, vivid pictures.

The CCD Camera is a product of RCA research–the kind of dedicated research that has been a tradition at RCA ever since Nipper started listening to His Master's Voice. Today, research and development of electronic products are funded at the highest level in our company's history. Our commitment is, as it has always been, to the advancement of technology–to the creation of products that expand the human horizon, whether at 9,000 feet below the Pacific or millions of miles away in space.


RCA
A tradition on the move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Established 1845 SCIENTIFIC AMERICAN March 1980 Volume 242 Number 3

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DEPARTMENTS

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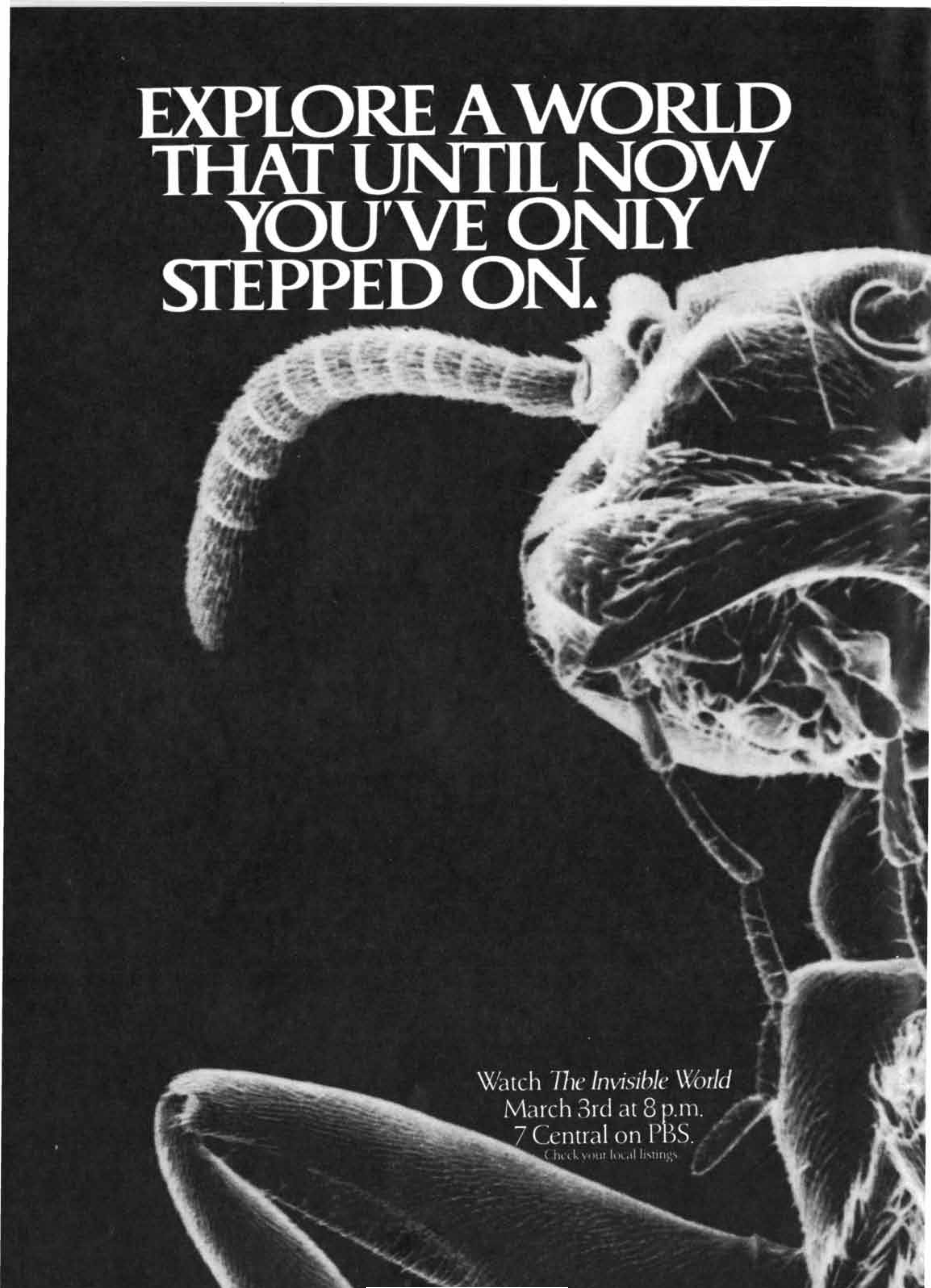
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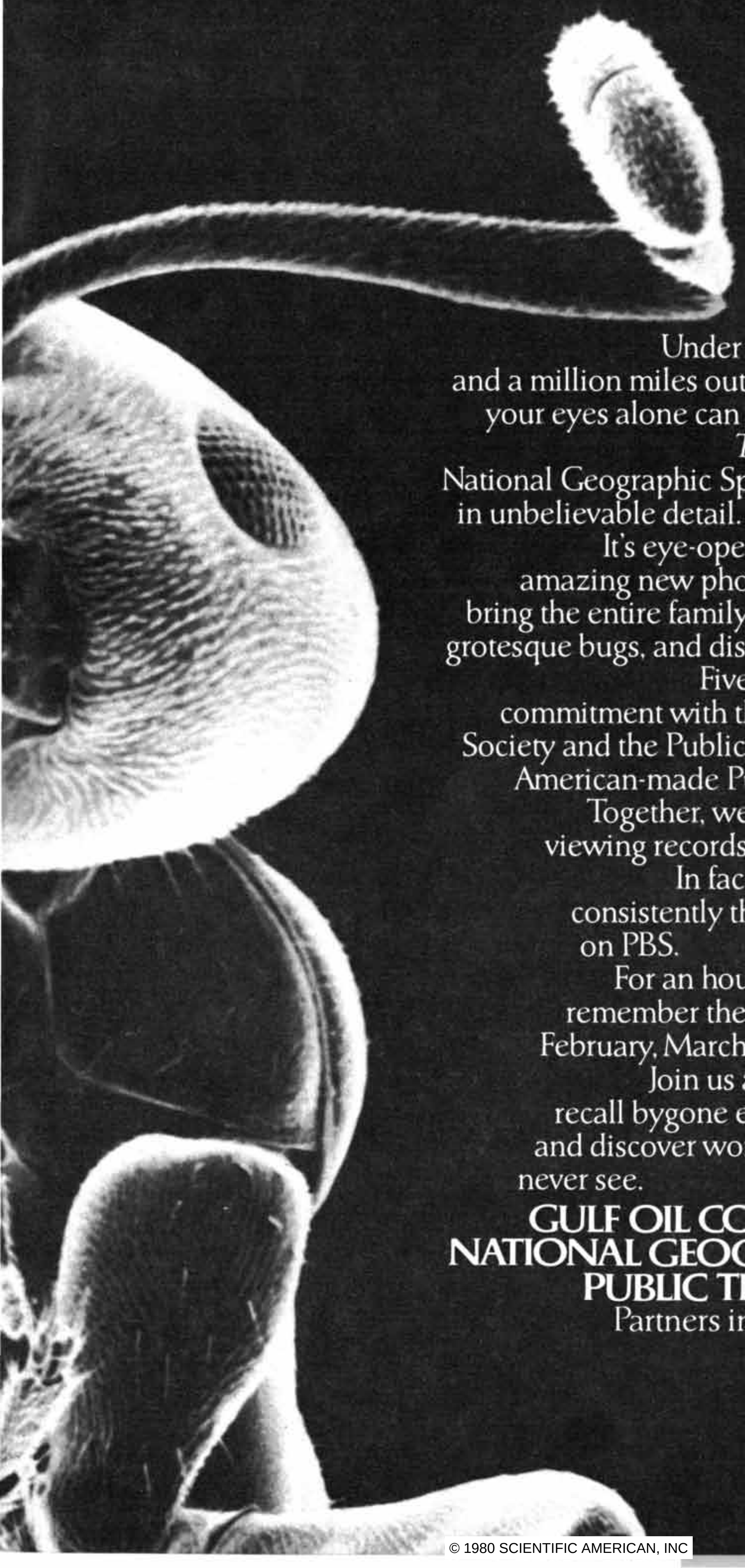

THE COVER

The painting on the cover is a head-on view of a diver in the course of executing a one-and-a-half somersault with a full twist from a one-meter springboard, based on a motion-picture study of the dive. Although at this stage the diver's body is straight, it is not vertical, whereby hangs a tale. After the diver leaves the springboard no additional torques, or rotational forces, can be applied to her body. (The torques resulting from the friction of the air are negligible.) Accordingly any maneuver the diver executes must be accomplished within the constraints of the conservation of angular momentum: no momentum can be added or subtracted. Somersaulting and twisting therefore call for shifting the distribution of mass within the system represented by the body, as by extending the arms outward or tucking the knees against the chest. In the one-and-a-half somersault with one twist shown on the cover the diver's slight inclination from the vertical is necessary for her to be able to complete the twist (see "The Physics of Somersaulting and Twisting," by Cliff Frohlich, page 154).

THE ILLUSTRATIONS

Cover painting by Robert G. Alcorn

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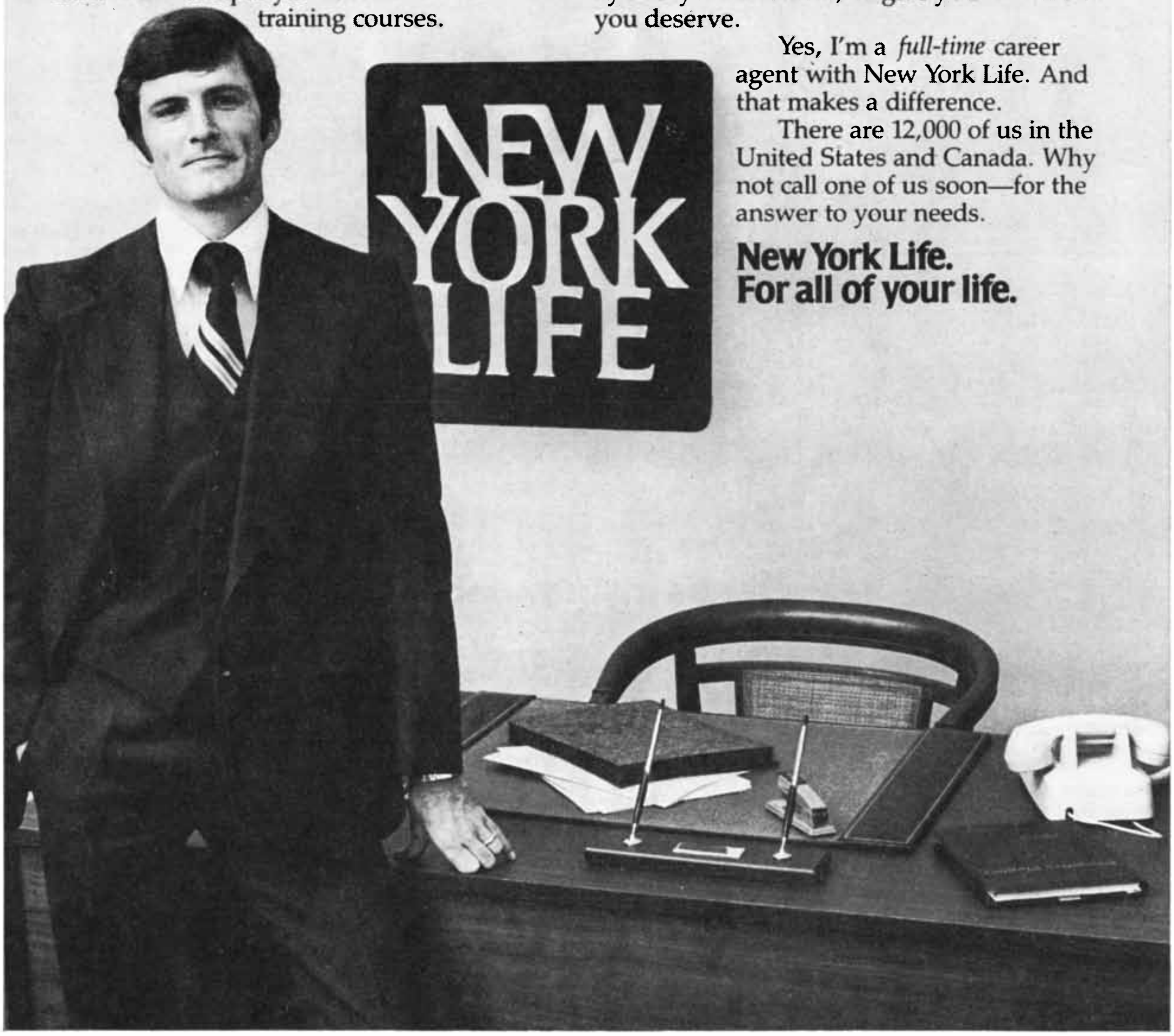
NEW
YORK
LIFE

LETTERS

Sirs:

It is not only in Europe and North Africa that the danger of eating fresh-killed quail was known [see "Science and the Citizen," SCIENTIFIC AMERICAN, January]. In Num. 11:31–33 appears the following passage: "And there went forth a wind from the Lord, and brought quails from the sea, and let them fall by the camp, as it were a day's journey on this side, and as it were a day's journey on the other side, round about the camp, and as it were two cubits high upon the face of the earth. And the people stood up all that day, and all that night, and all the next day, and they gathered the quails: he that gathered least gathered ten homers: and they spread them all abroad for themselves round about the camp. And while the flesh was yet between their teeth, ere it was chewed, the wrath of the Lord was kindled against the people, and the Lord smote the people with a very great plague."

GIDEON YUVAL

State University of New York at Buffalo
Amherst, N.Y.

Sirs:

In an effort to clear up the confusion concerning Halley's comet in your department "Letters" for December, 1979, I should like to make the following points.

The comet of 1680, and not Halley's comet of 1682, played an important part in the studies that led to Newton's *Principia* (1687). Although Newton initially thought the pre- and postperihelion apparitions of the 1680 comet were two different comets, he soon realized they were the same object. This realization, along with his theory of cometary motion, played an important part in confirming his theory of gravitational attraction. Working with the technique outlined by Newton in the *Principia,* Halley suggested in 1695 that the comets seen in 1682, 1607 and 1531 were the same object. In 1705 Halley published his correct prediction that the comet of 1682 would return in 1758. In the same treatise he erroneously suggested that the comets seen in 1532 and 1661 were the same object, and in a revised edition of his work he also erroneously suggested that the comets seen in 1680, 1106 and 531 and in 44 B.C. were the same object. The latter comet was thought to have an approximate period of 575 years.... Although it is comforting to know that a modern, informed, chronological listing of cometary appearances has recently been initiated, it should be pointed out that the Chinese have had such a record for nearly two millenni-

Friendly Comparison

Can JS&A offer a better telephone answering unit than the first one we introduced? Here's the story of American competition at its finest.

We've seen them all. Every telephone answering unit has its advantages and disadvantages.

So when JS&A selected our first telephone answering unit three years ago and called it the best remote system available, it soon became one of the most popular units on the market. Since 1976, JS&A has sold thousands of them.

SERIOUS COMPETITION

But that was three years ago. It finally took an enterprising company called Olympia to develop and introduce what we would call the first serious competition to our first telephone answerer.

So JS&A had a dilemma. Here we were, with an excellent relationship with a major supplier, and yet our reputation demands that we offer our customers only the most advanced products. Do we continue to carry both units, or do we break off relations completely and introduce a competitive model? To make the decision more difficult, you first have to understand the new technology in the Olympia unit.

A FAIR COMPARISON

The Olympia Master Telephone Recorder is a microprocessor-based system with a few features that make it a more advanced unit than the industry leader.

But to provide a fair comparison, there are a few disadvantages with the Olympia. The Olympia does not have a call counter that tells you at a glance how many calls you've received. And its outgoing announcement is not recorded as fast as with our first unit. But there are so many other features and advanced technology that the Olympia deserves your consideration.

ERASE OR SAVE

Most remote units and the Olympia have remote pagers. When you want to retrieve your messages, simply hold the pager up to the telephone, press a button, and the telephone answering unit rewinds to the start of your first message and plays them back.

That's great. But there was a disadvantage to the others. After you listened to your messages, you could not rewind. If you wanted to rewind to the beginning of the tape, you had to call your unit a second time. That's only a slight problem if you're calling locally from a phone booth, but very costly when you're calling long distance. And if you don't call back right away and rewind, you have another problem. Later, you'll have to listen to all those messages you previously heard because the unit doesn't know where the old messages stop and the new ones start.

The new Olympia Master Recorder has solved that problem. You have a choice. You can either hang up after you've heard your messages or you can rewind them to the beginning while you're on the phone.

NO MESSAGE/LAST MESSAGE

Let's say you call in and there are no messages for you. The Olympia has a special beep tone that tells you the moment you call in that there is no message. Or let's say there are three messages waiting for you. After the three messages are played back, another beep tone signals you that you've finished your last message. There is no provision like this on any of the popularly priced units.

YOUR OWN TAPE

The Olympia uses one commercially available cassette tape that will last a few years with normal use. Today's most popular unit uses a built-in tape that will last five years, and costs $17 to replace. With the Olympia unit, you remove the old cassette and pop in the new one which shouldn't cost more than $2.

TAPE SPEED

It costs time and money to listen to your old messages and to rewind. So the Olympia not only improved the concept by giving you a choice, they also improved the tape rewind speed. Now, when you retrieve your calls, your rewind time is faster than many other systems and as fast as the system we formerly sold.

Not only is the Olympia faster, but it measures only 2¼"x 6"x 10" and weighs only 36 ounces. You can place your phone on top of the unit or next to it without cluttering your desk.

We could probably present reasons why the Olympia Master Recorder will pay for itself with just the time you save retrieving messages–but there's more.

SINGLE SYSTEM

You record your outgoing announcement on one track of the cassette tape and you receive your incoming messages on the other side. This single cassette approach reduced the costs of the Olympia below those of the conventional recorders that required two separate record and playback systems. And like other units, when you play back your tape, you hear only your incoming messages–never the outgoing announcement.

To record an outgoing announcement, you simply press the record button and talk into a microphone supplied with the unit. The unit will record a 17 second outgoing announcement and a 30 second incoming message. Our previous unit records a 20 second outgoing announcement and a 30 second incoming message.

AND THEN THERE'S VALUE

Our previous unit sold for $269.95. The Olympia sells for only $169.95–a $100 savings before you even start to use the system.

But don't take our word for it. Order an Olympia from us on our 30-day telephone answering test. Personally see how quickly you can retrieve or rewind your messages without having to call in twice. See how this compact unit fits on your desk. And above all, note the quality and workmanship of this fine piece of equipment.

Then after 30 days of messages, decide if you want to keep your unit. If not, no problem. Just return your unit for a prompt and courteous refund including your $3.50 postage and handling.

If you decide to keep it, great. You'll own the most advanced unit of its kind. The Olympia Master Recorder is sold exclusivly by JS&A. We're America's largest single source of space-age products, and we have sold more telephone answering units than many of our competitors combined. We know the market.

MULTI-NATIONAL CORPORATION

Olympia is a multi-national corporation with eight national factory service and service-by-mail facilities–further assurance that your modest investment is well protected.

To order your Olympia, send a check for **$169.95** plus $3.50 postage and handling made payable to JS&A Group, Inc. (Illinois residents add 5% sales tax.) Credit card buyers may call our toll-free number below. We'll send your unit complete with recording microphone, one cassette tape, remote pager, AC adapter, instructions, and a 90-day limited warranty–everything you'll need for your 30-day test.

When we realized that the Olympia was the unit we should market, we called our previous supplier and told them of our decision.

In today's changing times, technology does not stand still. Despite our excellent relationship with our previous supplier, we felt it our obligation to introduce today's most advanced products–even at the risk of losing a valuable supplier.

If you're considering a new telephone answering unit, we can't recommend a better system than the Olympia Master Recorder. Why not order one at no obligation today?

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ums. In fact, we have recently used these ancient Chinese observations, along with the more modern observations, to improve the orbit calculations of Halley's comet. On the basis of these calculations the search for Halley's comet in advance of its expected spectacular apparitions of 1985 and 1986 is already under way at several observatories.

DONALD K. YEOMANS

Jet Propulsion Laboratory
California Institute of Technology
Pasadena

Sirs:

The speculation that Isaac Newton's famous breakdown was actually the result of heavy-metal poisoning ["Science and the Citizen"; SCIENTIFIC AMERICAN, December, 1979] is both plausible and suggestive of the possibility that a similar misfortune may have befallen another giant of physics.

In 1839 Michael Faraday, following the period of his most brilliant work, suffered a breakdown characterized by debilitation and loss of concentration so severe that he was unable to continue his researches until 1844, when he partially recovered. Faraday was in the habit of performing both chemical and electrical experiments involving mercury, and it seems likely that he inhaled its vapors. It would be interesting if some chemical evidence of the kind employed in New-

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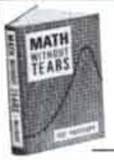

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ton's case could be found to either prove or disprove this hypothesis.

RICHARD B. KIDD

City College of San Francisco
San Francisco, Calif.

Sirs:

The description of the cover of your November 1979 issue, showing dung beetles rolling a ball of elephant dung, states that the female "will ride along passively" on top of the ball.

I am not persuaded that this is strictly true. If the female walks forward on top of the turning ball (backward in relation to the ground), she contributes to its rotation as a logroller spinning a log in the water does. Further, if she is not precisely on top of the ball but is on its forward curve, then she is climbing up the ball and her weight contributes to its rotation as does the weight of a circus bear that stands on a ball and rolls it up an incline.

You have not given Mom any credit for helping Pop, if indeed she does.

PENDLETON TOMPKINS, M.D.

San Mateo, Calif.

Sirs:

In your department "Science and the Citizen" for November, 1979, you covered some of the work of our laboratory on gluons. . . . I want to congratulate you on a very informative article.

Still, I hope you will not mind if I make a few comments. You say that the first detailed analysis of the results has been reported by a group led by Samuel C. C. Ting. I should like to remark that the TASSO experiment had reported first preliminary results at the European Physical Society conference in Geneva in July, and detailed and complete accounts of their work were presented by all four PETRA experiments (JADE, MARK J, PLUTO, TASSO) at the Fermi National Accelerator Laboratory conference in August. Indeed, I believe it was the results of the four experiments' corroborating and complementing one another that made the discovery of the gluon convincing.

It is also mentioned in the article that the third (the gluon) jet cannot be clearly resolved from the other two jets. Clear and beautiful pictures of three-jet events have been obtained by TASSO, and there are a lot more also from the other experiments. I believe we are now well on the way to investigating the characteristics of the gluon.

H. SCHOPPER

Deutsches Elektronen-Synchrotron
Hamburg

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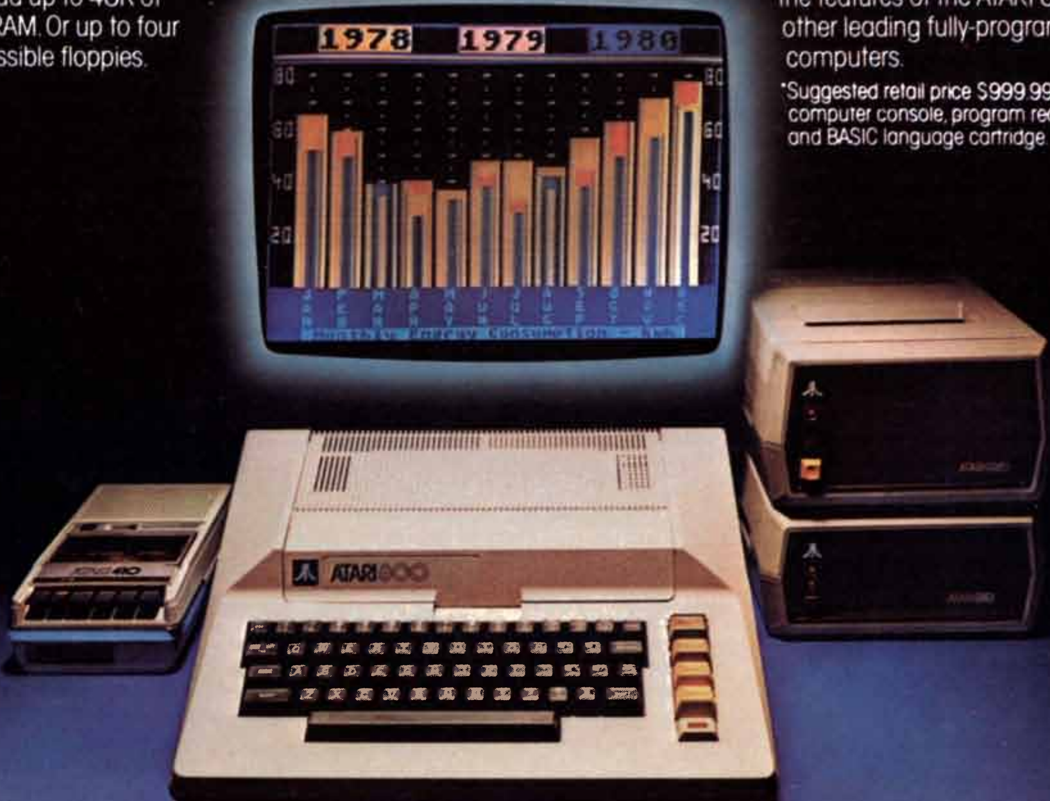

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Chez Renault

Profiles from the Paris Factory/One of a series

"As a 16-year-old student I spent the very first working summer of my life at the Renault plant near Paris, inspecting gear-box assemblies. To my surprise I soon learned this industrial giant had a very human side. With this insight, the whole direction of my life changed. Now, more than thirty years later, this human side of car-making continues to absorb me."

Dr. Claude Tarrière
Chef, du Laboratoire de Physiologie et de
Biomecanique/La Garenne-Colombes
Ingénieur Principal de la Direction
Recherches et Développements Appliqués/
Régie Renault

Co-professionals throughout the world as well as co-workers in France know Claude Tarrière as one of the handful of men who spend their work days trying to make driving today safer than it was yesterday. In countless scholarly papers delivered at professional symposia throughout the world, in the development of new research and testing techniques that have become industry standards, Tarrière demonstrates that putting human needs first is an appealing old Gallic idea whose time has come—again. "After all," says Tarrière, "we humans were here first: cars were meant to serve us, not to take over."

◆

Recalling his long-ago summertime job, he continues, "I suppose it was rare, thirty years ago, for a baccalaureate candidate in France to spend a summer gainfully employed rather than anxiously cramming for exams. But as a working class boy, I had to work, for I had made my mind up to become a doctor." After getting his medical degree, Tarrière went on to the Sorbonne where he completed a research thesis on Nervous Fatigue. "Having made all these scholarly efforts, I was thought odd by many when I went to work for a car factory. In some general, unspecific way I hoped to be part of the human side I had glimpsed that summer in my teens... maybe somehow to 'help' workers in the factory. Very soon I found my niche. And it wasn't so much in the human side of the industry. But, to my surprise, in the human side of the product."

◆

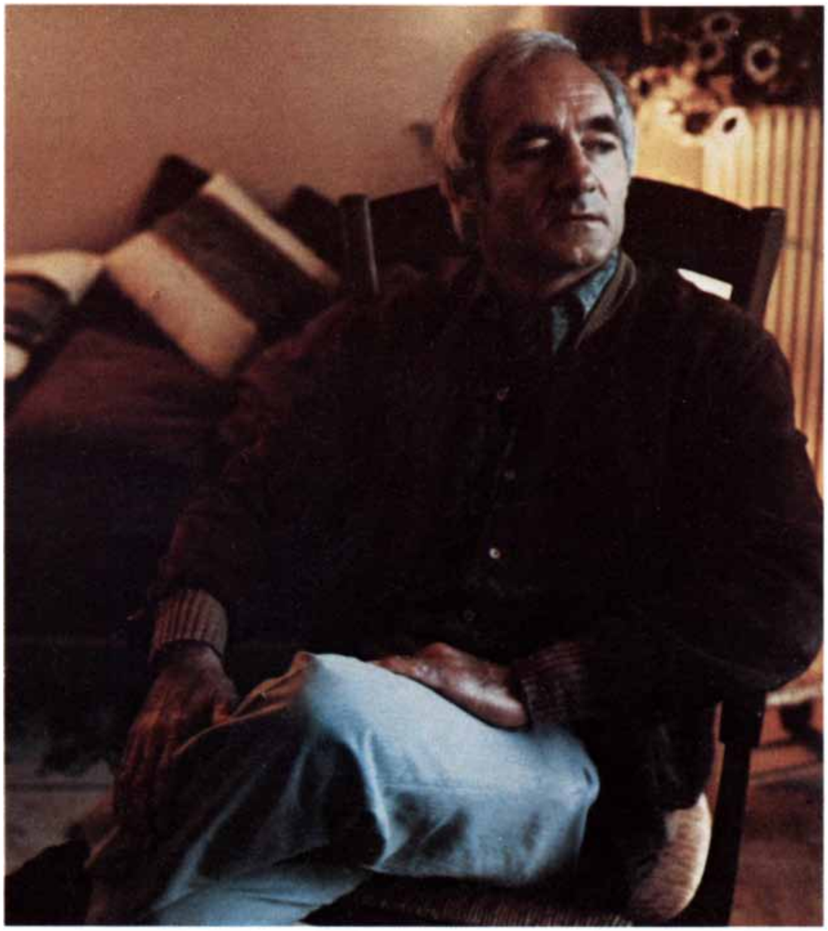
Today, Dr. Tarrière heads up Renault's "Safety and Comfort" Research. "Safety and comfort" might at first seem like a paradoxical coupling— what have leg-room and dashboard configurations to do with safer driving? But when Tarrière discusses the inter-relationship of comfort and safety he seems to be offering yet another Gallic insight that (like many Gallic insights) sounds like universal truth. "Comfort and safety really do fit together. After all, when all the parameters of comfort for the driver are successfully met, the driver's alertness, his responsiveness and, if you will, his safety-quotient are all at their peak."

◆

Another Tarrière nugget: "The human body is also a suspension system. Before we can refine a car's suspension system, we must know, analyze and understand this human suspension system. Only then can we effectively relate one to the other... only then can we make the second work best for the first."

◆

Tarrière's initial interest in automobiles may in part stem from his father who in the early '20's worked as an artisan-craftsman building wooden coach bodies (*un charron*



Portrait by Marie Cosindas, 1979.

forgeron) for the infant automobile industry. When the depression found Tarrière senior jobless, he returned to his natal village of Montsûrs (in the Mayenne between Le Mans and Brest) and to his original craft of making horsedrawn wagon bodies and handmade wood-and-metal wheels. Tarrière remembers half-playing, half-working at his father's side and fondly recalls his father often singing at his work

◆

Though there are no verified reports of Dr. Tarrière singing at *his* work, all indications are that he is absolutely the right man in the right place When he delivers one of his scholarly papers (in San Francisco, say, where his paper on "Pedestrian Protection" was termed best of the conference); or when he expands on his field of "Ergonomics" (the multidiscipline adaptation of the machine to fit man's capability and physiology); or when he discusses "Protection Criteria," you might think he *was* singing so rapt is his audience, so free and outgoing his performance

◆

Next to work, what Tarrière likes best is testing himself with an old fishing boat at a hide-away he rents on an island off the wild Côte du Nord in Bretagne. He fishes for mackerel, is adapting his old fishing dinghy to sails and, like fishermen all over the world, contends with Madame Tarrière's "lack of enthusiasm for my fighting with the elements— although she does like the fish I bring home." The Tarrières have four daughters and two sons, ranging in age from 11 to 21. Madame Tarrière has recently returned to work; she is involved in the celebrated *"Re-travailler"* project that guides mature women seeking to re-enter the work force. The younger Tarrières' interests range from the law and modern dance to agriculture. They exhibit much of the parental creativity and openness. One son having just back-packed up and down Africa for a year after *his* baccalaureate is now ready to cease "being a spectator, anxious to become a participant." This description by Tarrière of his son could be said to echo Tarrière's own attitude towards life: don't watch; participate.

◆

In June of 1979, in ceremonies in Paris, Tarrière was honored with an award from the U.S. Department of Transportation's National Highway Traffic Safety Administration for his contributions to automotive safety research. His methods for laboratory analyses have been adapted for use by manufacturers throughout the world. "When you develop insights about how to make driving a car safer, it's not the sort of thing you keep to yourself. . . it's the sort of thing you want everybody to know right away."

◆

"The outside world tends to think of the French in terms of chic, luxury and elegance; we French like to think of ourselves as guided by good old-fashioned bourgeois virtues— logic, caution, common sense. Yet, it seems to me, an important part of the French national character has to do with our all-too-human and repeated strivings to explore new areas, to extend knowledge, to test ourselves even as we test old ways. Although the elegance is appealing; although the common sense is seductive; what really makes the heart and mind leap is a bounding forth into some uncharted territory."

◆

We welcome your comments, questions or thoughts about any of the above. Write to: Renault, USA, Inc., Englewood Cliffs, N.J. 07632

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

MARCH, 1930: "Whether or not the general reading public is to believe that Professor Dayton C. Miller, the physicist who over the past several years has been re-performing at Cleveland and Mount Wilson the famous Michelson-Morley ether-drift experiment and obtaining with uniform consistency indications of an actual ether drift and hence the existence of an ether, is out to 'get' the Einstein theory of relativity, which dispenses with an ether, depends on what one reads. Quite a large section of the public has apparently become somewhat steamed up about these things, and the Einstein–anti-Einstein battle has taken on a new life. Let a world of blind admirers and enraged detesters of the theory beat the air with super-heated syllables, Einstein serenely smokes his pipe and says, 'If Professor Miller's research is confirmed, my theory falls, that's all.'"

"The steel industry controls even matters of a political nature, for the principal problem in Europe's political tangle is no longer to maintain a 'balance of power' but to maintain a 'balance of steel.' The world's production has risen to about 100,000,000 tons, valued at current market prices at about $36 per ton. The greatest body of iron ore in Europe was shared prior to the war by France, Germany and Luxembourg, and before the war Germany produced more steel than did the other three great steel-producing nations of the Old World—England, France and Belgium—combined, while the United States produced about the same total quantity, about 40 per cent of the world's annual supply. By the Versailles Treaty, France hoped to destroy Germany's commercial supremacy forever, for she thereby got Lorraine and the main portion of Germany's western ore deposits. But that has not won the economic battle for France, because she did not win the coal. She did not get the Ruhr coal deposits, and she got only a small part of the Saar. In the meantime our own steel production has been mounting. Since 1916 we have produced more than 50 per cent of the supply of the entire world."

"To Prince Louis-Victor de Broglie, brilliant French physicist, is due the credit for first suggesting the new concept of the wave atom. Since his first publication of this revolutionary concept it has been widely and frequently discussed throughout the world of science. Other capable workers, notably Erwin Schrödinger of Germany, G. P. Thomson of Scotland and C. J. Davisson and L. H. Germer of America, have taken it up and extended it until there is now a large literature about the wave atom. For his original suggestion de Broglie has just been awarded the 1929 Nobel physics prize. What de Broglie did was to synthesize some of the main concepts of physics that previously seemed contradictory. His hypothesis, as it has been put by the American physicist Paul R. Heyl, 'was that every mass-particle was surrounded by a group of waves traveling with the particle as a sort of bodyguard.' Thus electrons, the fundamental basis of matter, have some of the qualities of light; matter becomes less material and light more material, suggesting a kind of merger of previous concepts."

SCIENTIFIC AMERICAN

MARCH, 1880: "A little over 30 years ago grain was imported to this country from southern Russia. During the crop year on which the country is now entering it is certain that 160,000,000 bushels of wheat will be exported to Europe, and the amount may reach 200,000,000 bushels. The demand last year from Europe was 159,000,000 bushels out of a crop estimated at 420,000,000 bushels. The lowest estimate yet made places the 1880 crop at 360,000,000 and the highest at 440,000,000; a crop of 420,000,000 may be reasonably counted upon. This is an increase in 10 years of 133,000,000 bushels in the annual wheat production of this country, and an increase nearly equal to the total wheat harvest of 20 years ago."

"The House Committee on the Interoceanic Canal lately had before it Mr. Menocal, Civil Engineer, United States Navy, who has made several surveys on the isthmus, and heard his statement as to the relative advantages and disadvantages of the Nicaragua and Panama routes. Mr. Menocal strongly favored the Nicaragua route as being 660 miles shorter between San Francisco and New York. He expressed his conviction that the cost of the Nicaragua canal would not exceed $70,000,000, while that of a sea-level canal via the Panama route would probably be $400,000,000."

"The Garrett submarine torpedo boat, invented by the Rev. G. W. Garrett of England, has the power of sinking and remaining under water for very many hours and thus can easily enter any blockaded port unperceived. Where earlier vessels of this type have lacked for a mechanical means of propulsion, Mr. Garrett's boat is driven by steam. It has a coal-fired boiler and a retractable smokestack. The fire has to be extinguished before the vessel can submerge or it would exhaust the air in the vessel, but enough steam remains in the boiler for traveling several miles under water. The air in the boat is maintained at its normal composition by a chemical apparatus invented by Mr. Garrett. In December last Mr. Garrett, Captain Jackson and Mr. George Rice entered the boat in the Great Float, Birkenhead, to start for Portsmouth, but after 36 hours' journey in thick fog, a great part of the time being spent under water, they had to put into Rhyl, there not being many comforts on board for an extended trip. The boat, the inventor tells us, is in every way a success and thus becomes one of the deadliest of all weapons of naval warfare."

"At Shaw's Water Chemical Works in Greenwich the motive power to drive a circular saw, a turning lathe and a vertical boring machine is furnished by electricity. Two Siemens dynamo-electric machines and a water turbine are employed. The turbine is driven by a neighboring waterfall, and one of the machines is driven by the turbine. The current from this machine is conveyed to a second machine in the workshop 150 yards distant and keeps the latter going. From this machine the tools are driven by belting."

"At a late public meeting in London Mr. Ernest Hart delivered an important address on the relations of smallpox vaccination to public health. Dr. Andrew Clarke presided, and in introducing the speaker he remarked that ever since the introduction of vaccination there had been two opinions on the subject. One party had held that it was an almost unmixed good to mankind—that it had checked the ravages of a loathsome disease, and that the dangers of this disease had been so lessened that its fatality was almost banished in those who were vaccinated. On the other hand, the opponents of vaccination held that it was an almost unmixed evil—that it had lessened neither the disease nor the mortality from it, that it had introduced other diseases into the human frame and that for those who practiced it hanging was too good. Mr. Hart remarked that if the like mortality occurred in England to that which was constant before vaccination, the annual death rate from smallpox would be 70,000. Before the days of vaccination a third of all the deaths of children arose from smallpox, and all classes suffered equally from it. This was instanced from the fact that King William III had lost his wife, his mother and his father to the disease."


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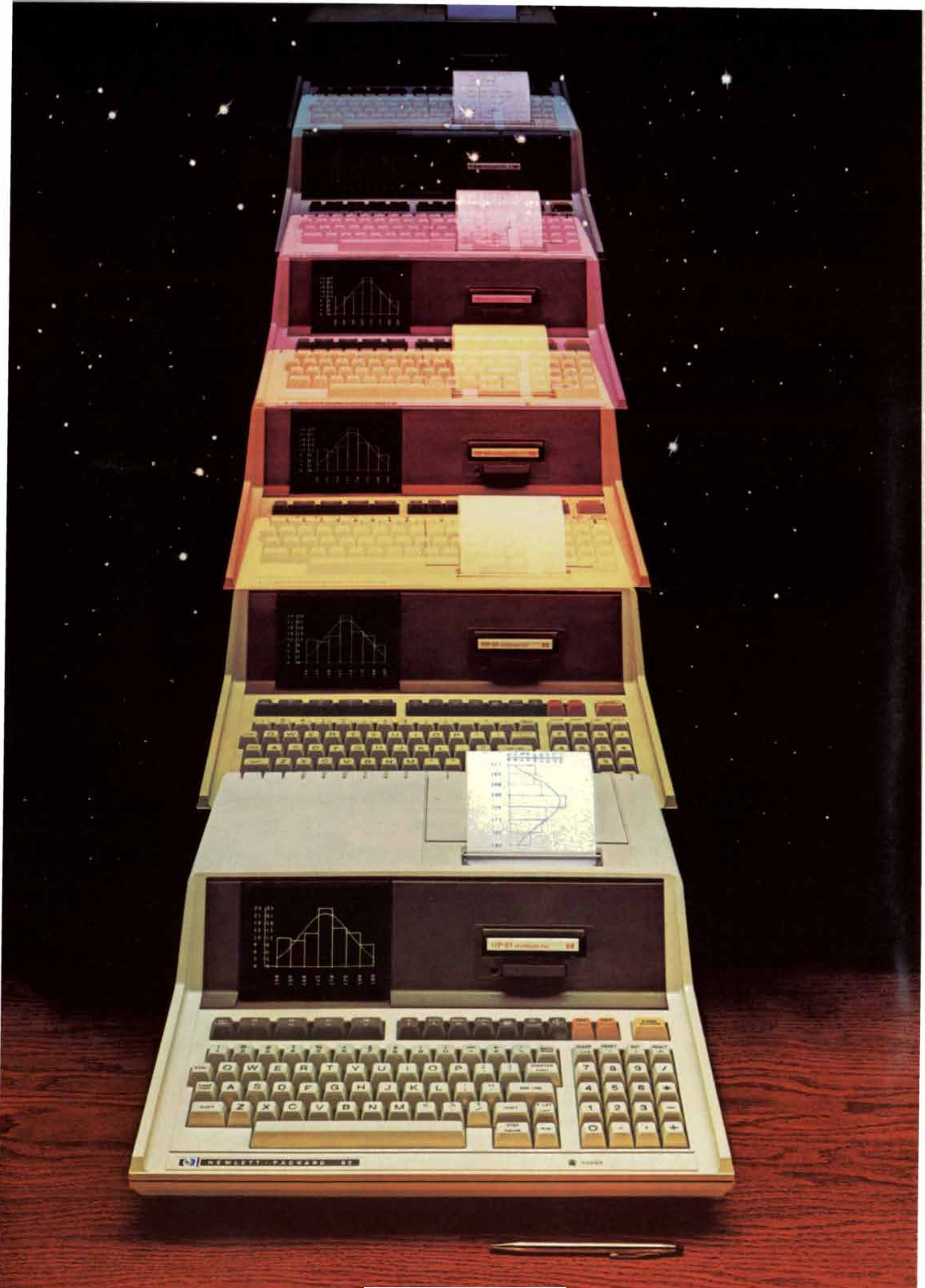
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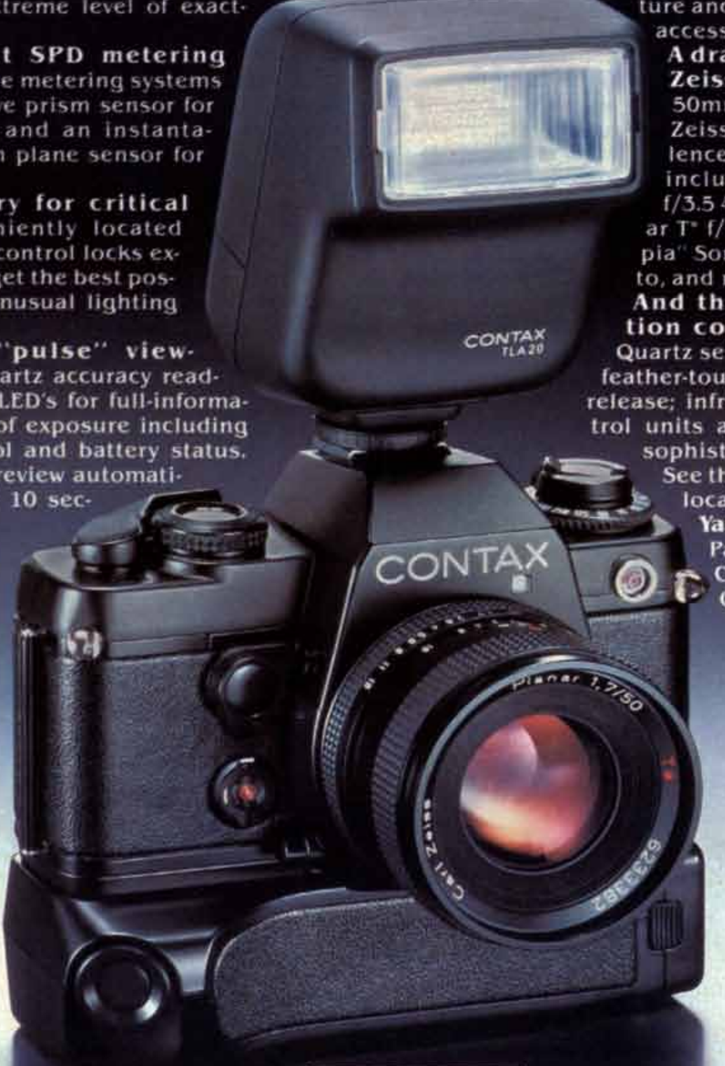
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THE AUTHORS

HAROLD W. LEWIS ("The Safety of Fission Reactors") is professor of physics at the University of California at Santa Barbara. A graduate of New York University, he obtained his Ph.D. in 1948 from the University of California at Berkeley, where he studied physics under J. Robert Oppenheimer. After teaching for a time at Berkeley, followed by a year as a visiting member of the Institute for Advanced Study in Princeton, N.J., he joined the technical staff of Bell Laboratories in 1951. He returned to academic life in 1956, becoming professor of physics first at the University of Wisconsin and later at Santa Barbara. In recent years Lewis has become deeply involved in both the technical and the public-policy aspects of nuclear-reactor safety; he was chairman of the American Physical Society's study group on light-water-reactor safety in 1975, and two years later he was appointed chairman of the Risk Assessment Review Group, a special committee convened by the Nuclear Regulatory Commission to review the findings of the earlier Reactor Safety Study (also known as the Rasmussen report); he continues his involvement as a member of the NRC's Advisory Committee on Reactor Safeguards.

MAURICE JACOB and PETER LANDSHOFF ("The Inner Structure of the Proton") are theoretical physicists with a common research interest in the interactions of elementary particles at high energies. Jacob is on the staff of the European Organization for Nuclear Research (CERN). A French citizen, he was graduated from the École Normale Supérieure in Paris in 1957 and received his doctorate in science from the same institution in 1961. He has been affiliated with CERN since 1967. Jacob's work involves close contacts with physicists at accelerator laboratories in other countries, including France and the U.S., and he currently serves this international community of scholars as editor of *Physics Reports*. Landshoff, who is reader in mathematical physics at the University of Cambridge, obtained his Ph.D. from Cambridge in 1962 and has been a fellow of Christ's College there since 1963. A specialist in parton physics and quantum chromodynamics, he is the coauthor, with A. J. F. Metherell, of *Simple Quantum Physics*, an introductory undergraduate textbook published last year by Cambridge University Press that applies quantum mechanics to the theory of lasers and transistors.

PETER V. ADDYMAN ("Eburacum, Jorvik, York") is director of the York Archaeological Trust, an organization he was instrumental in setting up in 1972. Himself a Yorkshireman, he was graduated from the University of Cambridge. Before taking up his present work he was lecturer in archaeology at the Queen's University of Belfast and at the University of Southampton. During his years on university faculties he conducted excavations at a number of Anglo-Saxon towns and villages in Devonshire, Hampshire and Northamptonshire. He also uncovered Henry III's great hunting castle at Ludgershall in Wiltshire. Addyman currently serves as vice-president of the Royal Archaeological Institute and as chairman of the Standing Conference of Unit Managers, a group of British archaeologists concerned with rescue excavations.

EDWARD RUBENSTEIN ("Diseases Caused by Impaired Communication among Cells") is associate dean of postgraduate medical education and professor of clinical medicine at the Stanford University School of Medicine, where he has been a member of the faculty for the past 25 years. He is also editor-in-chief of *Scientific American Medicine*, a new, regularly updated reference text for practicing physicians. Since receiving his M.D. from the University of Cincinnati College of Medicine in 1947, he has devoted himself mainly to the study of thromboembolic disease and to the development of improved methods of education and communication in both basic and applied medical science. In line with the latter interest he recently served as writer-producer for the Public Broadcasting Service's documentary "Being Human," a television program dealing with "the physical and behavioral characteristics that set human beings apart from other creatures." A longtime avocational interest in the field of particle physics has led Rubenstein to a current research project on the use of synchrotron radiation for noninvasive angiography.

FRED L. WHIPPLE ("The Spin of Comets") is Phillips Professor of Astronomy emeritus at Harvard University and senior scientist at the Smithsonian Astrophysical Observatory, of which until his recent retirement he had been director since 1955. He went to Harvard in 1931, the year he received his Ph.D. from the University of California at Berkeley. He remains affiliated with the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory. His research, he writes, "centers on physical processes in the evolution of the solar system. My recent work is mostly on comets, determining the rotation peri-

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ods of their nuclei and evaluating the significance of these results with regard to the physical nature of comets and their origin. I also spend considerable effort in advising on and encouraging space missions to comets." Whipple is discoursing on comets for the third time in SCIENTIFIC AMERICAN; his first article, titled "Comets," was published in July, 1951.

RICHARD E. DICKERSON ("Cytochrome *c* and the Evolution of Energy Metabolism") is professor of chemistry at the California Institute of Technology. A graduate of the Carnegie Institute of Technology, he obtained his Ph.D. in physical chemistry from the University of Minnesota in 1957. After a year of postdoctoral training at the University of Cambridge and four years on the faculty of the University of Illinois he moved to Cal Tech in 1963. A specialist in the X-ray analysis of the structure of crystalline proteins, he is the author or coauthor of six textbooks on chemistry, biochemistry and biology. This is Dickerson's third article for SCIENTIFIC AMERICAN; his last, "Chemical Evolution and the Origin of Life," appeared in the issue on evolution for September, 1978.

CLIFF FROHLICH ("The Physics of Somersaulting and Twisting") is a seismologist at the Marine Science Institute in Galveston, Tex., a geophysics laboratory associated with the University of Texas at Austin. He was introduced to both physics and diving, he says, "as a sophomore at Grinnell College in 1966, and in spite of an undistinguished career as a diver I went on to receive my Ph.D. from Cornell University in 1976. My research on twisting somersaults began after a trampoline accident forced my interest in twists to change from the real to the academic."

WILLIAM G. EBERHARD ("Horned Beetles") works at the University of Costa Rica and the Smithsonian Tropical Research Institute in the Panama Canal Zone. His degrees are from Harvard University: an A.B. in 1965 and a Ph.D. in 1969, the latter awarded for a thesis on the ecology and behavior of an orb-weaving spider. From 1969 to 1979 he was a member of the faculty at the Universidad del Valle in Colombia. He writes: "Early in graduate school I learned how incredibly little is known about the ecology and behavior of invertebrates, even in comparatively well-studied areas such as the northeastern U.S., let alone in the Tropics. Since then I have more or less let my fancy dictate my research interests." In Eberhard's present tropical setting his fancy has led him to study a variety of insects, including flies, wasps, bugs, damselflies, beetles and moths.

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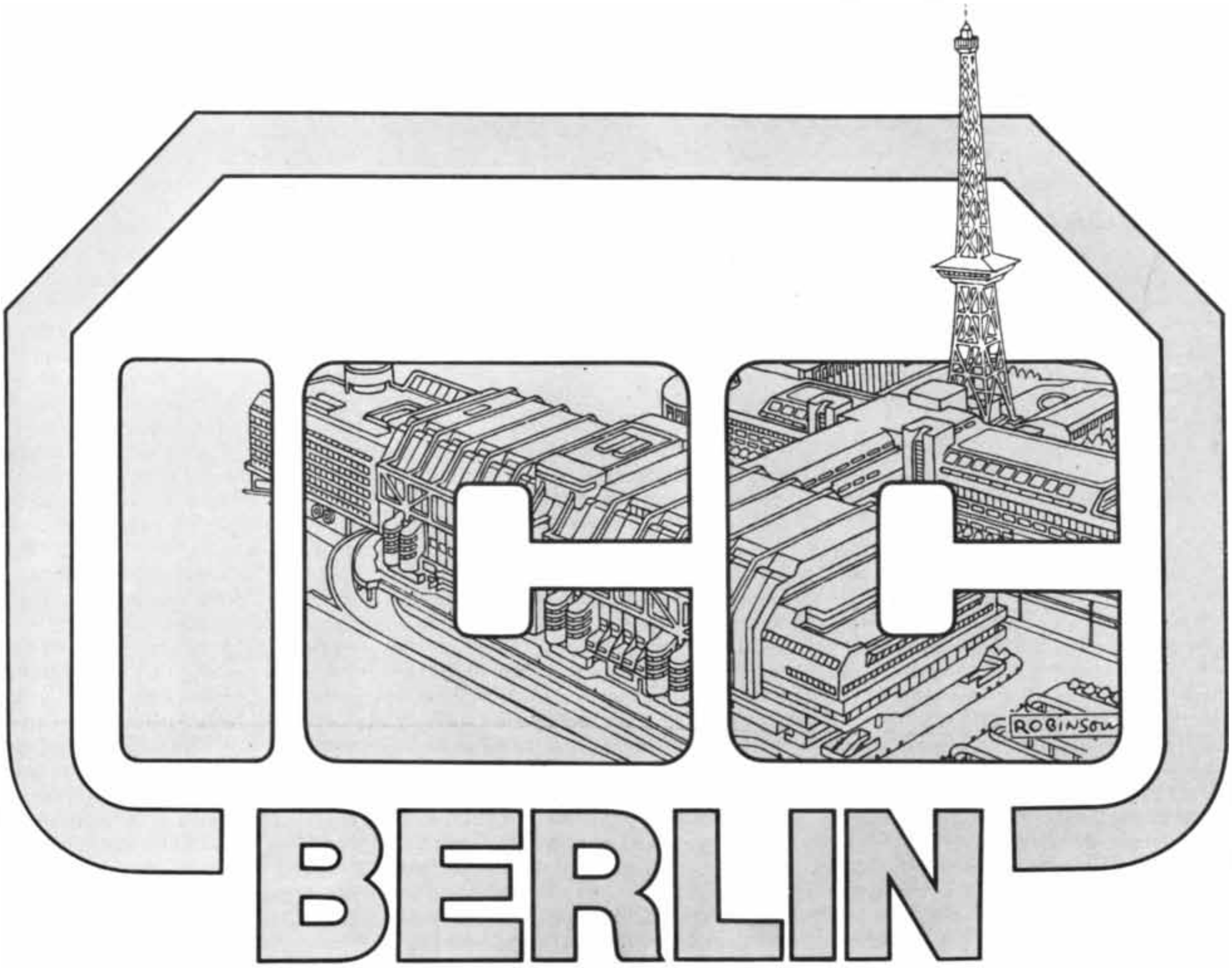
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MATHEMATICAL GAMES

Graphs that can help cannibals, missionaries, wolves, goats and cabbages get there from here

by Martin Gardner

Stranger in car: "How do I get to the corner of Graham Street and Harary Avenue?"

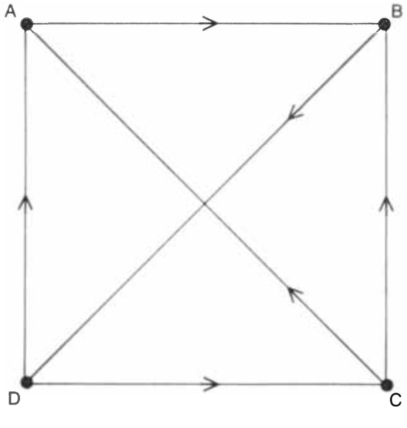
Native on sidewalk: "You can't get there from here."

In graph theory a graph is defined as any set of points joined by lines, and a simple graph is defined as one that has no self-loops (lines that join a point to itself) and no parallel lines (two or more lines joining the same pair of points). If an arrowhead is added to each line of a graph, giving each line a direction that orders its end points, the graph becomes a directed graph, or digraph for short. Digraphs are the subject here, and the old joke quoted above is appropriate because on some digraphs it is actually impossible to get from one specified point to another.

A digraph is called complete if every pair of points are joined by a line. For example, a complete digraph for four points is shown at the left in the illustration below. The figure at the right is the adjacency matrix of the digraph, which is constructed as follows. Think of the digraph as a map of one-way streets. Starting at point *A,* it is possible to go directly only to point *B,* a fact that is indicated in the top row of the matrix (the row corresponding to *A*) by putting a 1 in the column corresponding to *B* and a 0 in all the other columns. The remaining rows of the adjacency matrix are determined in the same way, so that the matrix is combinatorially equivalent to the digraph. It follows that given the adjacency matrix it is easy to construct the digraph.

Other important properties of digraphs can be exhibited in other kinds of matrixes. For example, in a distance matrix each cell gives the smallest number of lines that form what is called a directed path from one point to another, that is, a path that conforms to the arrowheads on the graph and does not visit any point more than once. Similarly, the cells of a detour matrix give the number of lines in the longest directed path between each pair of points. And a reachability matrix indicates (with 0's and 1's) whether a given point can be reached from another point by a directed path of any length. If every point is reachable from every other point, the digraph is said to be strongly connected. Otherwise there will be one or more pairs of points for which "you can't get there from here."

The following theorem is one of the most fundamental and surprising results about complete digraphs: No matter how the arrowheads are placed on a complete digraph, there will always be a directed path that visits each point just once. Such a path is called a Hamiltonian path after the Irish mathematician William Rowan Hamilton. Hamilton marketed a puzzle game based on a graph equivalent to the skeleton of a dodecahedron in which one task was to find all the paths that visit each point just once and return to the starting point. A cyclic path of this type is called a Hamiltonian circuit. (Hamilton's game is discussed in Chapter 6 of my *Scientific American Book of Mathematical Puzzles & Diversions.*)



	A	B	C	D
A	0	1	0	0
B	0	0	0	1
C	1	1	0	0
D	1	0	1	0

Complete digraph for four points **(left)** *and its adjacency matrix* **(right)**

The complete-digraph theorem does not guarantee that there will be a Hamiltonian circuit on every complete digraph, but it does ensure that there will be at least one Hamiltonian path. More surprisingly, it turns out that there is always an odd number of such paths. For example, on the complete digraph in the illustration on this page there are five Hamiltonian paths: *ABDC, BDCA, CABD, CBDA* and *DCAB.* All but one of them (*CBDA*) can be extended to a Hamiltonian circuit.

The theorem can be expressed in other ways, depending on the interpretation given the graphs. For example, complete digraphs are often called tournament graphs because they model the results of the kind of round-robin tournaments in which each player plays every other player once. If *A* beats *B,* a line goes from *A* to *B.* The theorem guarantees that whatever the outcome of a tournament is all players can be ranked in a column so that each player has defeated the player immediately below him. (It is assumed here that, as in tennis, no game can end in a draw. If a game did allow draws, they would be represented by undirected lines and the graph would be called a mixed graph. Mixed graphs can always be converted into digraphs by replacing each undirected line with a pair of directed parallel lines going in opposite directions.)

Tournament graphs can be applied to represent many situations other than tournaments. Biologists have used the graphs to diagram the pecking order of a flock of chickens or, more generally, to diagram the structure that any other kind of pairwise dominance relation imposes on a population of animals. Social scientists have used the graphs for modeling dominance relations among people or groups of people. Tournament graphs provide a convenient means of modeling a person's pairwise preferences for any set of choices, such as brands of coffee or candidates in an election. In all these cases the theorem guarantees that the animals, people or objects in question can always be ordered in a linear chain by means of the one-way relation.

The theorem is tricky to prove, but to convince yourself of its validity try labeling a complete graph of *n* points so that no Hamiltonian path is created. The impossibility of the task suggested the

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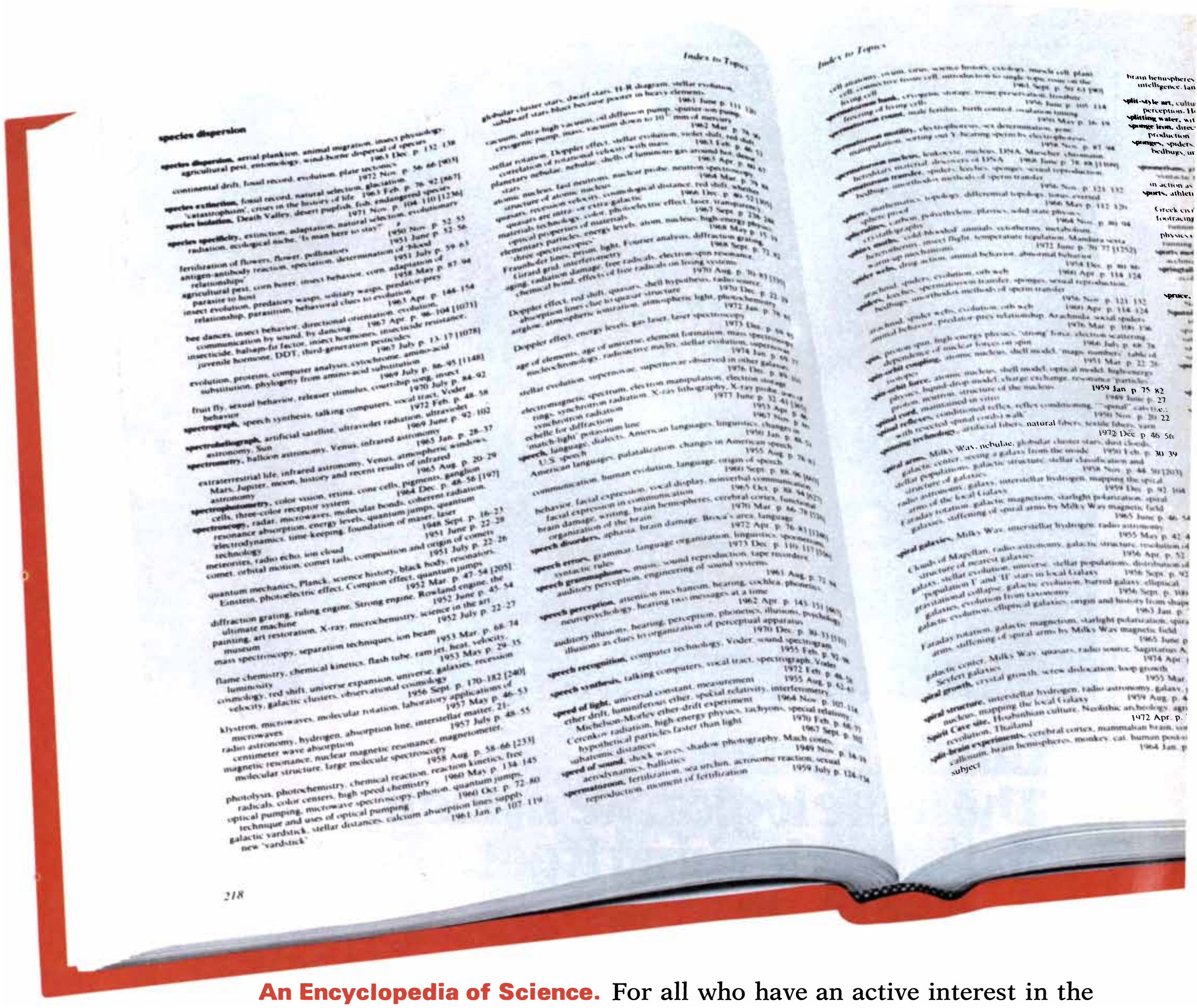

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Index to Proper Names—the names of all persons mentioned in the articles and Science and the Citizen and of places and institutions featured in a primary role.

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Index to Authors—an alphabetical listing of authors of all articles.

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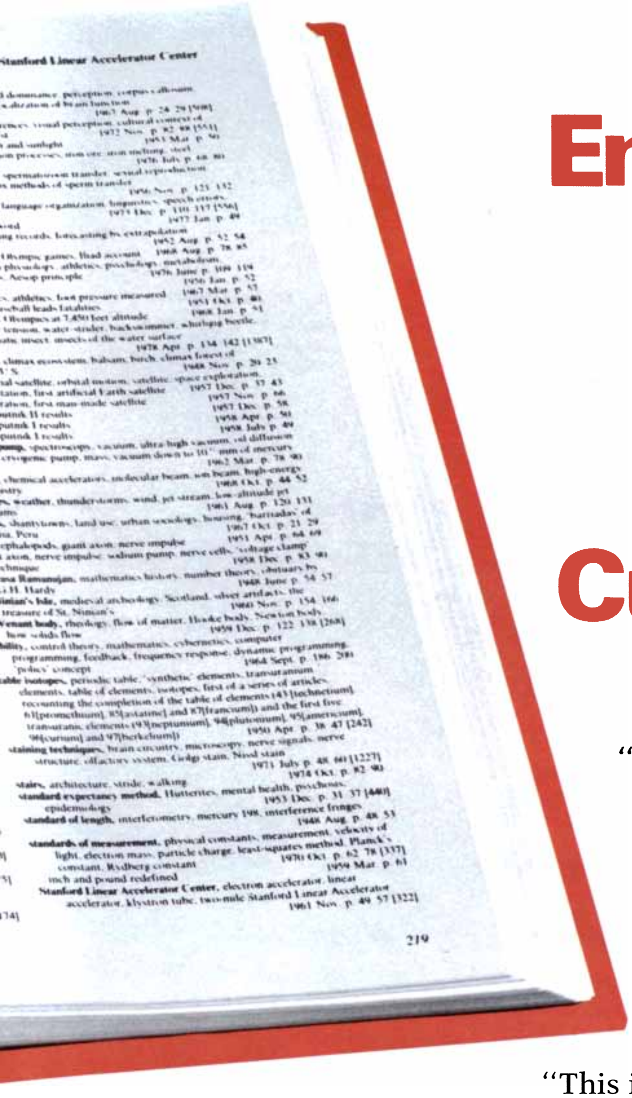
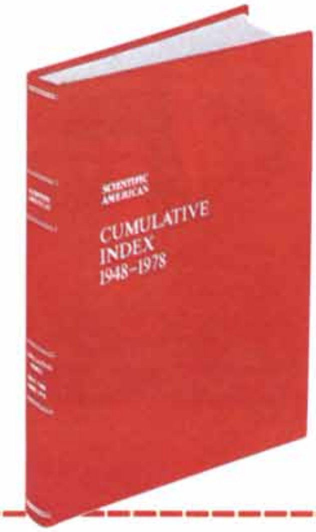
Index to Book Reviews—a listing of the longer book reviews in three parts: authors of books, titles and reviewers.

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 all 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 Waker.

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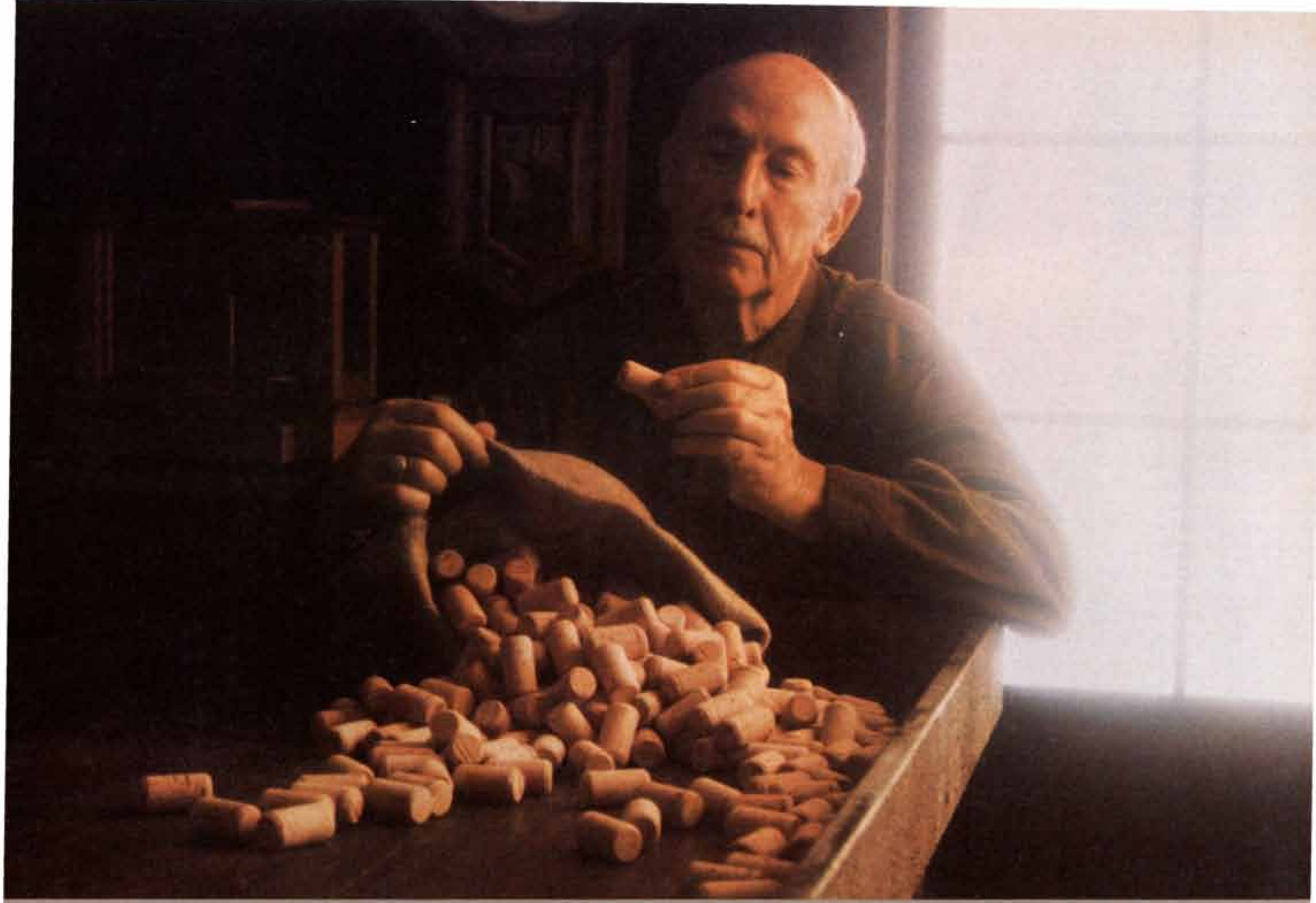
1948-1978



BECAUSE the cork is the guardian of the wine, the corksmith judges the quality choosing only the finest straight-grained Portuguese cork to protect our crisp French Colombard. Every step we take, we take with care because THE WINE REMEMBERS

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ERNEST & JULIO
GALLO

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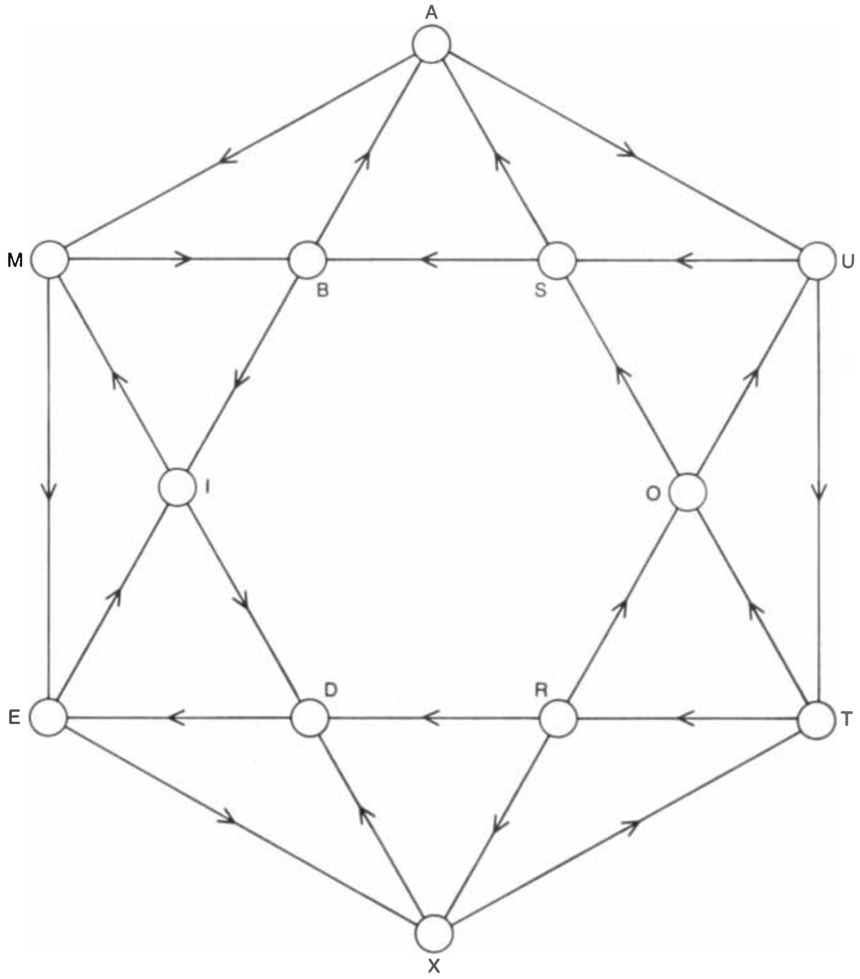
following pencil-and-paper game to the University of Cambridge mathematician John Horton Conway. Two players take turns adding an arrowhead to any undirected line of a complete graph, and the first player to complete a Hamiltonian path loses. The theorem ensures that the game cannot be a draw. Conway finds the play is not interesting unless there are seven or more points in the graph.

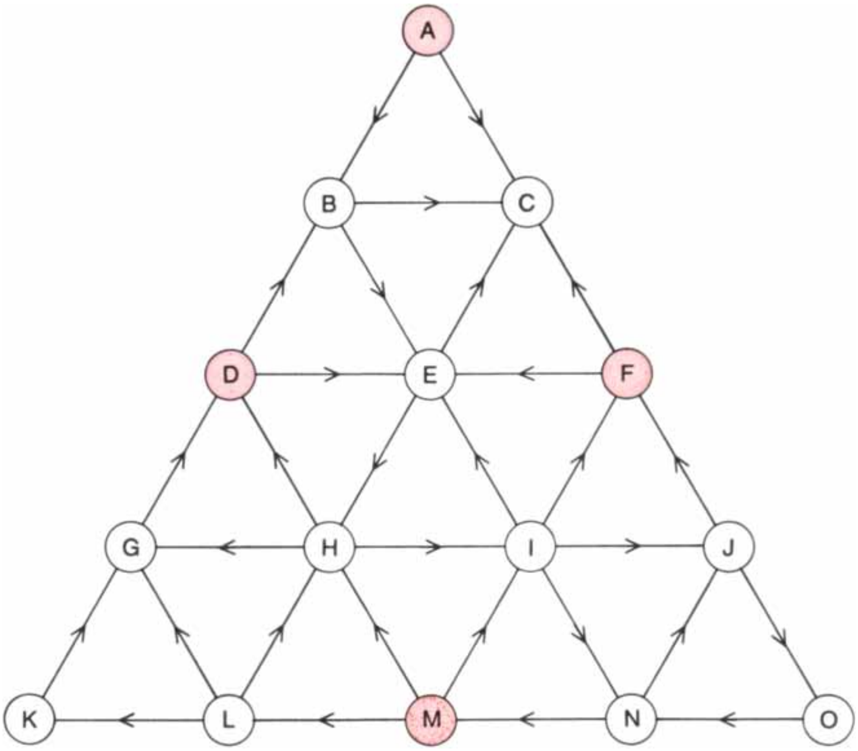
The digraph in the top illustration at the right appeared as a puzzle in the October 1961 issue of the Cambridge mathematical annual *Eureka*. Although it is not a complete digraph, it has been cleverly labeled with arrowheads so that it has only one Hamiltonian circuit. Think of the graph as a map of one-way streets. You want to start at *A* and drive along the network, visiting each intersection just once before returning to *A*. How can it be done? (Hint: The circuit can be traced by a pencil held in either hand.) Next month I shall give the unique solution to this puzzle.

Digraphs can provide puzzles or be applied as tools for solving puzzles in innumerable ways. For example, the graphs serve to model the ways a flexagon flexes, and they are valuable in solving moving-counter and sliding-block puzzles and chess-tour problems. Probability questions involving Markov chains often yield readily to a digraph analysis, and winning strategies for two-person games in which each move alters the state of the game are frequently found by exploring a digraph of all possible plays. In principle even the game of chess could be "solved" by examining its digraph, but the graph would be so enormous and so complex that it will probably never be drawn.

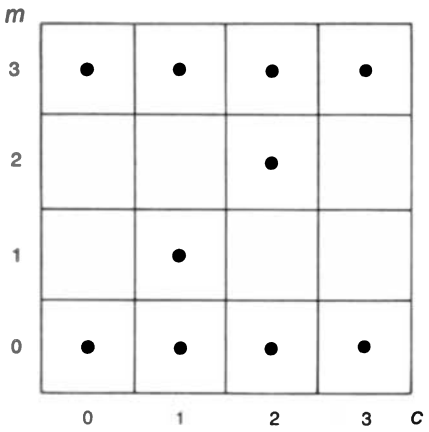
Digraphs are extremely valuable in the field of operations research, where they can be applied to solve complicated scheduling problems. Consider a manufacturing process in which a certain set of operations must be performed. If each operation requires a fixed amount of time to perform and certain operations must be completed before others can be started, an optimum schedule for the operations can be devised by constructing a graph in which each operation is represented by a point and each point is labeled with a number that represents the time needed for completing the operation. The sequences in which certain operations must be done are indicated by arrowheads on the lines. To determine an optimum schedule the digraph is searched, with a computer if necessary, for a "critical path" that completes the process in a minimum amount of time. Complicated transportation problems can be handled the same way. For example, each line in a digraph can represent a road and can be labeled with the cost of transporting a particular product on it. Clever algorithms can then be applied to find a directed path



Find the unique Hamiltonian circuit



The game of Traffic Jam

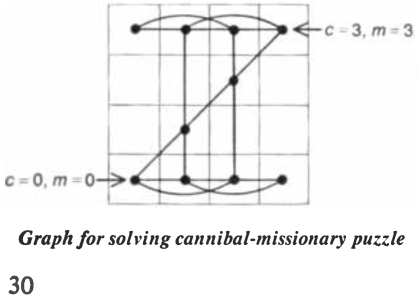


Matrix for the cannibal-missionary puzzle

that minimizes the total cost of shipping the product from one place to another.

Digraphs also serve as playing boards for some unusual board games. Aviezri S. Fraenkel, a mathematician at the Weizmann Institute of Science in Israel, has been the most creative along these lines. (For a good introduction to a class of digraph games Fraenkel calls annihilation games, see "Three Annihilation Games," a paper Fraenkel wrote with Uzi Tassi and Yaacov Yesha for *Mathematics Magazine,* Vol. 51, No. 1, pages 13–17; January, 1978.) In 1976 the excellent game Arrows, which Fraenkel developed with Roger B. Eggleton of Northern Illinois University, was marketed in Israel by Or Da Industries and distributed in the U.S. by Leisure Learning Products of Greenwich, Conn.

Traffic Jam, another Fraenkel game, is played on the directed graph in the bottom illustration on the preceding page as follows. A coin is placed on each of four spots: *A, D, F* and *M.* Players take turns moving any one of the coins along one of the lines of the graph to an adjacent spot as is indicated by the arrowheads on the graph. A coin can be moved to any adjacent spot whether or not the spot is occupied, and each spot can hold any number of coins. Note that all the arrowheads at *C* point inward. Graph theorists call such a point a sink. Conversely, a point from which all the arrowheads point outward is called a source. (If the graph models a pecking order, the sink is the chicken all the other chickens peck and the source is the chicken that pecks all the others.) In this case there is just one sink and one source. (A complete digraph can never have more than one sink or more than one source. Do you see why?)



Graph for solving cannibal-missionary puzzle

When all four coins are on sink *C,* the person whose turn it is to move has nowhere to go and loses the game. In Conway's book *On Numbers and Games* (Academic Press, 1976) he proves that the first player can always win if and only if his first move is from *M* to *L.* Otherwise the opponent can force a win or draw. (It is assumed that both players make their best moves.) With the powerful game theory that Conway has developed it is possible to completely analyze any game of this type, with any starting pattern of counters.

An ancient and fascinating class of puzzles that are best analyzed by digraphs are those known as river-crossing problems. Consider a classic puzzle that turned up last year in the title of Mary McCarthy's latest novel: *Cannibals and Missionaries.* In the simplest version of this problem three missionaries and three cannibals on the right bank of a river want to get to the left bank by means of a rowboat that can hold no more than two passengers at a time. If the cannibals outnumber the missionaries on either bank, the missionaries will be killed and eaten. Can all six get safely across? If they can, how is it done with the fewest crossings? (I shall not enter here into the current lively debate about whether cannibalism ever actually prevailed in a culture.)

Benjamin L. Schwartz, in an article titled "An Analytic Method for the 'Difficult Crossing' Puzzles" (*Mathematics Magazine,* Vol. 34, No. 4, pages 187–193; March–April, 1961), explained how to solve such problems by means of digraphs, but his method deals not directly with the digraphs but rather with their adjacency matrixes. I shall describe here a comparable procedure using the digraphs themselves that was first explained by Robert Fraley, Kenneth L. Cooke and Peter Detrick in their article "Graphical Solution of Difficult Crossing Puzzles" (*Mathematics Magazine,* Vol. 39, No. 3, pages 151–157; May, 1966). The paper has been reprinted with additions as Chapter 7 of *Algorithms, Graphs and Computers* by Cooke, Richard E. Bellman and Jo Ann Lockett (Academic Press, 1970). The following discussion is based on that chapter.

Let *m* stand for the number of missionaries and *c* for the number of cannibals, and consider all possible states on the right bank. (It is not necessary to consider states on the left bank as well because any state on the right bank fully determines the state on the left one.) Since *m* can be equal to 0, 1, 2 or 3, and the same is true for *c,* there are 4 × 4, or 16, possible states, which are conveniently represented by the matrix in the top illustration on this page. Six of these states are not acceptable, however, because the cannibals outnumber the missionaries on one of the banks. The 10 acceptable states that remain are marked by placing a point inside each of the 10 corresponding cells of the matrix.

The next step is to connect these points by lines that show all possible transitions between acceptable states by the transfer of one or two persons to the other side of the river. The result is the undirected graph in the bottom illustration on this page. This graph is then transformed into a mixed graph by adding arrowheads to show the direction of each transition. The transformation of the undirected graph to a mixed graph must be carried out in accordance with two rules:

1. The object is to create a directed "walk" that will start at the point at the upper right ($c = 3$, $m = 3$) and end at the point at the lower left ($c = 0$, $m = 0$), so that all the cannibals and missionaries end up on the left bank. (This route is called a walk rather than a path because by definition a path cannot visit the same point more than once.)

2. The directed walk must alternate movements down or to the left with movements up or to the right, because each step down or to the left corresponds to a trip from the right bank to the left bank, whereas each step up or to the right corresponds to a trip in the opposite direction.

With both of these rules in mind it takes only a short time to discover that there are just four walks that solve the puzzle. Their digraphs are shown in the top illustration on page 34. Each walk completes the transfer in 11 moves. Note that the fifth, sixth and seventh steps are the same in all four walks. The four variants arise because there are two ways to make the first two steps and two symmetrical counterparts for the last two steps.

If the problem is altered to deal with transporting four cannibals and four missionaries (and all the other conditions remain the same), the digraph technique can be applied to show there is no solution. Suppose now that the boat is enlarged to hold three passengers and that on the boat, as on the bank, the cannibals must not outnumber the missionaries. Under these conditions all eight can cross safely in as few as nine steps. Five cannibals and five missionaries can also cross in a boat that holds three passengers (in 11 steps), but six cannibals and six missionaries cannot.

It is easy to see that given a boat holding four or more passengers any group evenly divided between cannibals and missionaries can be safely transported across the river. One cannibal and one missionary simply do all the rowing, transporting the others one cannibal-missionary pair at a time until the job is done. Now let *n* be the number of cannibals (or missionaries). If the boat holds just four passengers, the problem is solv-

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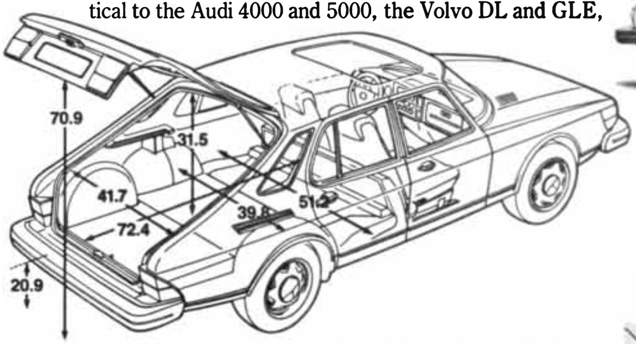

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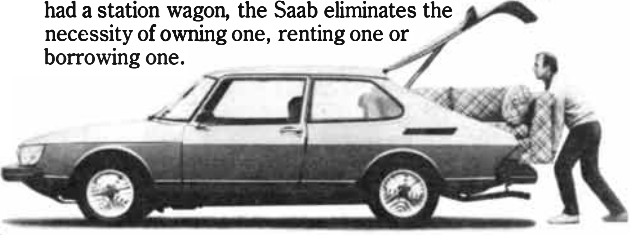

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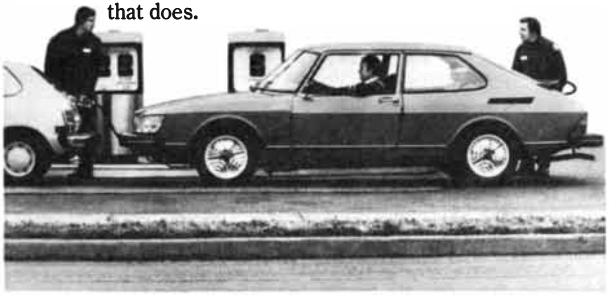

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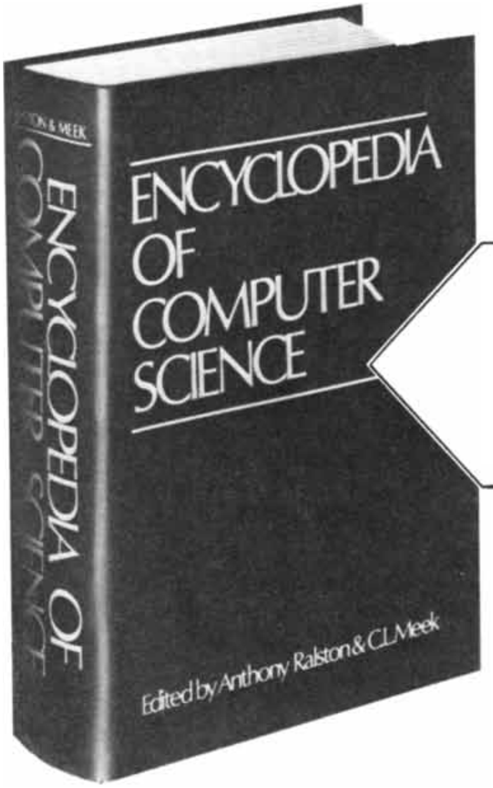

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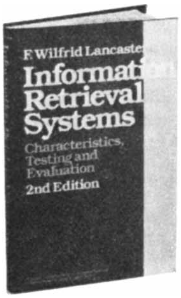

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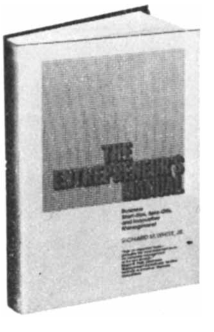

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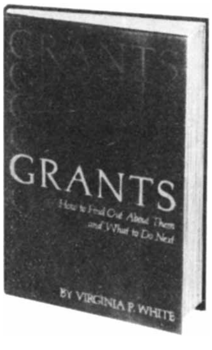

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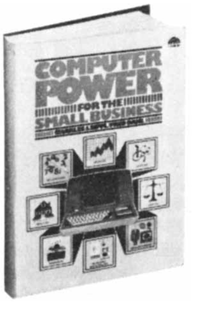

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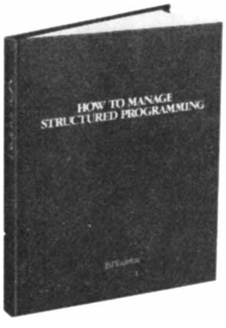

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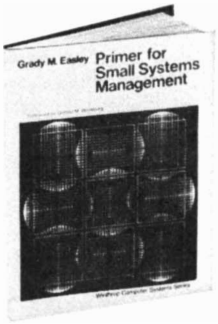

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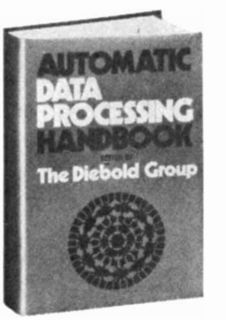

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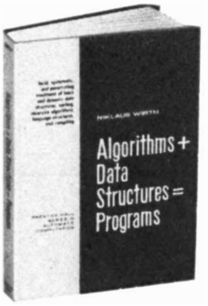

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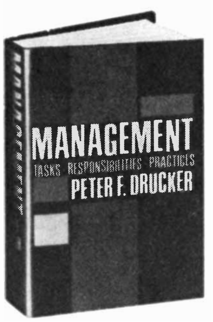

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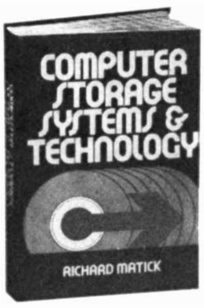

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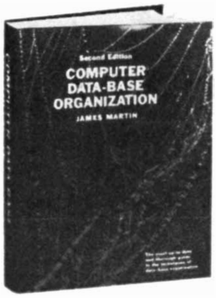

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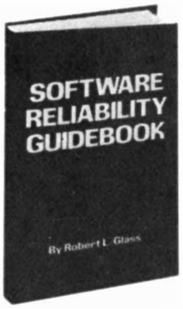

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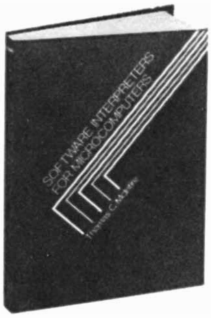

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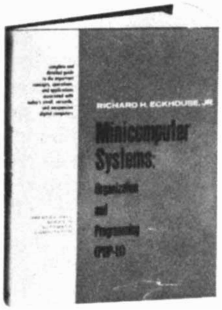

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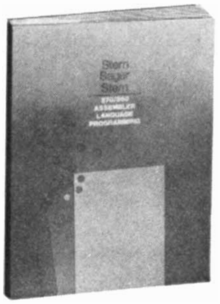

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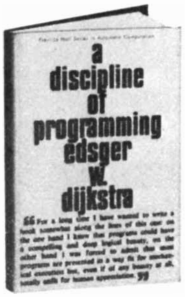

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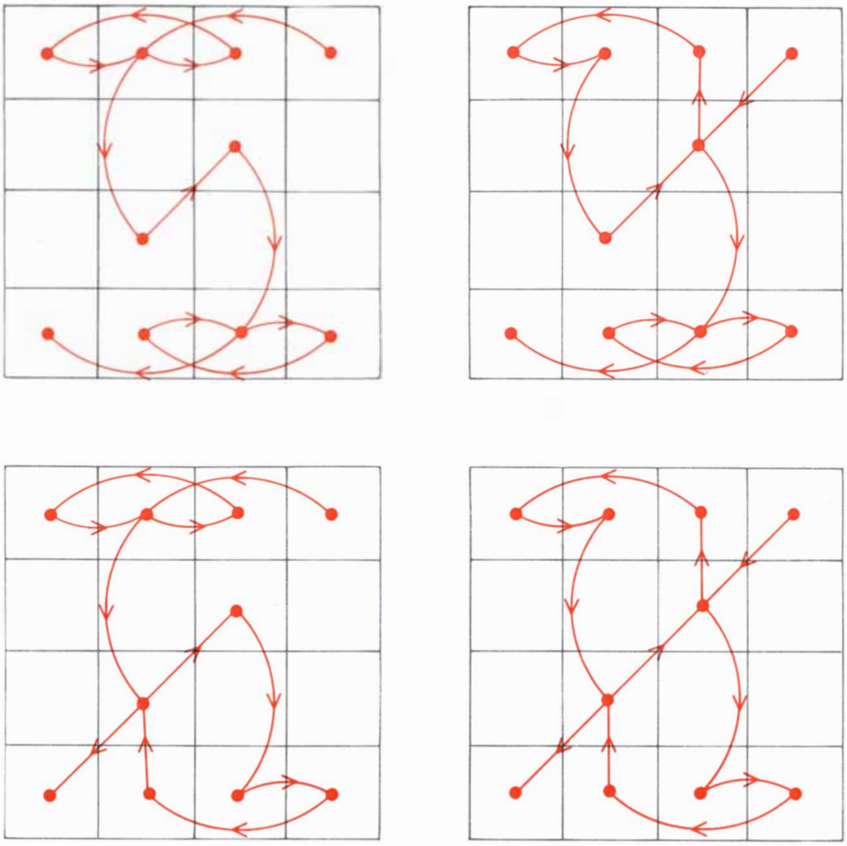
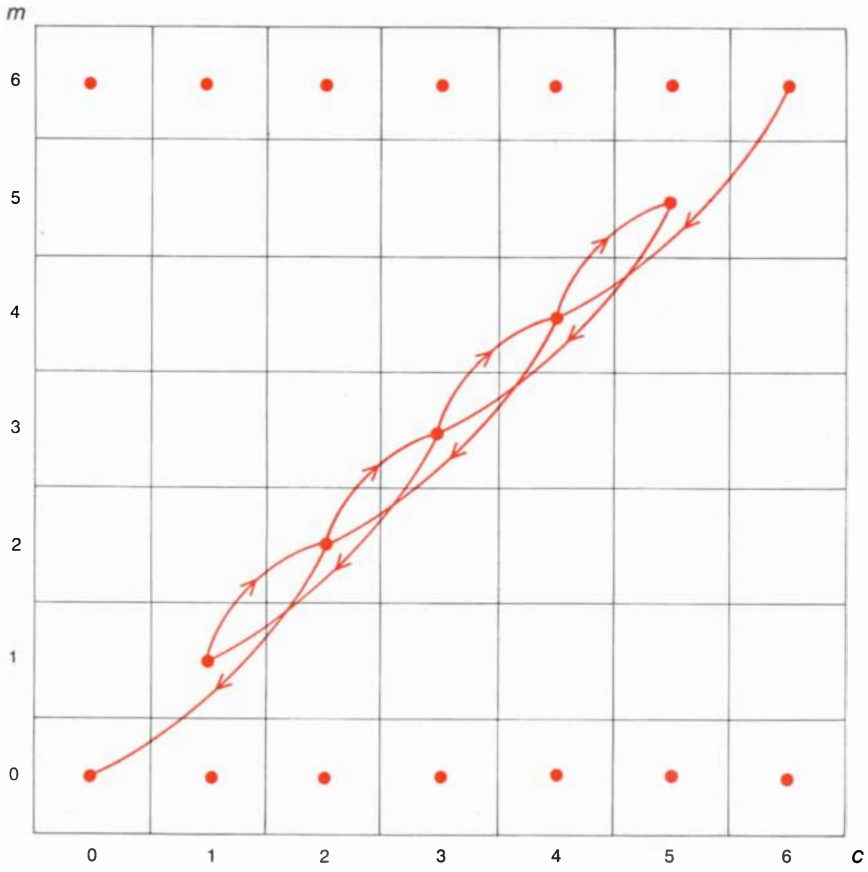


Digraphs giving the four solutions to the cannibal-missionary puzzle



Nine-step diagonal solution for six missionaries, six cannibals and a four-passenger boat

able in $2n - 3$ steps. If the boat holds an even number of passengers that is greater than 4, more than one cannibal-missionary pair can of course be taken each time. The technique of always keeping the same number of cannibals and missionaries on both sides of the river is diagrammed as a braided pattern along the diagonal of the matrix of the problem as is shown in the bottom illustration at the left. This nine-step digraph solves the cannibal-missionary problem when n equals 6 and the boat holds four passengers.

When the capacity of the boat is an even number greater than or equal to 4, the diagonal method always gives the best solution. If the number of cannibals n is just one more than the capacity of the boat, which is an even number greater than 4, then there is always a five-step minimum solution. Actually the diagonal method is more powerful than this last case implies. With a boat that holds an even number greater than 4 it will always provide a five-step minimum solution for any case from $b + 1$ cannibals through $(3b/2) - 2$ cannibals, where b is the capacity of the boat.

If the number of passengers the boat can hold is odd, moving down the diagonal does not always give the best answer. For example, if n equals 6 and the boat holds five, the diagonal method gives the same nine-move solution shown in the bottom illustration at the left, but the problem also has a seven-step solution. More generally, if the boat holds an odd number of passengers that is greater than 3 and one less than n, there always is a minimum solution in seven moves. Can you find one of many seven-step solutions for six cannibals and six missionaries crossing the river in a boat that holds five passengers? This is the simplest of an infinity of examples in which, for a boat with an odd capacity, there is a procedure superior to the diagonal procedure. (I am ignoring here the trivial cases of a boat with an odd capacity of one or three, where the diagonal method will not work at all.) The next-simplest case is the one where n equals 10 and the boat holds seven passengers.

The digraph method can be applied to almost any kind of river-crossing problem. One famous problem, which goes back at least to the eighth century, concerns three jealous husbands and their wives, who want to cross a river in a boat that holds two passengers. How can this goal be accomplished so that a wife is never alone with a man who is not her husband? If you construct the digraph for the problem, you may be surprised to discover that it is solved by the same four walks as the classic cannibal-missionary problem and has no other solutions. The only difference—and this applies also to generalizations of the jealous-husband variant of the puzzle—is that the pairings of individual men and women have to be manipulated to meet

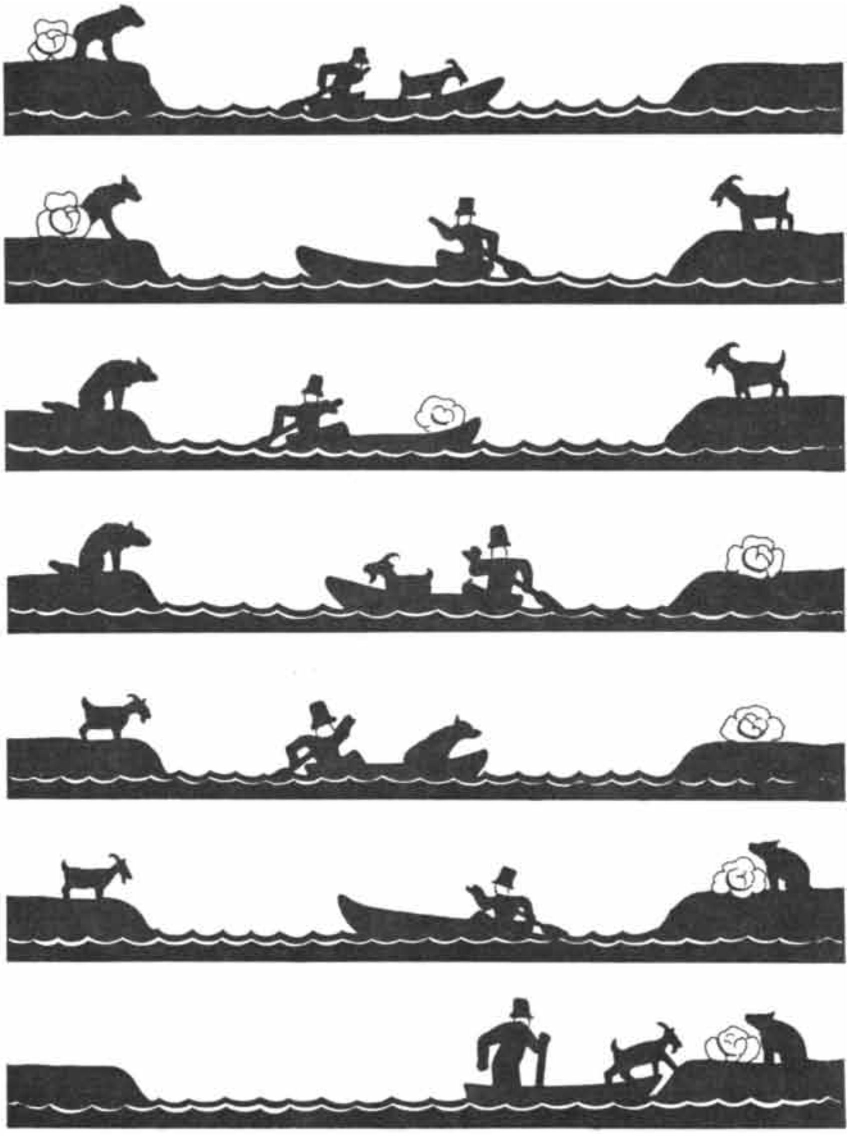
Fluorescence image reproduced from a photomicrograph by Dr. R.S.K. Chaganti, Memorial Sloan-Kettering Cancer Center, New York City.

conditions not essential to the cannibal-missionary version.

Many puzzle books include more exotic variations of the cannibal-missionary problem. For example, in some cases only certain people may be able to row. (In the classic problem if only one cannibal and one missionary can row, the solution requires 13 crossings.) The boat may also have a minimum capacity (greater than one) as well as a maximum capacity. Or missionaries may outnumber cannibals and be safe only if they outnumber them at all times. An island in the river may also be employed as a stopover spot, and certain pairs of individuals may be singled out as being too incompatible to be left alone together.

An ancient problem of this last type (it too can be traced back to the eighth century) is about a man who wants to ferry a wolf, a goat and a cabbage across a river in a boat that allows him to take only one of them at a time. He cannot leave the wolf alone with the goat or the goat alone with the cabbage. In this case there are two minimal solutions, each of which requires seven trips. One of these solutions is shown in the illustration below, taken from *Moscow Puzzles,* by Boris A. Kordemsky (Charles Scribner's Sons, 1972). Interested readers will find a good selection of such river-crossing problems in books by the British puzzle expert Henry Ernest Dudeney.

I have space for one more digraph puzzle. Paul Erdös has shown that on a complete digraph for *n* points, when *n* is less than 7, it is not possible to place arrowheads so that for any two specified points it is always possible to get to each point in one step from some third point. The top illustration on page 38 shows a complete graph for seven points. Think of the points as towns joined by one-way roads. Your task is to label each road with an arrowhead so that for any specified pair of towns there is a third town from which you can drive directly to each of the other two. Next



Solution to the wolf-goat-cabbage puzzle

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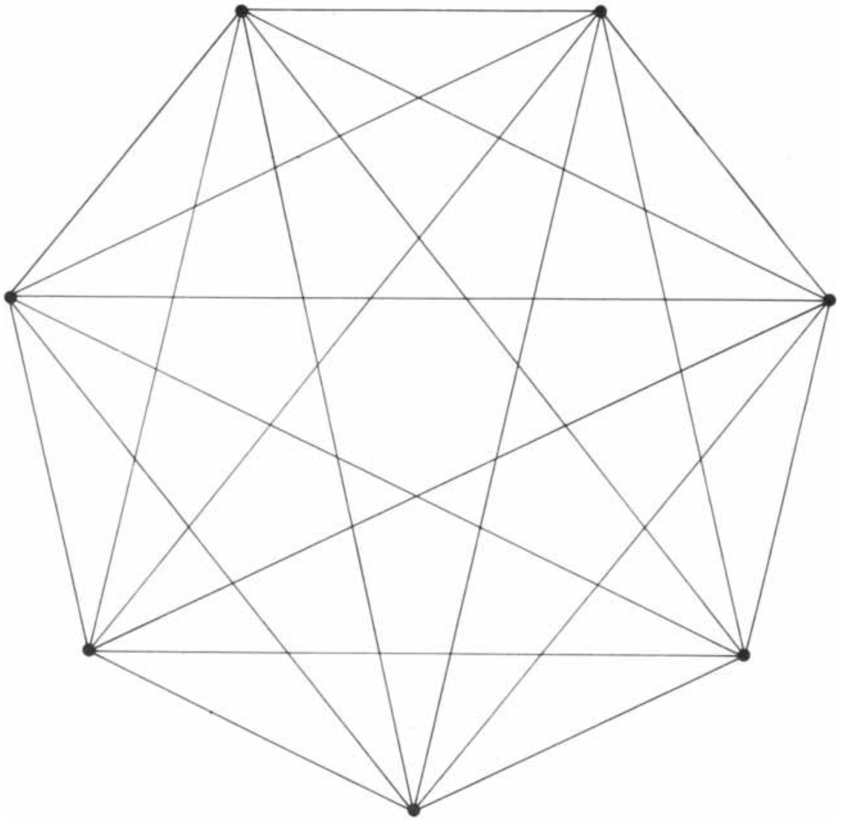
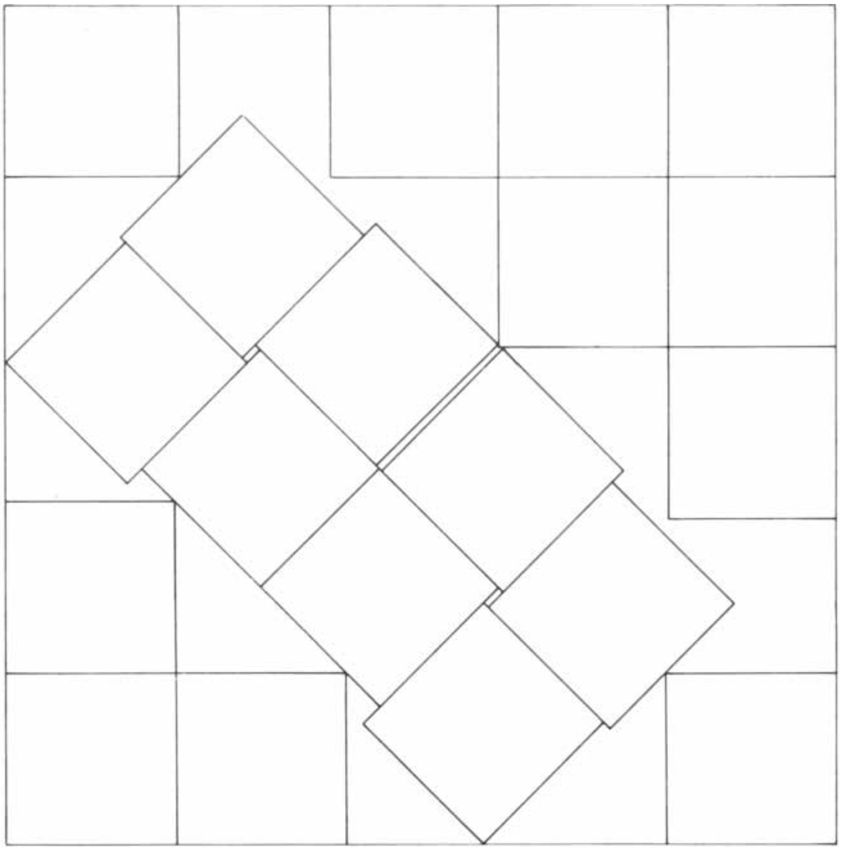


Paul Erdös' third-town problem



Packing of 19 unit squares into a square of side $3 + (4/3)\sqrt{2}$, or 4.885+

month I shall give Erdös' solution and the reference for his analysis of the general problem.

The map-coloring problem given last month is from Howard P. Dinesman's collection of brainteasers *Superior Mathematical Puzzles, with Detailed Solutions* (Simon and Schuster, 1968). It can be answered as follows. Nevada is surrounded by a ring of five states: Oregon, Idaho, Utah, Arizona and California. Color Nevada with color 1. If only three colors are used, each state in the ring must be colored with either color 2 or color 3 to avoid conflict with Nevada, and these two colors must alternate around the ring. Since the ring consists of an odd number of states (five), however, there is no way to avoid giving two adjacent states the same color. Therefore a fourth color is necessary.

This property of rings that consist of an odd number of regions plays a basic role in map-coloring theory. Consider how it applies to L. Frank Baum's land of Oz. Oz is made up of five regions, each region with a dominant landscape color: the green Emerald City is surrounded by a ring consisting of the yellow Winkie country, the red Quadling country, the blue Munchkin country and the purple Gillikin country. Surrounding all of Oz is the great Deadly Desert. Because four is an even number, a map of Oz can be colored with three colors, but of course no Oz cartographer would use fewer than five for Oz and a sixth for the surrounding desert.

The improved solution I gave in November for the problem of packing 19 unit squares without overlap into the smallest possible square has been improved a second time. Robert T. Wainwright was the first of many readers to realize that the eight squares in the tilted rectangle could be displaced as is shown in the bottom illustration at the left. This adjustment reduces the side of the containing square to $3 + (4/3)\sqrt{2}$, or 4.885+.

As hundreds of readers have pointed out, the "impossible problem" given in this department for December turned out to be literally impossible. Because I gave an upper bound of 20 for the two selected numbers the solution became totally inapplicable. I have since learned that the problem, with its correct upper bound of 100, was first submitted by David J. Sprows to *Mathematics Magazine,* where it appeared in March, 1976 (Vol. 49, No. 2, page 96). An accurate solution appeared there in November, 1977 (Vol. 50, No. 5, page 268). Richard Hess and Thomas Truscott were the first of many who sent me proofs that 62 is the lowest upper bound that allows a solution. I shall comment more fully on this problem in a future column.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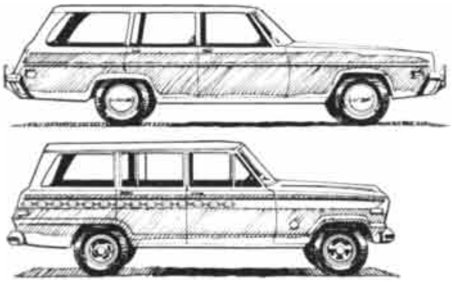
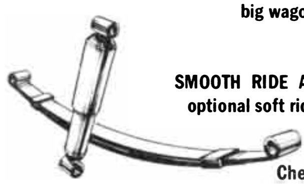
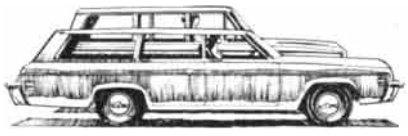






BOOKS

Medieval materials science, the art of breaking and cutting, and a feedback view of the earth

by Philip Morrison

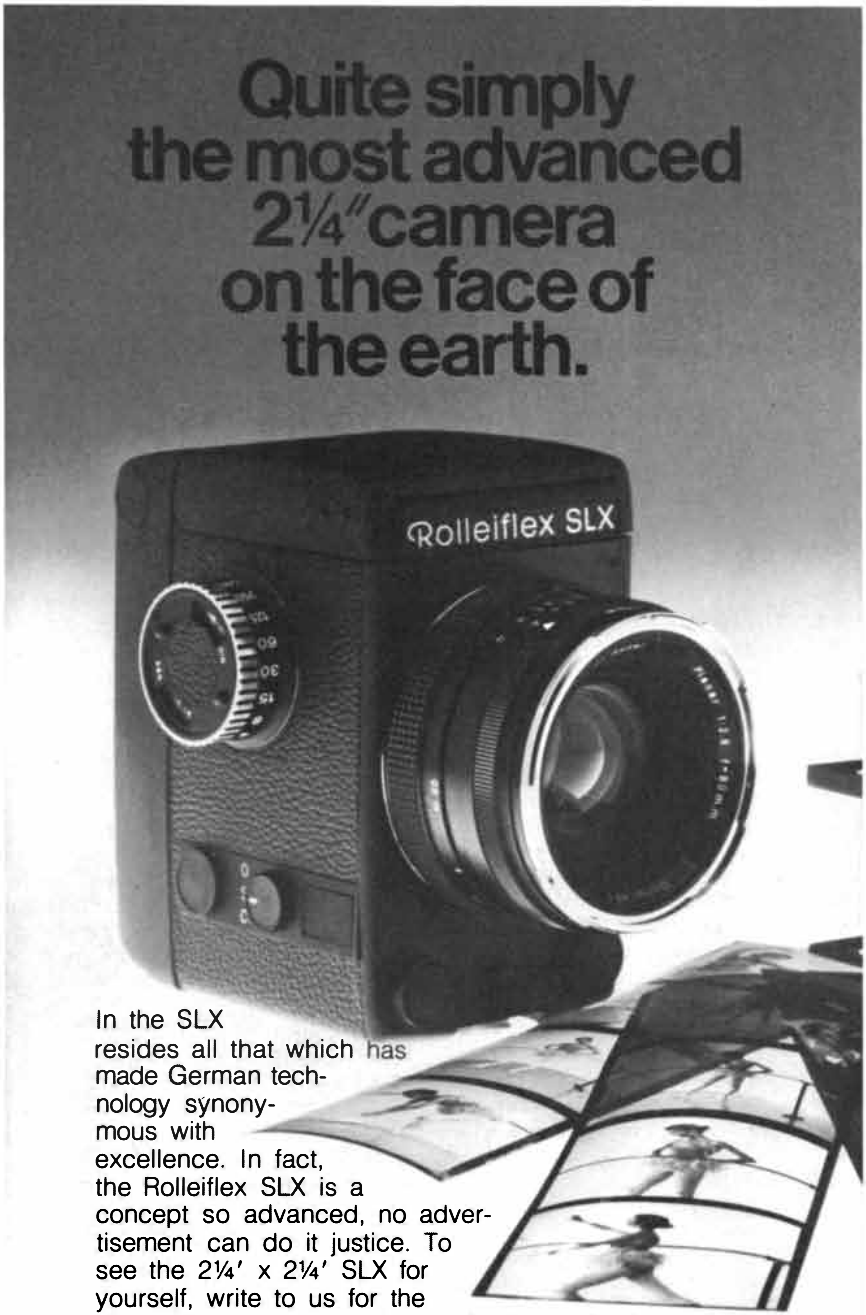
THEOPHILUS: ON DIVERS ARTS, translated from the Latin with introduction and notes by John G. Hawthorne and Cyril Stanley Smith. Dover Publications, Inc. ($5). MAPPAE CLAVICULA: A LITTLE KEY TO THE WORLD OF MEDIEVAL TECHNIQUES, translated by Cyril Stanley Smith and John G. Hawthorne. The American Philosophical Society, Independence Square, Philadelphia ($7). In this our world inundated by books, technology is fully described by experts. Artful secrets still abound, since the skills of hand and eye cannot always be transmitted by means of word and picture. Direct documentation is nonetheless broad and rich. When people in Western lands could read only what authors wrote in their own hand or what compilers and scribes made by hand and eye, this was not so. The granulation of the dazzling gold ornaments of the Etruscans and the rigging of the pyramid builders are not the topics of any contemporary texts at all. If we can read the old crafts tolerably well today, it is because we can read the objects, the old quarries, the occasional images of the artist or once in a while the witness of curious travelers; it is almost never because we can read the words of the knowing man or woman at the workbench.

There is one tradition of technical writing that deals primarily with the materials themselves and rather less with the tedious or subtle processes by which they were wrought. That tradition is truly old. It comes to us first in wedge marks left on clay tablets: for 50 years we have known of a number of recipes, the earliest being a list of ingredients for glassmaking set down in Assyrian before 1600 B.C. "The substance of many of the Assyrian recipes appears unchanged" in papyruses of the third century B.C., now "elegantly written in Greek." A considerable body of manuscripts of these recipes has proliferated. They were evidently copied and recopied (with little refreshment from reality but with a good admixture of error) by scholars who apparently felt such antique texts must have value (even if the later compilers themselves would consider them only sources of engaging lore and old Latinity). The odor is unmistakably one of the library lamp, not one of the glowing furnace.

The book signed by Theophilus the Priest, a bargain reissue of the first edition of a translation published by the University of Chicago Press in 1963, first opened wide the workshop door. The work has long been under study by philologists; there are many manuscript versions of it, the oldest one datable to the middle of the 12th century. It bears an added title page on which a 17th-century hand has offered an identification of the author, supplied no doubt by verbal tradition. But "all the evidence converges to support the belief that the manuscript... was written by the Benedictine monk and metalworker Roger of Helmarshausen." In a valley 20 miles west of Göttingen, Helmarshausen was an important center for all the arts described by the modest author under the Byzantine pseudonym by which the work is known.

What does Roger promise? "If you study diligently, you will find here whatever kinds of the different pigments Byzantium possesses and their mixtures; whatever Russia has learned in the workings of enamels and variegation with niello; whatever Arab lands adorn with repoussé or casting or openwork; whatever decoration Italy applies to a variety of vessels in gold or by the carving of gems and ivories; whatever France loves in the costly variegation of windows; and whatever skillful Germany applauds in the fine working of gold, silver, copper and iron, and in wood and precious stones." He is as good as his word.

More than two-thirds of the text treats of metalworking: not only the materials but also the processes, the tools and utensils, the furnaces and the housekeeping and management of a shop able to keep perhaps a dozen craftsmen at work. Their purpose was "to complete whatever is still lacking in the house of the Lord... chalices, candlesticks, censers, cruets, ewers, caskets for holy relics, crosses, missal covers." We can admire contemporary samples, some from Roger's own hand and others elaborated as if to provide examples of all the techniques he describes. The nonmetallurgical first third of the book is divided into



two parts. One, on the art of the painter, gives recipes for pigments and directions for mixing, fixing and applying them; the second, on glassmaking, has a page or two about clear glass sheet and the rest about colored glasses and glass painting for the mosaic church windows of the time.

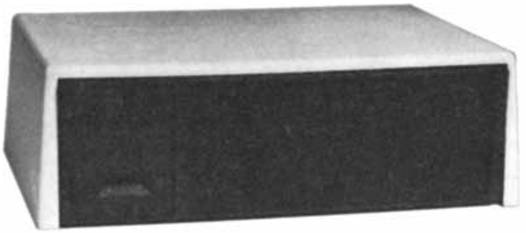
These pages are filled with convincing and comprehensive eyewitness accounts, modern in tone. They bring us to a real place and time. "At the first hour next morning, if you want to make sheets of glass," Roger says, after having described for several pages how to procure beechwood logs and reduce them to ashes and how to build a work furnace, an annealing furnace and a furnace for "spreading out and flattening." For the metalwork section he begins: "Build a high, spacious building whose length extends to the east. In the south wall put as many windows as you wish and are able to, provided that there is a space of five feet between any two windows." He describes the forge, the bellows and the workbench, anvils, stakes, files and other hand tools. The fires of the workmen are fueled with charcoal and blown with bellows; the text describes a cupola for melting bell metal and big reverberatory furnaces in the glass shop, and there is a neat little design for a wind-blown furnace for making brass. Together these incorporate, say the learned translators, "the principles of all metallurgical furnaces prior to the introduction of gas and electricity."

There is no allusion to any energy sources other than fire and human muscle; there are no large machines at all, not even a hoist or crane for the big molds in which the shop cast large church bells with clappers. Theophilus describes several machines: a couple of simple specialized lathes, a grinding mill and a device (not very practical) with which to prepare iron surfaces for precious-metal overlays. All of these are hand-powered. Roger's shop was not a factory but an ensemble of craftsmen. They could, however, make quantitative judgments as well as aesthetic ones: Roger alludes to (but does not furnish) complete tables of dimensions for the maker of organ pipes and of bells.

Here and there, even in the metalwork chapters, which obviously lie nearest to his own talents, Roger includes some pure hearsay and lore, most of it dealing with materials he acquired through trade and of whose winning he knew only vicariously. The beechwood ashes these artisans could prepare for themselves, but copper, zinc and precious metals came mainly from afar. Roger offers one chapter of sheer magic: an elaborate procedure for making basilisk powder (magically, from the ashes of half-serpent chicks), which turns copper into "Spanish gold" that is "suitable for all kinds of work." Entirely untypical of

Burglar Alarm Breakthrough

A new computerized burglar alarm requires no installation and protects your home or business like a thousand dollar professional system.

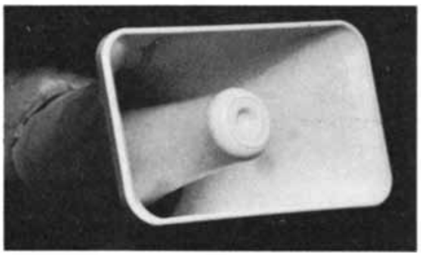


The Midex security computer looks like a handsome stereo system component and measures only 4"x 10½"x 7."

It's a security system computer. You can now protect everything–windows, doors, walls, ceilings and floors with a near fail-safe system so advanced that it doesn't require installation.

The Midex 55 is a new motion-sensing computer. Switch it on and you place a harmless invisible energy beam through more than 5,000 cubic feet in your home. Whenever this beam detects motion, it sends a signal to the computer which interprets the cause of the motion and triggers an extremely loud alarm.

The system's alarm is so loud that it can cause pain–loud enough to drive an intruder out of your home before anything is stolen or destroyed and loud enough to alert neighbors to call the police.



The powerful optional blast horns can also be placed outside your home or office to warn your neighbors.

Unlike the complex and expensive commercial alarms that require sensors wired into every door or window, the Midex requires no sensors nor any other additional equipment other than your stereo speakers or an optional pair of blast horns. Its beam actually penetrates walls to set up an electronic barrier against intrusion.

NO MORE FALSE ALARMS

The Midex is not triggered by noise, sound, temperature or humidity–just motion–and since a computer interprets the nature of the motion, the chances of a false alarm are very remote.

An experienced burglar can disarm an expensive security system or break into a home or office through a wall. Using a Midex system there is no way a burglar can penetrate the protection beam without triggering the loud alarm. Even if the burglar cuts off your power, the four-hour rechargeable battery pack will keep your unit triggered, ready to sense motion and sound an alarm.

ARRIVE HOME SAFE

There's personal danger in arriving home and finding a burglary in progress. And, if you surprise the burglar, you risk the chance of serious injury. With the Midex 55 protecting your home, you can open your front door with the confidence of knowing that no burglar lurks inside.

When the Midex senses an intruder, it remains silent for 20 seconds. It then sounds the alarm until the burglar leaves. One minute after the burglar leaves, the alarm shuts off and resets, once again ready to do its job. This shut-off feature, not found on many expensive systems, means that your alarm won't go wailing all night long while you're away. When your neighbors hear it, they'll know positively that there's trouble.

PROFESSIONAL SYSTEM

Midex is portable so it can be placed anywhere in your home. You simply connect it to your stereo speakers or attach the two optional blast horns.

Operating the Midex is as easy as its installation. To arm the unit, you remove a specially coded key. You now have 30 seconds to leave your premises. When you return, you enter and insert your key to disarm the unit. You have 20 seconds to do that. Each key is registered with Midex, and that number is kept in their vault should you ever need a duplicate. Three keys are supplied with each unit.

As an extra security measure, you can leave your unit on at night and place an optional panic button by your bed. But with all its optional features, the Midex system is complete, designed to protect you, your home and property just as it arrives in its well-protected carton.

The Midex 55 system is the latest electronic breakthrough by Solfan Systems, Inc.–a company that specializes in sophisticated professional security systems for banks and high security areas. JS&A first became acquainted with Midex after we were burglarized. At the time we owned an excellent security system, but the burglars went through a wall that could not have been protected by sensors. We then installed over $5,000 worth of the Midex commercial equipment in our warehouse. When Solfan Systems announced their intentions to market their units to consumers, we immediately offered our services.

COMPARED AGAINST OTHERS

In a recent issue of a leading consumer publication, there was a complete article written on the tests given security devices which were purchased in New York. The Midex 55 is not available in New York stores, but had it been compared, it would have been rated tops in space protection and protection against false alarms–two of the top criteria used to evaluate these systems. Don't be confused. There is no system under $1,000 that provides you with the same protection.

YOU JUDGE THE QUALITY

Will the Midex system ever fail? No product is perfect, but judge for yourself. All components used in the Midex system are of aerospace quality and of such high reliability that they pass the military standard 883 for thermal shock and burn-in. In short, they go through the same rugged tests and controls used on components in manned spaceships.

Each component is first tested at extreme tolerances and then retested after assembly. The entire system is then put under full electrical loads at 150 degrees Fahrenheit for an entire week. If there is a defect, these tests will cause it to surface.

PEOPLE LIKE THE SYSTEM

Wally Schirra, a scientist and former astronaut, says this about the Midex 55. "I know of no system that is as easy to use and provides such solid protection to the homeowner as the Midex. I would strongly recommend it to anyone. I am more than pleased with my unit."

Many more people can attest to the quality of this system, but the true test is how it performs in your home or office. That is why we provide a one month trial period. We give you the opportunity to see how fail-safe and easy to operate the Midex system is and how thoroughly it protects you and your loved ones.

Use the Midex for protection while you sleep and to protect your home while you're away or on vacation. Then after 30 days, if you're not convinced that the Midex is nearly fail-safe, easy to use, and can provide you with a security system that you can trust, return your unit and we'll be happy to send you a prompt and courteous refund. There is absolutely no obligation. JS&A has been serving the consumer for over a decade–further assurance that your investment is well protected.

To order your system, simply send your check in the amount of **$199.95** (Illinois residents add 5% sales tax) to the address shown below. Credit card buyers may call our toll-free number below. There are no postage and handling charges. By return mail you will receive your system complete with all connections, easy to understand instructions and a one year limited warranty. If you do not have stereo speakers, you may order the optional blast horns at **$39.95** each, and we recommend the purchase of two.

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this practical compendium by a master craftsman, the fanciful account is nonetheless often cited for its flavor of sorcery, to support whatever lessons the modern commentator seeks to draw. "Theophilus" speaks for himself. There is a clear stream of experience and observation running between this learned, talented and devoted Benedictine and the craftsmen, engineers and discoverers of the Renaissance to come.

Behind Theophilus lie the recipe books, a scholars' world nearly three millenniums old. The same pair of translators (the late John G. Hawthorne was a Latinist at the University of Chicago and Cyril Stanley Smith is a distinguished materials scientist and historian at the Massachusetts Institute of Technology) have also given us readers of English a glimpse of that older work. A few years ago they put into English the text of a recipe book of the ninth century. A Latin manuscript now at the Corning Museum of Glass (one of the best sources of such manuscripts) is reproduced as a whole in facsimile, along with the annotated translation, in an erudite monograph. The recipes are staccato, not very readable, often confusing, and they float high above the workshop; these are hints, tricks and lists of ingredients rather than coherent accounts of how to proceed. They are logically and pedagogically most variable in form. (One crowded entry is a multiplication table, up to X times V equals L.) The differences between the recipe writer and Theophilus are convincing. Something new, some context of a single reality, began only in late-medieval Europe to unite the pen and the hammer.

Throughout both of these works, particularly the much more rewarding Theophilus, the reader is helped to a wider understanding by the discrimination and the soundly based commentary of the translators and by their diagrams, photographs and captions. Once again Clio has profited from knowledge won with the X-ray-diffraction camera, the pyrometer and the tools of the analytical chemist.

CUTTING FOR CONSTRUCTION: A HANDBOOK OF METHODS AND APPLICATIONS OF HARD CUTTING AND BREAKING ON SITE, by David Lazenby and Paul Phillips. John Wiley & Sons, Inc. ($19.95). Jackhammer and wrecking ball seem symbols of the turmoil of cities today. They are in fact quite modern tools, born largely of the paradoxical attributes of our architectural life: constant change amidst stable masses of poured concrete. The old masons could as a rule take apart their walls of brick and stone more easily than we can move the monoliths of our own construction: massive castings, reinforced with steel rods, found even in quite workaday buildings that are in no way monumental. This handbook by two experienced technical experts in Britain, who are careful students of the art on both sides of the Atlantic, is a modern survey for planners and consumers of a small but important industry. This knowledge is held in the fringes of a few large companies or as a "province of the small entrepreneurial operator." We hear it, but we hear little about it.

The impact methods are certainly fundamental mechanics, but nowadays the four ancient elements themselves are used against concrete. The earth yields diamonds, and diamond cutting tools are often the approach of economic choice, at least in the U.S. Here is an exception to the rule; diamond use prospers under the innovations and widespread information prepared by the well-managed diamond monopoly. The diamond-set tool—in a core drill, in a large rotary-disk saw for floors or walls or in a reciprocating saw that works through a starting hole in any slab—cuts its smooth and well-controlled way through concrete mass and steel rod. The case studies show the virtue of this technique, which in effect machines the reinforced concrete.

Diamond-tool cutting is a wet job, with cooling water flowing by a big saw at the rate of a ton or two an hour. A big saber saw, its diamond blade able to cut a four-foot slab at one pass (beyond the two-foot reach of the biggest rotary blades), requires some 25 horsepower, delivered by hydraulic flow from its engine trailer nearby. The slab could be cut in an average time of an hour and a half. (Concrete varies in hardness; the aggregates are crushed from locally available rock, and so careful maps are included giving the hardness to be expected anywhere in the U.S. or the U.K. Watch out for that hard stuff all along the Ohio valley!)

The element of fire works well too, although it does so more commonly in Europe than on this shore. The handheld oxygen cutting torch, burning acetylene or propane, is familiar wherever steel or iron is to be cut, even under water. The thermic lance is a less familiar tool of power. It is simple. A 10-foot-long piece of mild steel pipe is packed with strands of iron wire. (A patented improvement uses high-carbon steel and a magnesium alloy for faster results, at 4,000 degrees Celsius.) This "burning bar" is fed plenty of oxygen; well-equipped workers are likely to have a cryogenic tank trailer at the end of their supply hose. The pipe and wire burn swiftly, and the concrete and steel melt ahead of the lance, drain freely and harden into a brittle, easily removed slag of iron silicate. The bar cuts a neat hole; typically a meter of two-inch hole is burned through concrete in five minutes, consuming six meters of lance.

The element of water comes into play in a water-jet cutter. It will not sever reinforcing bars, but it erodes the "complex multiphase material...often...10 percent by volume of air and water," leaving the steel bars exposed and clean. The jet works by impact on the cement matrix, by cavitation of the sandy surface and by pressurizing the tiny cracks until the mass splits. Typically a 300-horsepower pump feeds a hand-held jet at a pressure of about 1,000 atmospheres and at a flow rate of 10 gallons per minute; such a jet will cut a wide swath down a thick wall at a foot or two of cut per hour.

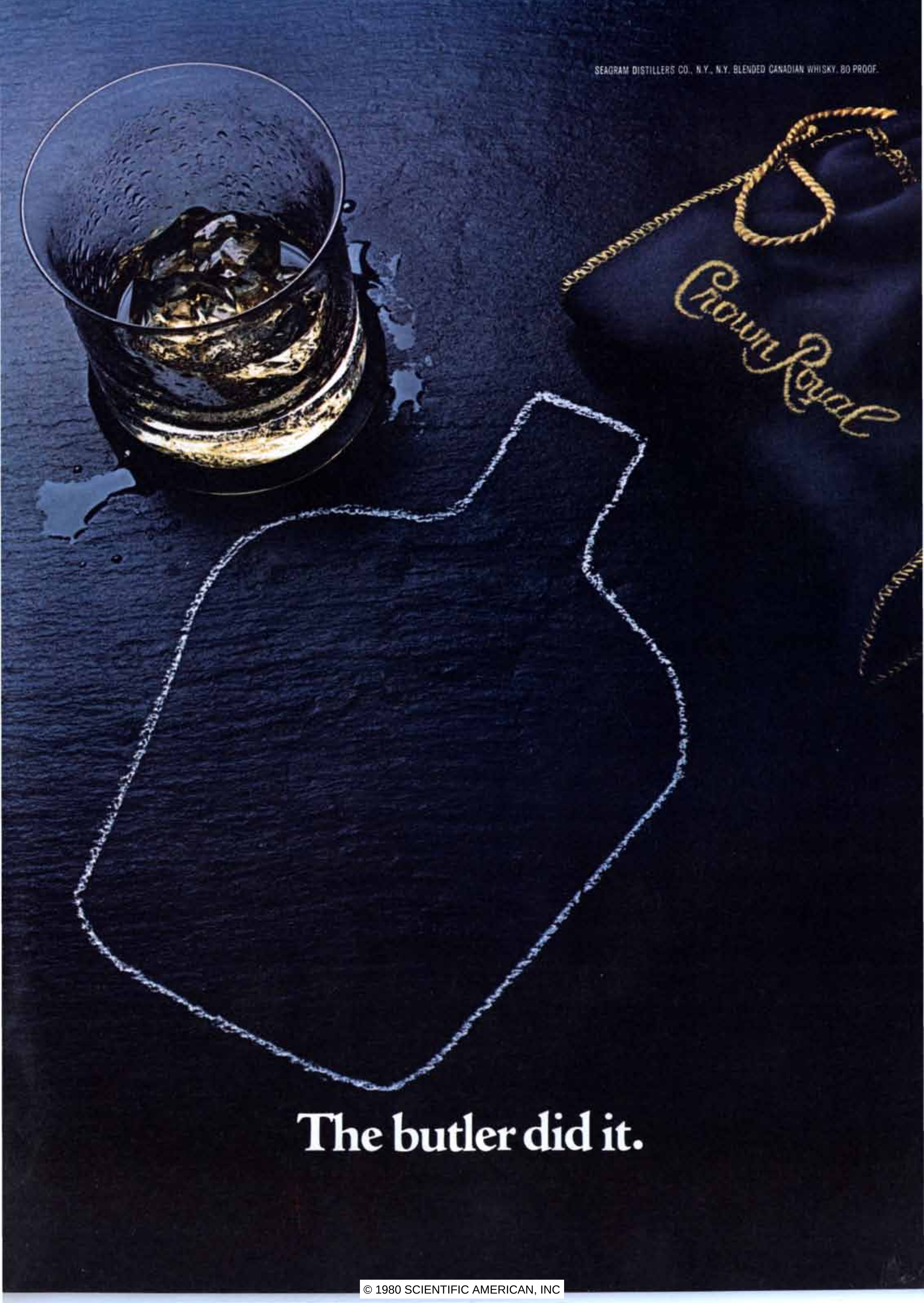
Those are cutting techniques; the breaking ones, which are more familiar, must often follow to dispose of the big pieces set free. One neat breaking device is the Nibbler, a proprietary British machine. A big-jawed tool mounted at the end of a boom on a tracked vehicle, the Nibbler catches a layer of slab between a large pointed tooth and a strong opposed jaw. It then prizes up the slab, bending it firmly a few inches upward. The slab snaps locally under the bending, and so the Nibbler quietly munches away the entire road or wall, like the tooth of time.

Explosives (among them shaped charges), hydraulic jacks and chemically detonated charges of liquid carbon dioxide are some other bursting techniques. The future looks even brighter for breaking. Plasma jets may replace the thermic lance; the heavy laser might make fault lines by means of thermal shock to begin the work; microwave cooking can break concrete by inducing stresses within that inner heterogeneity; eddy-current heating can be applied locally to expand prestressed members gradually and make their removal much safer.

This is a serious handbook, full of management detail and safeguards. It is meant for the prudent planner, but it opens a world for the general reader, who will browse in its surprising and well-illustrated pages. A raffish tendency in one reader was a little let down by the fact that among 15 case studies not one described the virtuoso work of a safecracker!

GAIA: A NEW LOOK AT LIFE ON EARTH, by J. E. Lovelock. Oxford University Press ($11.95). Gaia is "wide-bosomed Earth, the ever-sure foundation of all," Hesiod told us. In this entirely engaging small book the English physical organic chemist Jim Lovelock, a man as inventive and ingenious as he is lively and unorthodox, places a daring hypothesis before the general reader, a kind of geochemical myth for our time. He proposes to augment Hesiod's concept of a patient bearer with a more active and urgently necessary new Mother, so far known to us only by way of conjecture.

The possibility is clear. For three and a half billion years and more the ferment of life has been nourished unceas-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ingly by the earth. Not once over the sweep of time has the aimless drift of the continents, an odd supernova, a patch of galactic dust, a runaway volcano, the evolution of the sun, the ultraviolet-induced oxygenation of the air or any other parameter of our complex and changing planet brought fragile life to an end. Is that good luck, a neat balance of forces struck by chance alone or something deeper? Providence and Design have their proponents, but Lovelock opts for a "complex entity involving the Earth's biosphere, atmosphere, ocean and soil" that has come to maintain the fitness of the overall environment neither by chance nor under angelic custody but by an actively evolved feedback control, through a grand set of large-scale processes we can only dimly trace.

Let us follow one path among a number of paths that might bring a glimpse of Gaia, so powerful and so shy. We simply ask: Why is the sea salt? Since Leonardo's day people have come to realize that it is salt because rocks yield up to the rain soluble ions that flow in steady runoff down to the sea, which can recycle its waters over and over but seems to have no way to lose its salt; and so the sea becomes much saltier than the streams feeding it. The effort to deepen this insight to the quantitative runs into trouble. The present rate of runoff would have salted the seas in a small fraction of geologic time, about 60 million years. That is hardly credible in the face of the evidence that ocean life has not been very different from today's over a period 50 times longer. Moreover, the salts of continental runoff are augmented noticeably by sea-floor spreading, with ions coming from "doughy rocks" that well up on the ocean ridges and push the continents apart. The chemical oceanographers are unhappy; there is no clear way to keep the oceans less salty than a dense brine. Now, life does not like the environment of brine. Although a few hardy specialized forms have found physiologically expensive contrivances for living in an oversalty world, the membranes that enclose all normal cells cannot remain intact in a watery medium even only twice as salty as the present ocean; if there were no compensation, the end of normal life would lie quite near. And so the question has shifted: Why is the sea not saltier?

To be sure, the sea does lose salt. Great beds of dried salts are buried under all the continents and the continental shelves. Some famous ones are even exposed on land, where isolated arms of the sea, cut off long ago, evaporated to dryness faster than the local drainage could replenish them and so turned to salt. A balance is struck, with rates that apparently work out on the average to keep the ocean from greater brininess. But if those evaporated seas and their burials are entirely random, it is indeed good luck that the timely burials took place just when they were needed, over an epoch long enough to have strengthened the salt solution by more than an order of magnitude. Why has there been no lethal fluctuation over all the time of life on the earth?

Can it be that the vast shallow lagoons and narrow gulfs that sequester the excess salt are the geography of life itself? "Is it possible that the Great Barrier Reef . . . is the partly finished project for an evaporation lagoon?" Here is certainly engineering on a Gaian scale, now being built by a powerful consortium of living organisms. Perhaps even the subsequent burials by geological flows are part of the Gaian loop. The rain of silica to the ocean floor as the plankton die and sink may act to reduce heat loss and induce local melting under the sea floor. The limestone that living things secrete on the shelves might act as a flux to melt rock and aid the growth of volcanoes. After all, the weight of a man-made lake can cause a small earthquake, and a barrier reef or a limestone shelf is constructed on a far greater scale, to dimensions fit for Gaia.

We have no firm audit for this and half a dozen other balance sheets. The continental shelves might be the chief seat of slow and subtle processes absolutely indispensable to life in the long run, and yet still unknown. Lovelock is thus uneasier about proposals for large-scale farming of kelp than he is about pesticides and aerosol sprays. Kelp growing over wide new areas might threaten the ozone with its emissions of methyl chloride much more than all the spray cans. The monoculture of those valuable big fronds might easily inhibit "weed" algae, only partly known, which now control the balance of sulfur and selenium in the atmosphere, if Lovelock's ideas are right.

It is not the smokestacks of industry that most threaten unknown Gaia. Rather, it is large-scale changes in tropical lands and on the broad shelves offshore. There dwell the inconspicuous but abundant species that form the feedback loops of Gaia's geochemical controls; there are the agencies that might release large quantities of abnormal or damaging substances in a short time.

Of course, this book is no judicious review; it is the exciting and personal argument of an original thinker caught up in wonder. It wins and repays attention, although it deserved better editing than it was given, with its confusing references, too brief tables and lack of an index. One hopes that many a reader will read about Gaia. Even if she remains a myth, to be replaced by a less romantic mix of local good luck with blind renewals and burials of sea floor around the drifting plates, she is worth much thought. She will lead you, by way of an excursion into geochemical ecology, to an encounter with a rare and fast-

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moving form of life indeed: the candid, well-informed, logical and humorous iconoclast Jim Lovelock, in his private analytical laboratory in the quiet countryside.

MACHINES WHO THINK: A PERSONAL INQUIRY INTO THE HISTORY AND PROSPECTS OF ARTIFICIAL INTELLIGENCE, by Pamela McCorduck. W. H. Freeman and Company ($14.95). The search for the philosopher's stone has dwindled from high metaphysics maybe down to neutron flux, but the hunt for the philosopher's chips is in full cry. In this delicious book—witty, informed, open, rich in direct and candid testimony—a novelist reports her visits among the ambitious projectors and her estimates of what they do, say and plan. She offers a good deal of wise reflection but never one flow chart or formula. The illustrations are all photographs of people, natural intelligences every one, in itself enough to render the book unique in its semiarid domain. One is a little rueful to note that in the photographs nearly all the major figures in the field of AI (artificial intelligence) appear rather younger and more carefree than they look today. Long gone is the Ratio Club, an English AI group of the early 1950's whose rule was that "any member who reached the rank of full professor... automatically ceased to be a member." We can only hope that today a few Hypergeometric clubs exist unsuspected by their bosses, undisclosed even to such an ingratiating visitor.

These photographs include some "ancients" (the late Norbert Wiener, Warren McCulloch and John von Neumann and the living hero Claude Shannon) but not Walter Pitts or Alan Turing. The historical treatment is particularly apt, however, in its account of the life and work of Turing, perhaps the most important of all the pioneers. (The prehistory is reviewed in fine form, even to the mythic aspects that still mold the metaphors of the field, from Pygmalion and the Golem to Countess Lovelace and her friend Charles Babbage, Ultra at Bletchley Park, Isaac Asimov's Three Rules of Robotics and more.) Then we meet the "moderns," from Oliver Selfridge, an assistant to Wiener himself, through John McCarthy, Herbert Simon, Marvin Minsky, Seymour Papert, Allen Newell and more to a few of the "risen," such as Terry Winograd. Most of the visits the author made were to the four chief sites of the AI establishment in the U.S., at Stanford (doubled), the Massachusetts Institute of Technology and Carnegie-Mellon, with sources enough beyond them to provide outside perspective (freely offered too).

Like any thoughtful historian, McCorduck has divided her chronicle into periods. In Part I she treats of the beginnings, described above. Part II is headed "The Turning Point." She dates that to the first substantial U.S. conference on AI, at Dartmouth in 1956; there, she says, the social structure of the field was set. Newell and Simon arrived with a working computer program that could prove any of the theorems in Whitehead and Russell. The dozen-person summer session was less than impressed by this genuine accomplishment, which nonetheless fixed the style for the next decade: a concentration on the notion of computers as information processors that flowered into puzzle solvers, theorem provers, chess players and the like—attributes not of intelligence so much as of the young, bright, competitive, uncertainly cocky types who led AI.

The second phase can be understood from a wonderful remark made by Joel Moses at M.I.T. "The word you look for and you hardly ever see in the early AI literature is the word knowledge. They didn't believe you have to know anything, you could always rework it all. And it's a tremendously arrogant person who could believe that you could rework it all on the fly—start with this simple machine and just feed in a few things and all of a sudden you get Einstein's theory of relativity." It was perhaps the manipulative robots they sought to build that dispelled this illusion. Those machines existed in little tabletop worlds—real ones, not the world of puzzles and chess, where everything is set down in deductive rules. Edinburgh, M.I.T. and the Stanford Research Institute all built contrivances that could see and awkwardly modify their worlds, rather like a slow toddler. The three-dimensional world is a richer place than the linear *Principia Mathematica.*

Time: the present. How is a deal of knowledge to be represented, organized and used? It is too copious to search atomically. One needs it in chunks, mapped in some expressive language, not bit by bit but more powerfully. Applied AI arose out of this tendency. One gave up the view that some quite abstract kind of smartness could outguess anything in the world and instead saw that a lot of specialized knowledge helps in solving significant, if particular, problems. We now have DENDRAL, a first-rate organic chemist's assistant, a real help in finding plausible molecular frameworks to suit the dizzying skyline of peaks that comes from the mass spectrograph. There is a fine algebraic program too, a true calculator's assistant, and there is at least the promise of diagnostic aids for physicians. One serious program seeks to teach small children real mathematics: not just arithmetic but something deep the youngsters can learn and master, each in his own way.

A splendid couple of chapters deal with criticism of AI, an activity that has itself budded into a small intellectual discipline. The most interesting portion of that discussion is a chapter on a moral question: *Should* a machine think? The chapter centers on the thoughtful book of Joseph Weizenbaum of M.I.T., and it is as lively as it is judicious in discussing the reviews and the controversy. The debate has the flavor of apostasy, since Weizenbaum was the originator of the most exciting of early simulations of familiar human relations, the conversational but hollow program ELIZA, which was held by some to promise a cheap machine-made psychiatric session.

Outraged, Weizenbaum elaborated a serious moral position. Our author is less than convinced. Of course what should not be done by anyone should not be done by an AI machine, but more specific arguments against the intrinsic morality of AI do not yet persuade. When AI machines come into being, they might well deserve our respect: "We need all the practice in humility, in loving and respecting others, that we can get." That future is tentative nowadays, but it is not plainly impossible and not clearly immoral. AI will be Copernican, all right; it will move the center of mind, but we live too early to see little moons and ellipses.

It begins to look as though AI is learning that its model, natural intelligence (NI?), is something itself deep, social, in inner conflict, less than single-minded. Oh, dreamers are still around, such as the expert who sees the power of modern dense hardware and declares: "The guy who first develops a machine that can influence the world in a big way may be some mad scientist living in the mountains of Ecuador.... Once artificial intelligences start getting smart, they're going to be very smart very fast." His notion appears to be that of a machine capable of acting like "ten thousand coordinated people in a building." Some readers might recall that there are real organizations not unlike the one in Santa Monica or in Langley, Va.; quite apart from easy complaints, what have those coordinated groups of thinkers done for us lately?

Surely the lesson is that AI too will have its contradictions, its philosophical uncertainties, even its schools of thought. (Let those who will write the smart programs, with their platoons of chunky, well-stocked, cool goal seekers; let me write their songs. They will have songs, you know, or remain less than we are.) The day is far off when we will live in a silicon Eden watched over by machines of loving grace. More likely the AI machines to come will be a lot more like their putative makers: contentious, half arrogant, half patient, amusing, poetic, marvelously versatile and showing a strong tendency to abandon hard work for greener pastures.

This fine study exhibits the microsociology of a latent science, one that is more promise than product. It displays in open-eyed intimacy a coterie of hopeful artificers, forging new gods very haltingly in their own image.

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The Safety of Fission Reactors

By most standards they are quite safe. Three Mile Island nonetheless confirmed that decisions about their future call for greater reliance on quantitative methods of assessing risks presented by such systems

by Harold W. Lewis

At the dawn of the nuclear age, in the late 1940's and early 1950's, it was fashionable to believe that science, having "split the atom," had ushered in a new era of abundant, inexpensive energy. Such comments as the one that electricity would soon be so cheap that it would not be worth metering were perhaps excessive reflections of that euphoria, but Americans had, after all, been conditioned by a generation of science fiction to expect the arrival of atomic power in some form. Even in retrospect it is not easy to see how one could have foreseen that the next two decades would bring with them a widespread revolt against technology and, as a related event, a great debate about the desirability of nuclear power. This article is about one aspect of that debate.

Polls and ballot contests continue to show that a majority of the American people favor the further development of nuclear power, particularly when they are fairly presented with the alternatives. Nevertheless, a substantial, concerned and active minority have continued to raise three major issues: the potential role of fission-power reactors in the proliferation of nuclear weapons, the long-term disposal of radioactive wastes and the safety of the present generation of "light water" reactors. The further spread of nuclear weapons to untrustworthy parties is essentially a political problem with some technical components. Radioactive-waste disposal is a problem whose technical solution could take many forms, none of which has yet materialized, in part because of the agony of choice and in part for social and political reasons. Reactor safety, in contrast, would appear to be entirely a technical problem. Alas, it is not.

In the first place, it is a rare debate about reactor safety that does not involve some manifestation of the uneasiness that frequently accompanies the introduction of a new and unfamiliar form of technology. This social phenomenon seems, for example, to be a contributing factor in the transformation of many old antiwar groups into anti-nuclear-power groups, and it may even account for the apparent preference of some environmentalists for coal burning over atom splitting. These public positions have little to do with the narrow technical questions involved in the relative safety of generating electricity by heat from fission reactions.

In the second place, the study of reactor safety itself must make a considerable allowance for human behavior. The decisions and actions of reactor operators are important not only to the initiation and the management of accidents but also to such matters as quality control, equipment maintenance, security measures and the willingness of public utilities to spend money on safety precautions. In fact, the report of the President's Commission on the Three Mile Island accident, headed by John G. Kemeny of Dartmouth College, had little to say about improving the design or construction of light-water reactors. Instead it contained a blistering denunciation of everyone connected with the assurance of reactor safety, from the equipment manufacturers through the utility managers to the members and staff of the Nuclear Regulatory Commission (NRC). The Kemeny report asserted that a change in "mind-set," or mental attitude, was essential if nuclear safety were to be assured. Hence it emphasized such matters as the training of operators, the enforcement of safety regulations, the quality of leadership at the NRC, the adequacy of emergency-response plans for reactor accidents, the organization of control rooms and similar concerns. The report was notable for its lack of specific technical recommendations for the enhancement of reactor safety. In part this omission can be attributed to the fact that those technical changes that were clearly necessary after the accident were already being implemented by the NRC and the industry. It nonetheless remains true that the emphasis of the Kemeny report reflects the fact that there is a very real nontechnical component to the assurance of reactor safety.

How safe is safe enough? For the most part people do not seek a risk-free society, but they do find it hard to manage risks that are not fully understood and for which it is not easy to establish conceptual bounds. To properly match risks against benefits when they are measured in different units and when passions run high has proved to be almost impossible, and our society is not at its best in dealing with problems that have both a technical content and a social one. Indeed, our institutional forms are not designed for such matters. Accordingly far more attention has been paid to the assessment of safety, as distinguished from its assurance, than would be the case if the only objective were the enhancement of the benefit-to-risk ratio. The result is that there is at present no quantitative objective for reactor safety; instead there seems to be a tacit acceptance of the principle that anything that can be done to make reactors safer is good. This is obviously not a general principle of life, since if it were, no one would ever get out of bed in the morning, but it does serve as a handy way to fill a void in understanding.

On the record, reactors can be considered to be perfectly safe, since no member of the public has ever been injured by a commercial-reactor accident, including the one at Three Mile Island.

The expression "perfectly safe" is of course facetious, but the fact remains that a reactor accident with public consequences is demonstrably an extremely improbable event, for which there is no actuarial record. When any event, such as a putative reactor accident, has a very low probability but potentially severe consequences, it means that safety analysis must be based on theoretical calculations rather than on experience, and this leads to special problems. Before discussing these problems I should first briefly review what reactors are.

Nearly all the fission reactors in the U.S. are of a type that employs ordinary water to moderate, or slow down, the fast neutrons emitted in fission reactions in the reactor's core. (They are called light-water reactors to distinguish them from the type that uses heavy water, or deuterium oxide, as the moderator.) Light-water reactors in turn are classified as either pressurized-water reactors or boiling-water ones, and most operating light-water reactors are of the pressurized-water type. They are marketed by four venders: the Babcock & Wilcox Company, Combustion Engineering, Inc., the Westinghouse Electric Corporation and the General Electric Company, with only General Electric supplying the boiling-water type. The following discussion concentrates on pressurized-water reactors because they are the commoner type.

Economies of scale have been making these reactors increasingly large in recent years, and current designs provide more than 1,000 megawatts of electric power per reactor, derived from more than 3,000 megawatts of heat generated by fission reactions in the reactor core. In round numbers the core contains 100 tons of enriched uranium oxide, arrayed in tens of thousands of fuel rods. The uranium itself is enriched from a natural concentration of .7 percent of the fissionable isotope uranium 235 to approximately 3 percent. The core is enclosed in a steel pressure vessel, typically a few meters in diameter and 10 meters high, with walls several tens of centimeters thick. The core is cooled by two or more independent water loops, whose heated water (under a pressure of some 2,000 pounds per square inch) transfers its heat in a steam generator to a secondary loop, which in turn provides steam to a conventional steam turbine. (A boiling-water reactor lacks the intermediate loop; instead it relies on the heat of the reactor to directly boil water for the turbine.) The entire system costs about $1 billion.

An essential point, both for control and for safety, is that a nucleus undergoing fission (at the beginning of core life such nuclei are entirely those of uranium 235, but at the end there is a substantial contribution from the plutonium nuclei produced by nuclear reactions in the interim) does not produce all the secondary neutrons required for the chain reaction at once. Nearly 1 percent of the neutrons are delayed for intervals ranging from a fraction of a second to more than a minute; as a result it is possible for control systems with response times measured in seconds to adequately control the reactivity of a reactor in normal operation.

The normal operating mode of a reactor is one in which prompt neutrons alone cannot sustain a chain reaction, but prompt neutrons together with delayed neutrons can. Only the delayed neutrons are controllable; a situation in which a reactor became "prompt critical" would be a disaster. (Even so, it is physically impossible for a power reactor to explode like an atomic bomb, a fact that seems singularly hard to propagate.) It is the function of the control rods to control the reactivity in normal operation, to adjust for the gradual burnup of the fuel and to shut the reactor down in an emergency (by stopping the chain reaction). The latter operation is known as SCRAM, and failure to "scram" in an emergency could lead to extremely serious consequences. Such a failure has never happened.

The hazard associated with a nuclear reactor lies in its inventory of radioactive waste, coupled with the possibility that some of it might escape from the reactor's containment system. The reactor begins operation with a comparatively low level of radioactivity, but it gradually accumulates radioactive fission products in the fuel rods. If the reactor has been at full-power operation for a year or so, this inventory is on the order of 10 billion curies, an amount that can be put in perspective by remembering that as the curie was originally defined it was intended to represent the radioactivity of one gram of radium. Thus the maximum inventory is, roughly speaking, equivalent to 10,000 tons of radium, and the essence of reactor safety is to prevent the dispersal of this radioactivity into the biosphere.

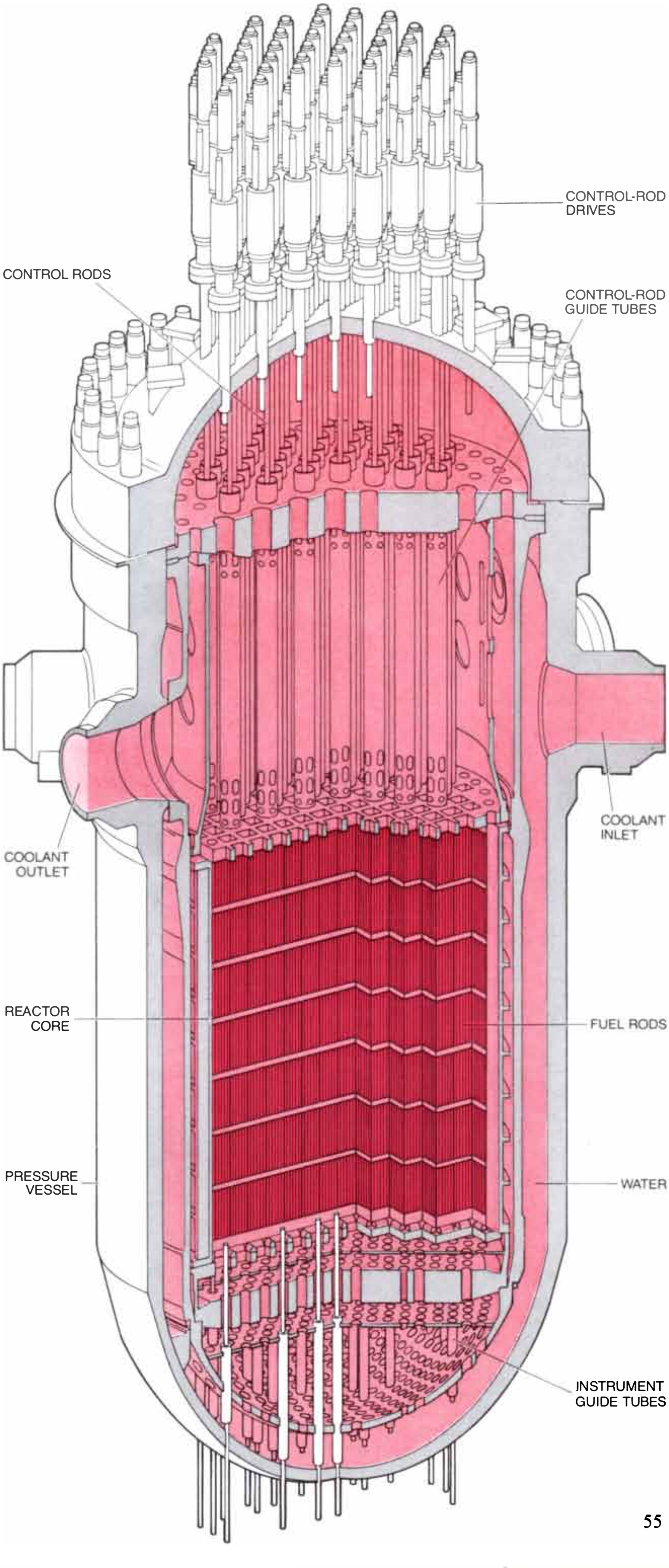
A reactor is a very complex device, and in the early days of nuclear power it was thought that it was beyond the state of the art to calculate the probability of a reactor accident. For this reason some early efforts concentrated on calculating the maximum public consequences of a hypothetical major reactor accident; it was quickly found that these effects could be very large indeed, mainly because there was no basis for choosing how improbable the hypothetical accident might be. (The importance of this point has become more widely recognized in the aftermath of the Three Mile Island accident.) In any case it was not until six years ago that a serious effort was mounted to calculate both the probability and the consequences of a major reactor accident.

Let us next consider what is known about the adverse health effects of radiation on people. Although there is some uncertainty on this point, there is far less than is often alleged, and the picture is approximately as follows. Large doses of radiation, on the order of 500 or 600 rems (a rem is a unit of radiation exposure, standing for roentgen equivalent man), are fatal to approximately half of the people exposed, but only a few people would be exposed to such large doses even in the severest reactor accident. One is mainly concerned with much smaller doses, received by much larger numbers of people; here the picture is somewhat less clear, and the consequences (latent cancers and genetic defects) are quite different. Nevertheless, there is a reasonable consensus among experts that latent cancers, appearing over a period of up to 30 or 40 years after the exposure, are the principal problem, and that the rate is approximately one latent fatal cancer per 10,000 man-rems of exposure.

According to this mode of analysis, known as the linearity hypothesis, such exposures add linearly, independently of the number of people exposed, the length of the exposure, the dosage or any other factor. It is by no means clear that the linearity hypothesis is correct, but it makes calculations easier and therefore is widely used as a basis for public policy. It is generally agreed by the experts (with little dissent) that the linearity hypothesis represents an upper limit on the damage due to low doses of radiation, and there is a substantial and respected minority, perhaps even a majority, who think that it is a gross overestimate. The issue is unresolved, and it would seem to be a prudent and conservative course to adhere to the linearity hypothesis.

This is the position that has been taken up to now, for example, by the Advisory Committee on the Biological Effects of Ionizing Radiations (the BEIR committee) of the National Academy of Sciences, largely because the effects of radiation become smaller as the dosage decreases, so that the data become sparser. In the middle of last year the BEIR committee issued a draft report that had a bare majority of the group supporting the linearity hypothesis and a vigorous minority who thought the data were now good enough to justify saying that the linearity hypothesis overestimates the risk of radiation damage by a considerable margin. The minority then became a majority, making necessary a retraction of the part of the report dealing with the linearity hypothesis; the question of whether it will be reissued with the same position or the opposite one (or some compromise) is at this point unclear. Either way it is fair to say that the segment of the expert community that believes the linearity hypothesis overestimates the effects of radiation is much stronger now than it was in previous years. If this view were to prevail, it would have a major impact on the calculated health effects of a large nuclear accident, since the calculated exposures from such an event are in just this low-dosage range.

Low-level dosages of radiation can be put in perspective by reference to everyday experience. All of us live in a sea of radiation from many sources, from which there is no escape. Cosmic rays, which impinge on the atmosphere from space, give each person on the earth an average dosage of approximately 50 millirems per year (a millirem is a thousandth of a rem), although people who live at high altitudes receive a substantially higher dosage from cosmic rays. Medical and dental X rays also provide an average exposure to Americans of approximately 50 millirems per year, although again there are wide variations in individual exposure. Natural background radiation from such sources as bricks and granite, and from one's own blood and bones, provides an-

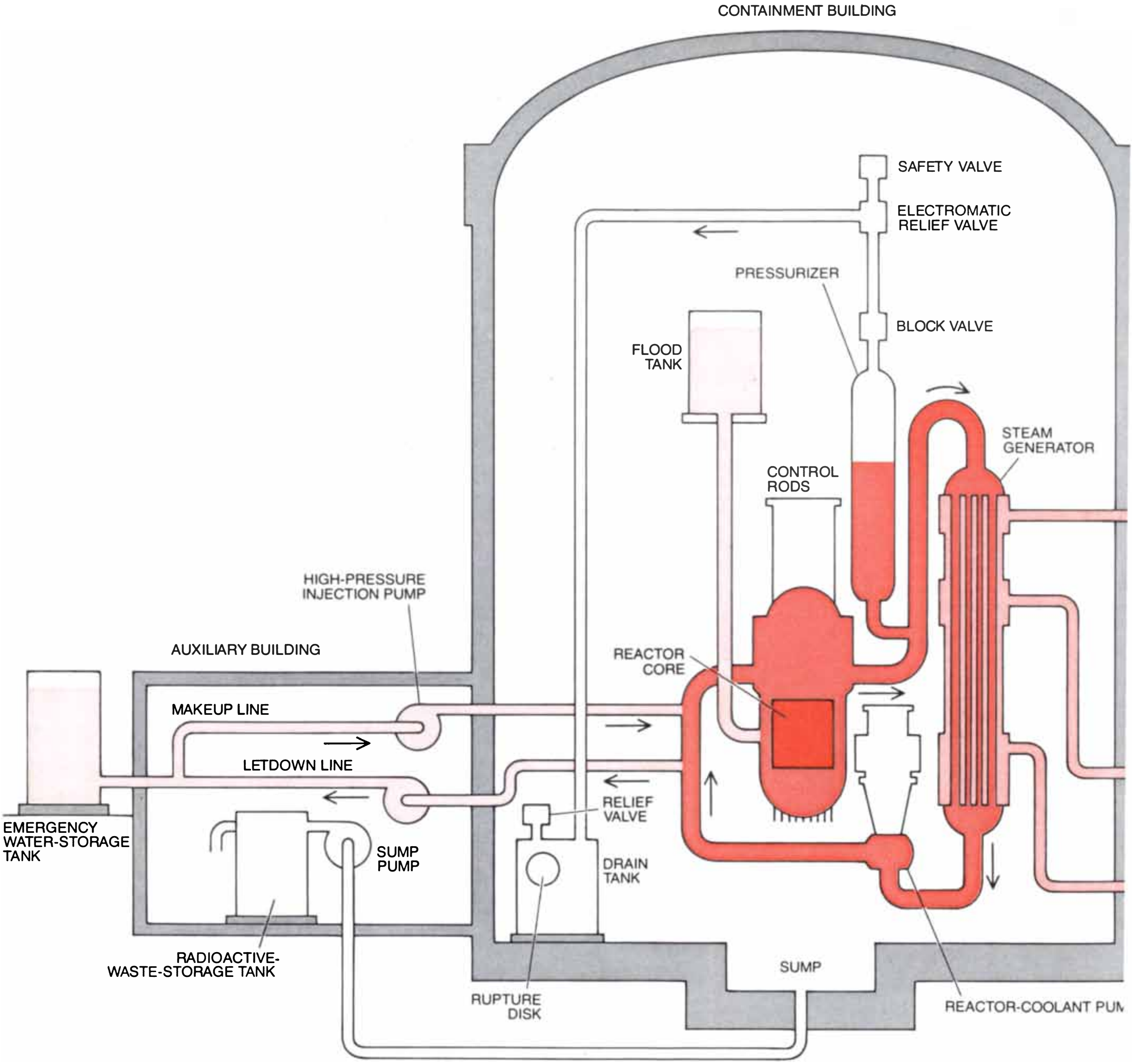


PRESSURIZED-WATER REACTOR of the same type as the ones installed at the Three Mile Island Nuclear Generating Station is depicted in this cutaway drawing. The core of such a reactor typically contains about 100 tons of low-enriched uranium oxide, arrayed in tens of thousands of fuel rods. The fuel assemblies are enclosed in a heavy steel pressure vessel, measuring roughly four meters across by 10 meters high. The particular reactor shown here is designed to be cooled by two independent water loops; in each loop superheated water at high pressure is circulated through a steam generator, transferring heat to a secondary loop, which in turn provides steam to drive a conventional turbine-generator set. (The ordinary water used to moderate, or slow down, the fast neutrons emitted by the core is commonly referred to as light water to distinguish it from the heavy water, or deuterium oxide, that serves as the moderator in another major type of reactor.) The function of the control rods is to modulate the reactivity of the core in normal operation, to adjust for the gradual burnup of the fuel and to shut down the reactor in an emergency. In the accident at Three Mile Island last March the control-rod drive mechanism worked properly, stopping the chain reaction in the core eight seconds after the beginning of the accident. Because of a sequence of human errors compounded by a key equipment failure, however, the supply of cooling water to the core was subsequently cut off, leaving the fuel assemblies uncovered for several hours. During this period the residual heat generated by the radioactive decay of fission products in the fuel caused substantial damage to the core. In addition hydrogen gas formed as a result of the oxidation of zirconium in the cladding of the fuel rods by steam from the boiling water collected in the top of the reactor vessel, leading to fears that the "hydrogen bubble" thus created might explode. It is now known, however, that there never was a chance of such an explosion inside the reactor vessel, owing to the negligible amount of free oxygen there.

other 50 millirems or so per year. The average American therefore receives approximately 150 millirems per year, or 10 rems in his lifetime, a dosage that would, according to the linearity hypothesis, contribute approximately .1 percent to his chance of dying of cancer in his lifetime. Mortality statistics show that the probability of dying of cancer at this time in the U.S. is somewhere between 15 and 20 percent.

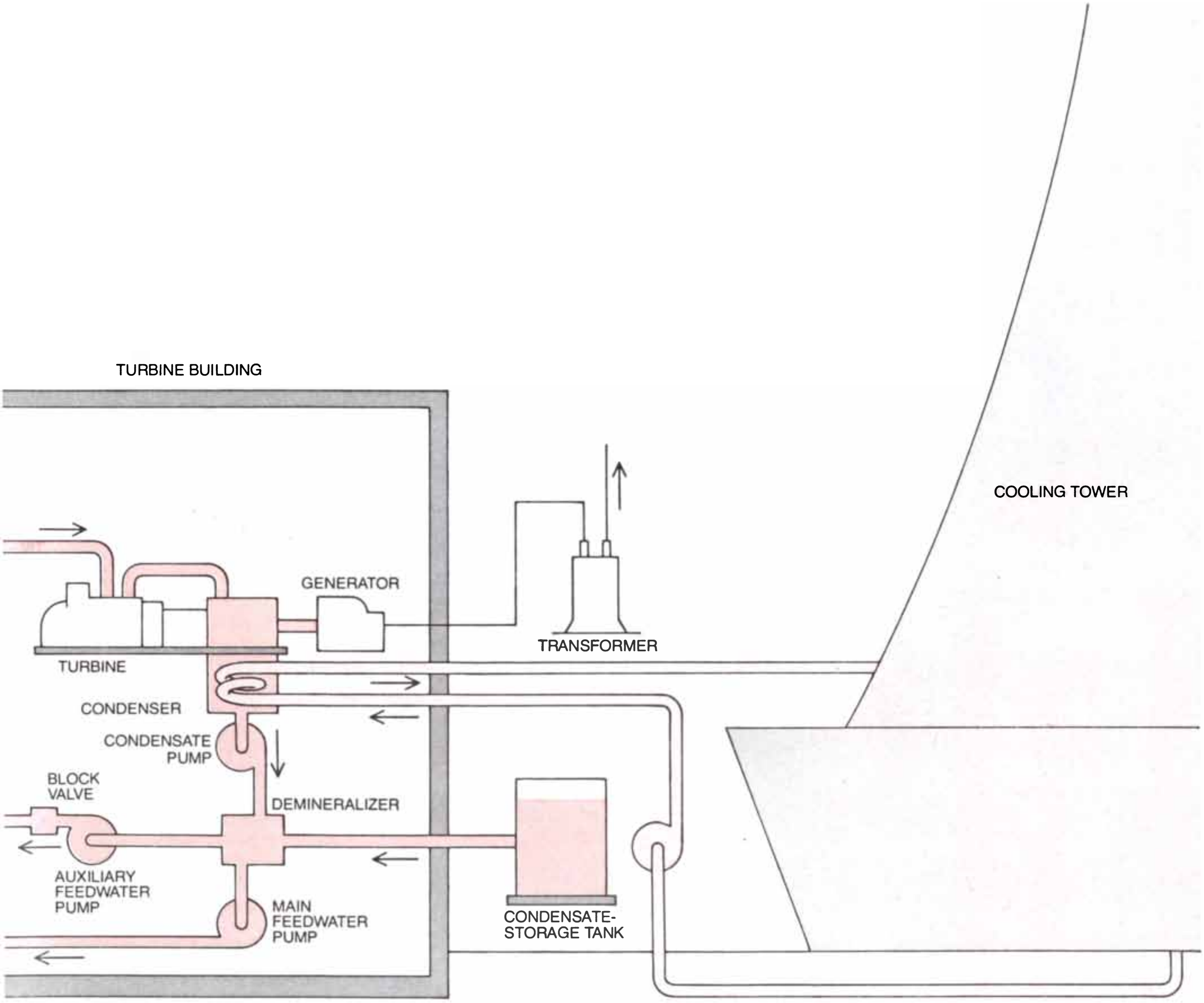
The principal health consequence of a reactor accident would arise from this induction of latent cancers through the release of radioactivity, and the objective of reactor-safety analysis is to determine what the probabilities of different releases are.

What, then, can go wrong with a reactor to release radioactivity, and what can be done about it? Because a reactor



SIMPLIFIED DIAGRAM of the nuclear-power plant known as Three Mile Island, Unit 2, can be used to trace the sequence of events involved in the accident. It all began when the main feedwater pumps in the lower level of the turbine building tripped, interrupting the removal of heat from the primary system. As a result the temperature and hence the pressure in the primary system began to rise, causing the pressure-relief valve at the top of the pressurizer tank in the primary loop to open; the increase in pressure also actuated the reactor's SCRAM mechanism, which promptly performed its designed function of inserting the control rods into the core, shutting down the reactor. At this point, however, two things were wrong that were not known to the operators: (1) a pair of block valves in the discharge lines of the emergency feedwater pumps, which were supposed to be open at all times during the normal operation of the plant, had inadvertently been left closed sometime before the accident, causing a loss of feedwater to the steam generators, which soon boiled dry; (2) more important, the primary pressure-relief valve failed to close after about 15 seconds, when the pressure had decreased sufficiently for it to do so, creating a hidden leak in the primary system. The closed block valves in the emergency feedwater lines were discovered and opened some eight minutes after the onset of the accident, probably soon enough to prevent damage to the plant, but the leaky relief valve was not discovered and blocked off until nearly two and a half hours into the accident. The operators, misled into believing there was too

is complicated, there are many sources of malfunction that can cause it to misbehave. In order for the public to be endangered, however, it is necessary for some of the inventory of radioactivity to escape from the containment building, and that is likely only if the core is damaged. For most accident scenarios this event in turn depends on the "afterheat" that continues to be generated by the decay of radioactive fission products in the fuel rods, which amounts to some 200 megawatts immediately after shutdown and decreases gradually over a period of seconds, minutes, days, weeks and ultimately months. The function of much of the safety equipment is to keep the reactor core cool in the aftermath of a malfunction. In principle this is accomplished through redundancy of vital functions, specifically engineered safety

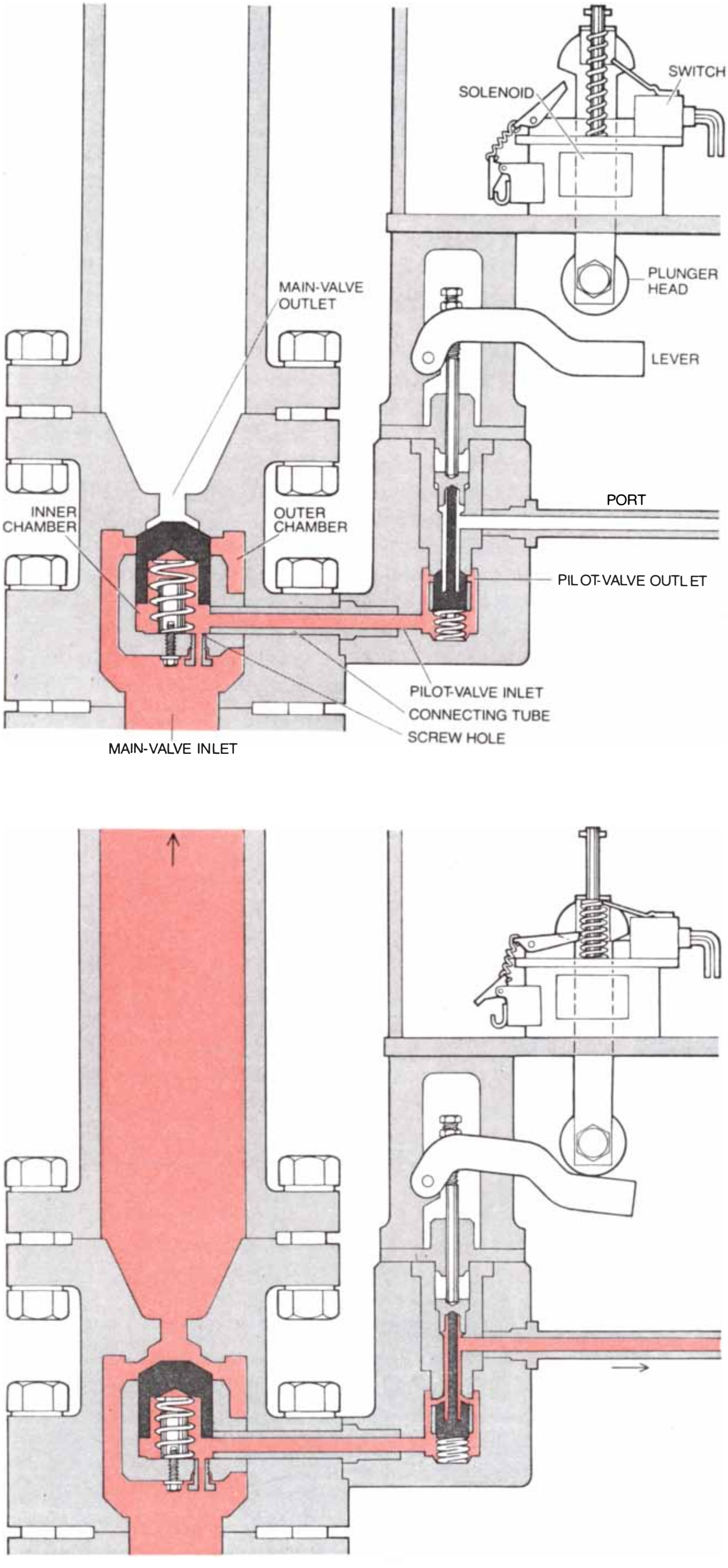


much water in the primary system whereas in fact there was too little, then took several actions that made the problem worse rather than better. They let the emergency core-cooling system, which had functioned properly, turning itself on automatically two minutes into the accident, run for only a couple of minutes before they turned it off; later they also stopped the four main coolant-circulating pumps in the primary loop, thereby further diminishing the ability of the system to remove heat from the core. It was as a direct result of these actions that the core sustained an unknown amount of damage during the period beginning about an hour and a half after the accident began. The loss of coolant through the defective relief valve also caused a large amount of water, some of it radioactive, to spill through a rupture disk in the drain tank, filling the sump of the containment building, from which it was pumped to a series of radioactive-waste storage tanks in the auxiliary building; these tanks in turn overflowed, leading to the escape of a small amount of radioactivity to the environment. At about nine and a half hours into the accident a pocket of hydrogen in the upper part of the containment building ignited, but the building appears to have suffered little if any damage from this "burn." The accident was essentially over some 16 hours after it began. The removal of the radioactive atmosphere from inside the containment building, the decontamination of the spilled radioactive materials and the disassembly of the damaged parts of the reactor itself are expected to keep the plant out of service for at least two more years.

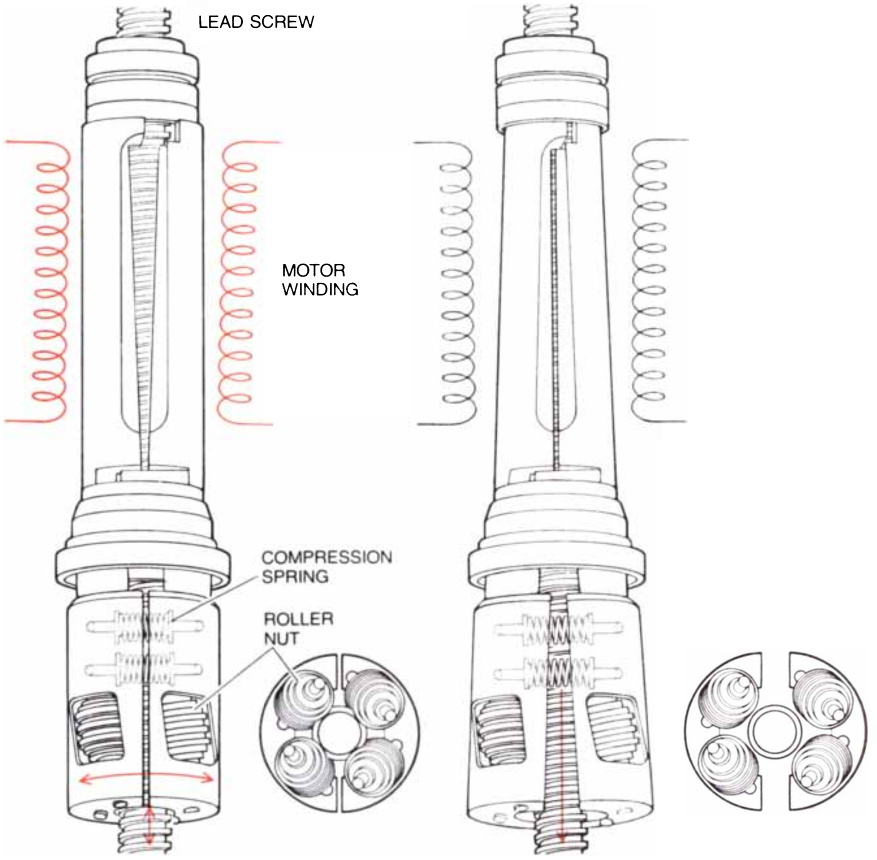
features, quality control and other precautions.

Until the Three Mile Island accident the most widely discussed type of reactor malfunction was the loss-of-coolant accident. A typical hypothetical major loss-of-coolant accident might go as follows. A large pipe in the primary cooling system ruptures, either by chance or as a result of another event, causing a sudden depressurization of the water in the pressure vessel, which is at 350 degrees Celsius and therefore boils. Boiling water does not provide adequate cooling to the core, which even after a successful SCRAM begins to heat up as a result of the radioactive afterheat. At this point the emergency core-cooling system comes on, flooding and spraying the core with new cooling water in sufficient volume to prevent the core from melting. In this scenario the procedure continues indefinitely until plumbing repairs are made and the reactor is put back in operation.

What if the emergency core-cooling system does not operate properly? The valves might not work; the injected water might simply boil out of the broken pipe without cooling the core; the calculations used to design the system might be in error (no full-scale test has ever been made); there might be a break in the pressure vessel below the level of the core; the operators might do something foolish that would prevent the safety



VALVE THAT FAILED to reseat, or close again, at an early stage in the Three Mile Island accident is shown in this detailed diagram in two positions: closed (*top*) and open (*bottom*). The valve, called an Electromatic valve by its manufacturer, the Industrial Valve and Instrument Division of Dresser Industries, Inc., is designed to operate as follows. Steam from the pressurizer enters the main valve from below and passes into an outer chamber. The steam also enters an adjacent inner chamber behind the valve disk through a hole in a screw; the pressure in the two chambers is the same when the disk of the pilot valve closes off the tube connecting the main valve to a port in the pilot valve. The pilot-valve disk is normally held closed by a spring and by the pressure of the steam in the pilot-valve chamber. The pilot valve is opened by a lever when the plunger of the solenoid mounted above it strikes the lever. Steam is then released from the inner chamber in the main valve through the connecting tube and out the port in the pilot valve at a rate faster than it is supplied through the screw hole. The resulting imbalance of pressures in the chambers of the main valve produces a force that moves the main-valve disk downward, allowing steam to escape from the outer chamber through the outlet to the discharge pipe. The solenoid plunger is actuated by a control system that can be operated in either a manual or an automatic mode. At Three Mile Island the position of the main valve was not sensed directly; instead an indicator lamp on the main control panel signaled that the solenoid had been actuated, and the position of the solenoid was considered to be indicative of the position of the valve.



"SCRAM" MECHANISM incorporated into the control-rod drive system of a pressurized-water reactor is shown here both before (*left*) and after (*right*) an emergency actuation. Ordinarily the control rods are moved in bundles into and out of the core by means of a drive line connected to a magnetically driven, collapsible rotor through a set of four roller nuts. The rotation of this assembly, which is held in place magnetically, moves the lead screw of the control-rod drive line up and down during normal operation. In an emergency the magnetic field is turned off, the rotor collapses (with an initial spring assist), the roller nuts disengage from the drive line, and the control rods fall by gravity into their fully inserted position in the core, thereby achieving rapid shutdown of reactor. No reactor has ever failed to "scram" in an emergency.

systems from doing their job, and so on. In any of these cases the core could melt, but even then there might not be a disaster. One hears of the "China syndrome," which is a way of saying that the core might simply melt its way down into the earth and never be heard from again. In that event the site would present a problem, but little if any harm would come to the public. On the other hand, the molten core might interact with the water in the system to cause a steam explosion or to simply breach the outer containment building through the development of excessive steam pressure. In that event part of the inventory of radioactivity could be released, the accident everyone wants to prevent.

I have gone through the preceding scenario simply to illustrate the fact that a reactor accident requires a long sequence of events, each having a "what if" associated with it. It is absolutely correct to say that any of these things could happen, just as it is correct to list thousands of other possible scenarios that could be realized, but listing all the things that could happen is only a small step toward the understanding of reactor safety. One does not play the same game with airplanes because they are more familiar, but a simple exercise along these lines, without quantification, would greatly enhance one's fear of flying. It is therefore extremely important not only to list the possible accident sequences but also to associate with each sequence some kind of probability of occurrence and also some estimate of the amount of radioactivity released. Only then can one make rational choices about the places for concern, programs to enhance reactor safety and so forth.

Some six years ago the Atomic Energy Commission asked Norman C. Rasmussen, professor of nuclear engineering at the Massachusetts Institute of Technology, to put together a team to make just such a quantitative analysis of the safety of light-water reactors. The 60-member team was to look in great detail (generalizations are of little use in the serious discussion of the safety of such systems) at one typical pressurized-water reactor and one typical boiling-water reactor, to determine the most significant sequences of events that could lead to an accident and to estimate both the probability of each sequence and the consequences. The consequences were to include prompt fatalities, the induction of latent cancers, genetic defects and property damage. It was a monumental task. The final report, issued in 1975, is referred to variously as WASH-1400, NUREG-75/014, the Reactor Safety Study or simply the Rasmussen report. It is one foot thick.

The Rasmussen group estimated the overall probability of a sequence of events leading to a core melt as one chance in 20,000 reactor-years of operation; they found that the average core melt would itself not present a major threat to the public health and safety, and they concluded (in a widely quoted and equally widely criticized statement) that the likelihood of an average citizen's being killed in a reactor accident is about the same as the chance of his being killed by a falling meteorite.

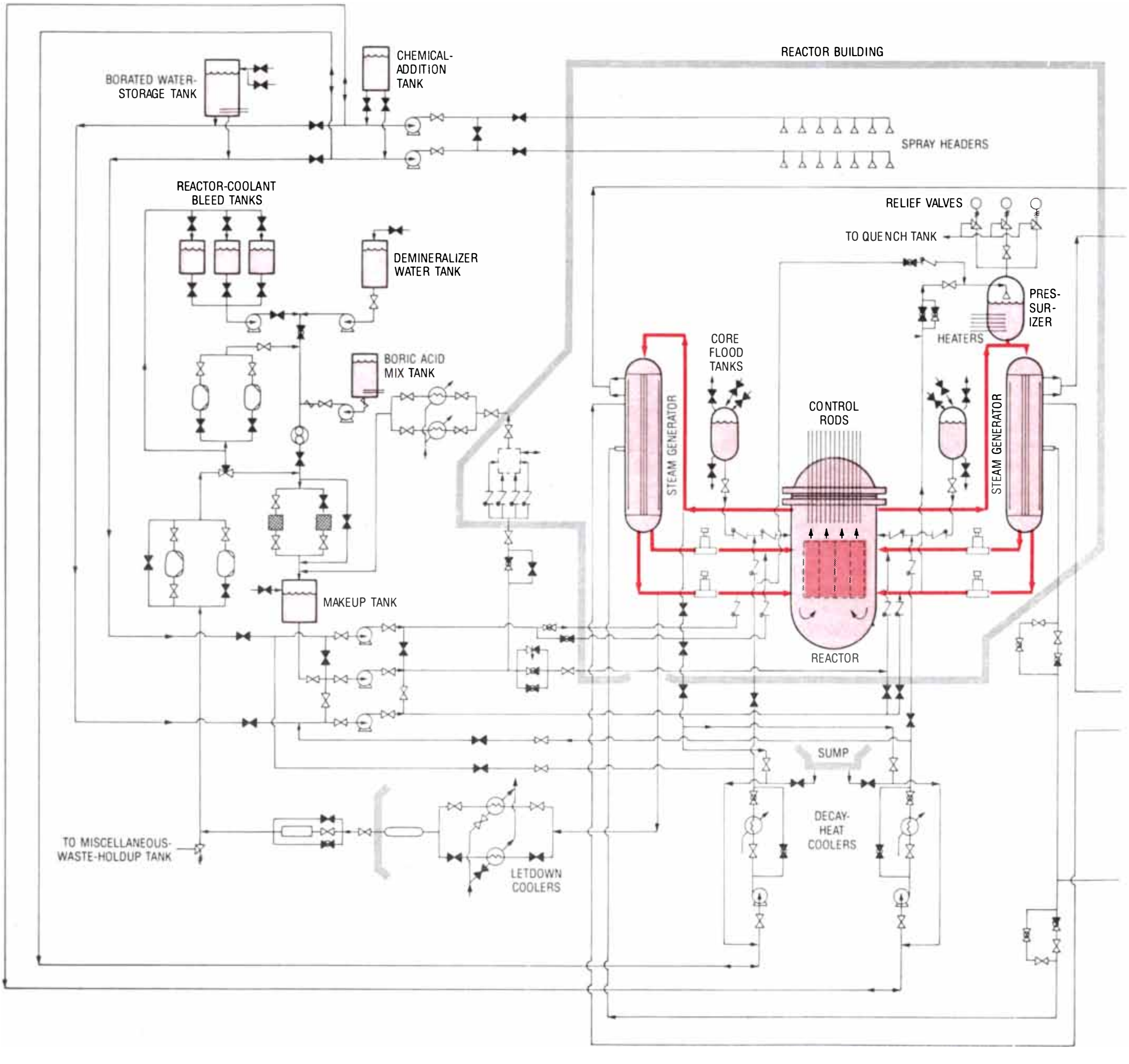
Given the temper of the times it was not surprising that the Rasmussen report came under a storm of criticism, some cogent and proper, some strident and irrational. Among the objections raised were the following: (1) The system is simply much too complex to quantify, (2) the data base on component-failure rates does not support such a calculation, (3) improper and incorrect statistical procedures were followed, (4) common-cause failures (in which several ostensibly independent components fail at once owing to a separate common cause such as an earthquake) were inadequately treated, (5) low-probability events are intrinsically impossible to quantify, (6) human behavior was inadequately treated, (7) the role of quality assurance and failures thereof were inadequately treated, (8) and so forth.

All these issues are indeed difficult, particularly the last, and there is no way to do justice to them in a short article. Many of the criticisms are also justified, and the NRC subsequently solicited a report of another committee, the Risk Assessment Review Group, that labored for a year on all these questions and ended up by describing in its own report a number of serious deficiencies in the Rasmussen one. Nevertheless, the review committee (of which I was the chairman) strongly supported the objective of quantitative safety analysis, commended the Rasmussen group for a pioneering effort and urged the NRC to make much more extensive use of quantitative analysis in the regulatory process. I shall discuss these issues below, but first I should like to illustrate the character of the technical questions by mentioning a few selected problems in connection with the analytic approach taken in the Reactor Safety Study.

On the issue of statistical procedures

the most famous (but not necessarily the most important) case concerns the control rods in a boiling-water reactor. An average reactor of this type suffers some kind of mishap requiring operation of the SCRAM system between five and 10 times a year. Electrical outages, turbine trips, control failures and similar malfunctions are examples of events in which it is necessary to terminate the nuclear chain reaction promptly in order to prevent damage to the reactor (or worse). To assess the safety of the reactor it is therefore necessary to know what the probability is that the SCRAM mechanism will fail.

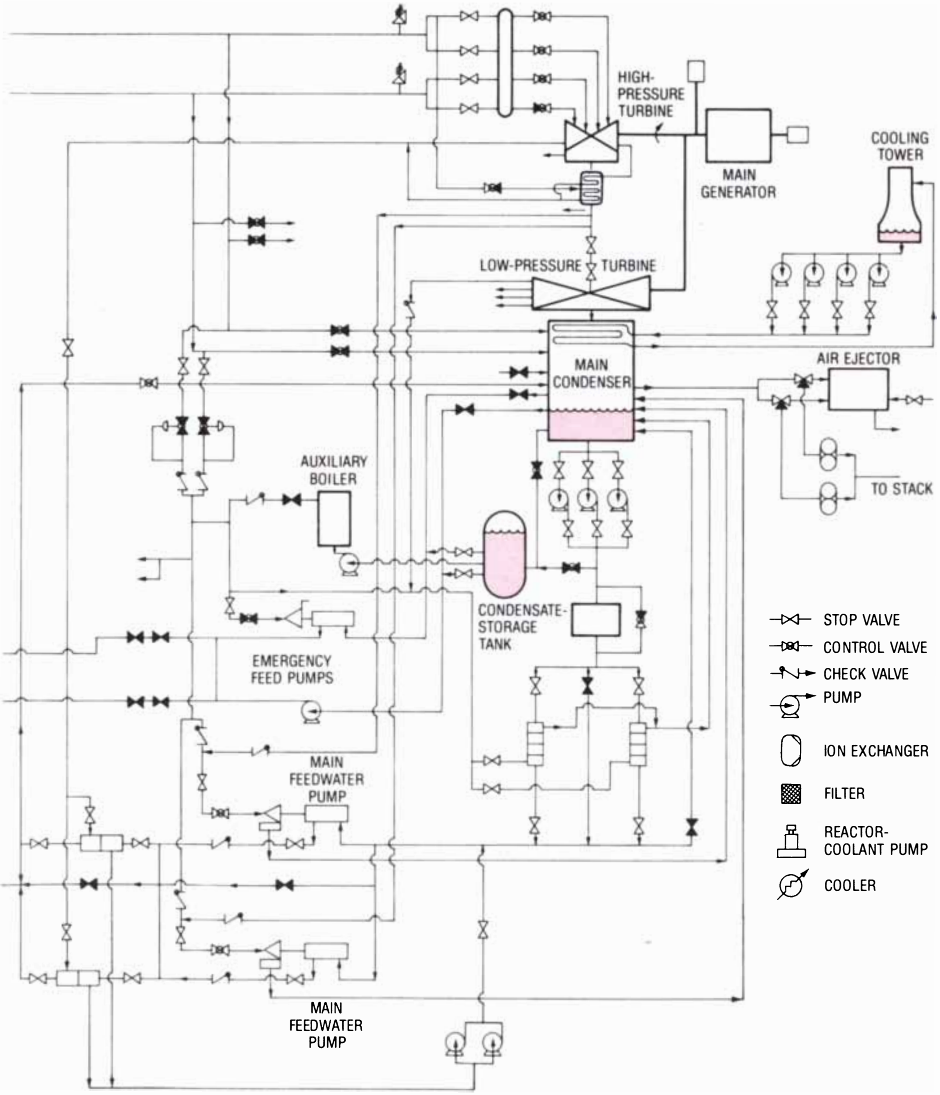
The problem encountered in estimating this probability is that the SCRAM systems are so important and so well designed that the event in question (SCRAM failure on demand) has never happened, and therefore there is no basis in experience from which to assess the reliability of the system. On the other hand, there are cases where individual rods have failed to insert fully (approximately once every 10,000 requests), and so one can begin to assess the likelihood that a single rod might not do its full job. One rod failure, however, does not make a SCRAM failure, and the first problem is to decide exactly how much failure within a system constitutes a failure to "scram." The Rasmussen report simply asserted that the failure of three adjacent rods could be considered a failure to "scram" and that the probability of this event's occurring through independent failures of any particular triplet is therefore the product of 10^{-4} multiplied by itself three times, or 10^{-12} (that is, one chance in a trillion). This is a ridiculously small number, reflecting the fact that the fortuitous failure of three adjacent control rods is really not a major threat to a reactor, and so one must look elsewhere for a source of SCRAM failure.



COMPLEXITY OF THE FLUID SYSTEM associated with a large pressurized-water reactor is suggested by this schematic diagram taken from an operator-training manual prepared by the staff of the Nuclear Training Center of the Babcock & Wilcox Company. The system illustrated is that of a simulated nuclear-power plant that is similar in size and design to the two units at Three Mile Island, both of

At this stage one brings in experience with other systems, which indicates that component failures are most often isolated but approximately 1 percent of the time are part of a more general system failure. If this were true of the control rods in the preceding example, then one would expect that of the 10^{-4} probability of failure for a single rod about 1 percent, or 10^{-6}, would be the result of some more general common-cause contribution that would carry the other rods with it. In that case the probability of SCRAM failure (before due allowance for the number of triplets of adjacent rods in a reactor) would be 10^{-6}.

One has here two completely different models of triplet failure, one model based on individual malfunctions and the other on the existence of some kind of external cause. It was maintained in the Rasmussen report that there was no good way to choose between the models and that the truth must lie somewhere between them; the procedure resorted to was simply to take the geometric mean of the two numbers, which is 10^{-9}, or one chance in a billion. There may somewhere be a statistician who believes this is a valid procedure, but he has yet to make himself known. One sympathizes with the Rasmussen team in their compulsion to quantify the probability of something that has never happened and for which a mechanism of occurrence has not even been formulated. Although better estimates of the probability of SCRAM failure exist, no estimate is very satisfactory. It is simply a most unlikely event that is poorly understood.



which were built by Babcock & Wilcox. The figure is described in the manual as "a simplified composite diagram showing the nuclear steam system, steam and power conversion system, and major auxiliary systems." Key at lower right gives components. Primary loops are in color.

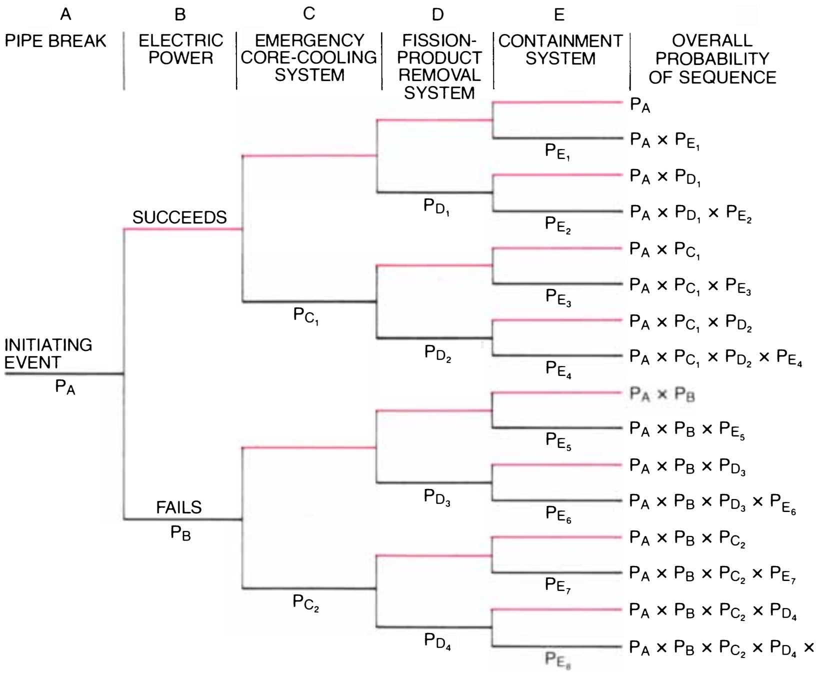
Another issue worth mentioning is the problem of conservatism v. realism. It is universally assumed, and regarded by some as obvious, that the regulatory process in the nuclear industry and other industries that can affect the public health and safety requires a generous measure of conservatism in estimating risk. A great deal of ignorance can be masked by conservatism, and it is an accepted way of life in the design of safety measures. (Clearly there are some cases where such conservatism is scarcely even considered. For example, if the wings of an airplane were designed as conservatively as a bridge is, the airplane would be too heavy to fly. Therefore airplane wings are designed to a safety factor of 1.5, a fact that frightens many people who learn of it.)

The relevance to the Reactor Safety Study is that the mission of Rasmussen's team was to make realistic estimates of reactor-failure probabilities, employing people whose entire life training was to err on the side of conservatism. It is hard to shake the habits of a lifetime, and the Rasmussen group did not escape the trap. For example, in the case mentioned above the very definition of control-rod failure was conservative, in that a rod was deemed to have failed if it did not insert fully. A rod that misses full insertion by a few inches may well do most of its job of controlling the neutron flux, but by this definition it is still a failed rod. There are many other examples of this kind of assumption scattered through the Reactor Safety Study, so that this particular factor lends a conservative bias to the Rasmussen report.

The only other problem area I shall discuss specifically is the one of human behavior. In spite of all the automatic control systems, reactors are operated by people, and compared with machines people are marvelously innovative and resourceful and at the same time fallible. In the early stages of any possible reactor accident it is the automatic control systems that sense the disruption of normal operation and trigger the reactor's SCRAM mechanism, turn on auxiliary pumps and actuate auxiliary diesel generators or whatever is needed to replace the vital function lost. Nevertheless, the proliferation of possible scenarios soon exceeds the capability of any automatic system to sense the proper response, and human judgment comes into play. At this point human action may be curative, it may be ineffective or it may aggravate the problem in the reactor. In fact, the entire sequence of events may have begun because of an error of human performance. It is extremely difficult, in fact impossible at present, to quantify human behavior on the average, let alone under stressful and unforeseen conditions. The history of technology provides many examples of cases where human beings have deviated from the norm in both directions, sometimes by extraordinary amounts.

The Rasmussen group recognized the problem of accounting for this uncertainty, and they consulted many of the right people, but there is a limit to what they could accomplish in this area. The conclusion is, as knowledgeable people have been saying for years, that human performance on the negative side is one of the ultimate limits to the safety of nuclear reactors, whereas human performance on the positive side is one of the great unquantifiable assets to safety in the course of an accident. Although one can make more significant statements than this one, it remains, and it probably will remain, a fact that the quantification of human behavior is far less advanced than the quantification of, say, the probability of a break in a pipe.

I have given these few examples simply to illustrate that the detailed calculation of the probability of a reactor accident through the "fault tree/event tree" technique utilized in the Rasmussen report is extremely difficult. Reflecting on the problem, the Risk Assessment Review Group concluded that the calculations of the Reactor Safety Study were not as good as had been maintained but that it was not possible to determine whether there was any net bias in either the positive or the negative direction. In other words, one could not say that the probability of a major reactor accident was either larger or smaller than the one calculated in the Reactor Safety Study; one could only say that the uncertainty of the calculation was far greater than had been stated in the Rasmussen report. This is not a particularly helpful conclusion, but it describes the true state of affairs.



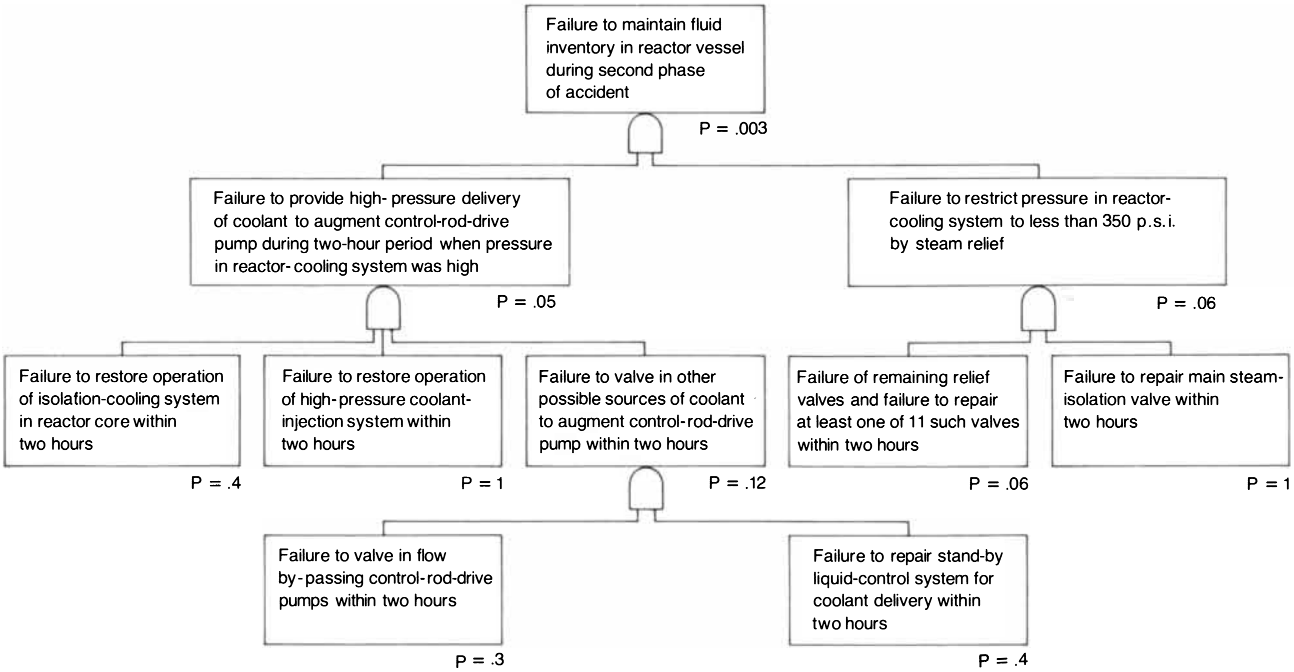
EVENT-TREE ANALYSIS is one of two logical techniques devised to assess the safety of nuclear reactors. Both event-tree analysis and its inverse, fault-tree analysis (*see illustration on opposite page*), are based on a form of binary logic in which an event is deemed to have either happened or not, or a component is deemed to have either worked properly or not. Events in which something is partially degraded are not included in fault-tree/event-tree analysis, and that is one of its imperfections. An event tree begins with some initiating event and follows the consequences of that event through a large number of possible chains, assigning to each branch a probability of occurrence; the end result is a long list of the possible consequences of the initiating event in which each consequence has associated with it a certain probability. In this simplified event tree for a large loss-of-coolant accident, for example, the initiating event is assumed to be a pipe break, the probability of which is signified by P_A. The subsequent events depend on whether the break occurs at a time when the electric power is on or off, and a probability P_B is assigned to the failure of electric power at the time of the break. (Since the probability of such a failure is generally less than .1, the probability of success, or $1 - P_B$, is always close to 1. Hence the probability associated with the upper branches in the tree is assumed to be 1.) One then follows each of the two branches, asking next what the probability of failure of the emergency core-cooling system is, which in turn will depend on the availability or nonavailability of electric power. In the example shown the probability of failure of the emergency core-cooling system in the absence of electric power is P_{C_2}, and that branch leads farther down the tree. The worst possible case is that given at the bottom, in which the electric power, the emergency core-cooling system, the fission-product removal system and the containment system have all failed, resulting in a very serious accident. The topmost branch illustrates the situation in which the pipe does indeed break, but all the other systems perform flawlessly, so that no risk to the public ensues. The task of event-tree analysis is to estimate the probabilities of all intermediate chains of events in such a way that an overall assessment of the risk can be made.

The Risk Assessment Review Group also concluded that the techniques of quantitative risk assessment, epitomized by those used in the Reactor Safety Study, were extremely valuable and should be far more widely applied in the process of regulating the nuclear industry. Such probabilistic techniques, which provide guidance on the important issues in reactor safety, would be helpful in determining the priorities of the NRC both in its safety-research program and in the deployment of its regulatory and inspection resources. The issue of whether risk assessment should be deterministic or probabilistic is a controversial one, and I shall not go into it here.

What does all this have to do with the accident at Three Mile Island? A full discussion would be beyond the scope of this article, but the main features of the story are as follows.

The nuclear reactor known as Three Mile Island, Unit 2, is on an island in the middle of the Susquehanna River, near Middletown and Harrisburg, Pa. Since it is a pressurized-water reactor, it has both a primary cooling system designed to carry the fission heat to the steam generator and a secondary cooling system to carry steam from the steam generator to the turbine and condensed water back to the steam generator. Each of these systems has its own group of pumps, the former called the reactor-cooling-system pumps and the latter the feedwater pumps. Both systems are required to transfer heat from the reactor core to the outside world, beyond the containment building.

At almost exactly 4:00 A.M. on March 28, 1979, the main feedwater pumps tripped, so that the mechanism for removing heat from the primary system was interrupted. Since this is not an unusual event, there are safety systems whose function it is to replace the main feedwater pumps. They consist of a set of three pumps, two electric and one steam-driven (so that at least one will work in the event of a complete loss of electric power). All three of the pumps went on automatically, as they were supposed to. Nevertheless, it takes some time, approximately 15 seconds, for the pumps to build up to their normal de-



FAULT-TREE ANALYSIS proceeds in exactly the opposite direction, tracing backward in time the many different ways a particular defect in a reactor could have begun and assigning to each of these paths a probability, so that in the end the overall probability of that fault's occurring can be calculated. In this case the logical structure of the analysis is Boolean algebra, and its language consists of "gates," several of which are indicated in the diagram, which is adapted from the Reactor Safety Study's analysis of the probability that the accidental fire at the Brown's Ferry No. 1 reactor in Alabama in 1975 could have been much more serious than it actually was. In that event the fluid inventory in the core of the reactor was maintained by resorting to the control-rod-drive pumps, which were not designed for that purpose. There were a number of options open to the operators at the time, however, and a failure to maintain the fluid inventory would have meant that none of these options was successfully implemented; accordingly this particular fault tree consists entirely of "and" gates, symbolized by the half-rounded figures in the diagram. (An "and" gate signifies that all the input statements must be true before the output statement is true, and therefore the input probabilities must be multiplied by each other in order to compute the output probability.) Suppose, for example, that in the right-hand branch of the diagram one seeks to know the probability that the operators would have been unable by the stratagem of steam relief to keep the pressure in the primary reactor-coolant system below 350 pounds per square inch, the pressure above which the control-rod-drive pumps would not work. There were two ways this failure could have come about, either by a failure to repair the main steam-isolation valve or by a failure of the other 11 relief valves. The former failure was considered certain, whereas the latter was assigned a probability of 6 percent (or *P* = .06) by the authors of the Reactor Safety Study; hence they calculated that the probability of the loss of pressure control through steam relief was also 6 percent. There was a possibility at the time of the accident, however, that the operators could have provided an alternative high-pressure coolant-delivery system to augment the control-rod-drive pumps. The study group assigned a 95 percent probability to the chance that this approach would have been successful, leaving a 5 percent probability of failure. Since both negative circumstances (the loss of steam relief and the failure to provide high-pressure water injection) were necessary to cause a loss of cooling ability, the two probabilities are shown multiplied in an "and" gate, leading to an overall probability of .3 percent (*P* = .003) for failure to cool the core. In other words, the study concluded that there was roughly one chance in 300 that the Brown's Ferry accident could have led to a core melt. In spite of limitations of such analyses, the author maintains that "the use of this methodology in the Reactor Safety Study was a giant step forward in the rational analysis of nuclear safety."

sign pressure, and in the interim the primary system was heating up and its pressure was increasing. In response to the increase of pressure the SCRAM system went into action, shortly after a pressure-relief valve had opened to relieve the pressure in the primary system. All of this was quite proper and according to plant design.

Unfortunately there were at this point two things wrong that were not known to the operators. The first problem was that the emergency feedwater pumps had in their discharge lines two block valves that are normally used for maintenance. These valves are supposed to be open at all times during the operation of the plant (although one valve at a time may be closed for short periods), but they had been inadvertently left closed at some time not yet firmly established, but probably about two days before the accident. Therefore the secondary system had no pumping capacity whatever and the steam generators soon boiled dry. The second problem was that the primary-system relief valve, which is at the top of the pressurizer, had been de-energized after about 15 seconds but had failed to reseat. Hence the primary system itself now had a leak, unknown to the operators. (This particular valve was known to be leaky, and the plan had been to replace it at the next routine maintenance of the plant.)

There then followed a long and complex series of events and actions, during which the inadvertently closed block valves were discovered and opened (approximately eight minutes after the onset of the accident, probably soon enough to prevent damage to the plant), but the leaky relief valve was not discovered and blocked off until nearly two and a half hours into the accident. During this period the operators had been misled into believing they had too much water in the primary system whereas in fact there was too little. For example, when the automatic emergency core-cooling system turned itself on two minutes into the accident and began to do its proper job of cooling the core, the operators let it function for only a couple of minutes before turning it off. The result was that the core ultimately lay uncovered for a period of hours, during which substantial fuel damage (but probably no melting) occurred, before the situation was finally brought under control. It was during this period that the well-publicized "hydrogen bubble" was formed from the oxidation of zirconium in the cladding of the fuel rods and collected in the upper part of the reactor's pressure vessel. The bubble and the dramatic race against time to see whether it could be disposed of before enough oxygen collected in it to produce an explosion occupied the nation's attention for several days. It is now known that there was never any chance of a hydrogen explosion in the reactor vessel.

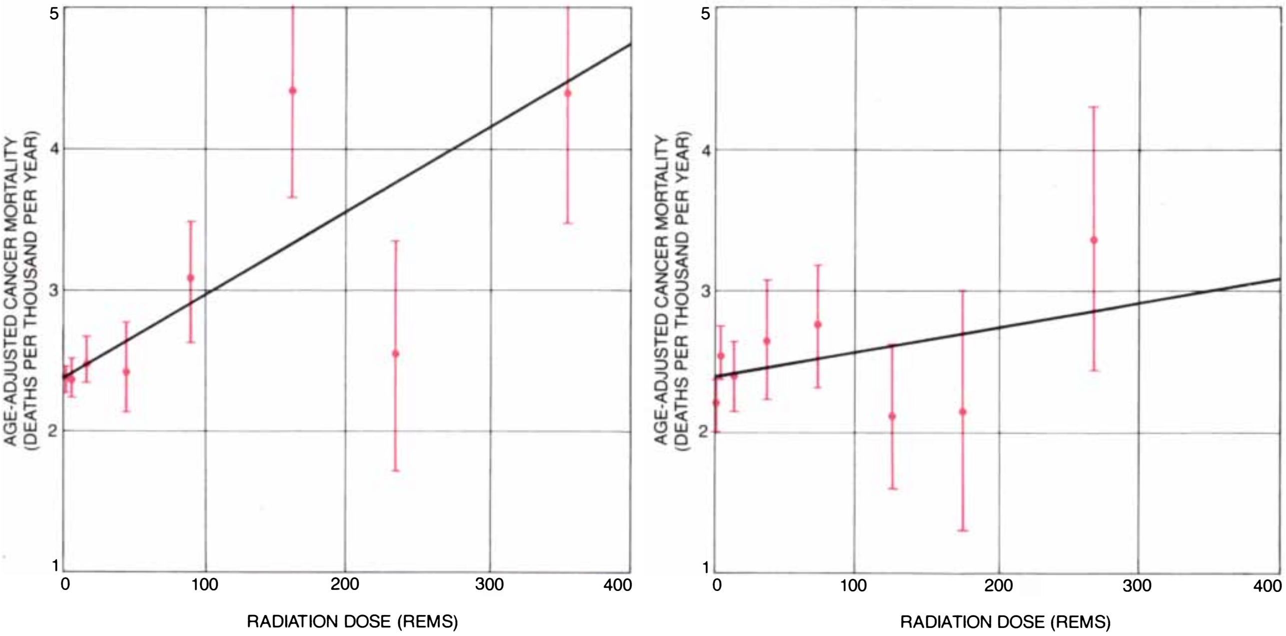
It would be possible to write a book about the details of the Three Mile Island event, and such books are now being written. This brief sketch, however, is sufficient both to bring out the major safety points and to assess the public reaction to the accident.

First of all, was this kind of accident predicted by the authors of the Reactor Safety Study? The Rasmussen report did in fact consider the possibility that the two block valves on the emergency feedwater system could be inadvertently left closed during routine maintenance. Although this valve closure may not have contributed to the damage in the reactor, it certainly did contribute to the early confusion and therefore to the subsequent course of events. The further development of the accident, and in particular the formation of the hydrogen bubble, was not foreseen by any of the early analyses, in part because analyses never go more than a few steps down the sequence. Hence after a fairly short time the operators were dealing with a situation that had not been foreseen and for which they had no relevant training. It was at this point that actions were taken that in retrospect clearly seem to be inappropriate but for which the justification seemed adequate to the operators on the scene. One should be slow to second-guess trained people operating in a crisis situation.

There are two interesting lessons to be learned from the Three Mile Island event, one technical and the other social. On the technical side it is now easy to look back and see that there were three main ingredients to the accident sequence: a transient (a temporary abnormal condition) exacerbated by human behavior (the closed block valves), followed by a small loss-of-coolant accident (the stuck relief valve) and subsequent human error. It is interesting that experts have been saying for years that these three elements are major threats to a reactor and that the NRC has not been paying enough attention to them. It may well be that the regulators have been so busy fighting off the interveners, who most frequently and most vigorously have brought up the issue of a large loss-of-coolant accident, that they have not been able to give enough attention to the real hazards. There is also a great deal of institutional inertia, however, compounded by a lack of commitment to regulatory guidance through probabilistic risk assessment.

It is instructive to quote a passage from the report of the Risk Assessment Review Group: "The achievements of WASH-1400 in identifying the relative importance of various accident classes have been inadequately reflected in NRC's policies. For example, WASH-1400 concluded that transients, small LOCA [loss-of-coolant accidents] and human errors are important contributors to overall risk, yet their study is not adequately reflected in the priorities of either the research or regulatory groups." These three items—transients, small loss-of-coolant accidents and human errors—were the central features of the Three Mile Island accident.

It is also clear that the present nuclear-regulatory structure in the U.S. does not have a well-organized means of



LINEARITY HYPOTHESIS asserts that at the low levels of radiation exposure expected as a result of a major nuclear-reactor accident the long-term likelihood of death due to a radiation-induced cancer is roughly proportional to the dose of radiation received. Assuming that the hypothesis is true, the best current estimate of the coefficient of proportionality is that approximately one latent cancer would result from 10,000 man-rems of radiation exposure. (The estimate remains the same whether 10,000 people receive one rem each or 1,000 people receive 10 rems each.) As these two graphs illustrate, however, the data on which the linearity hypothesis is based are sparse. The graphs show the age-adjusted cancer-mortality rates as a function of estimated radiation dose among the survivors of the atomic-bomb explosions at Hiroshima (*left*) and Nagasaki (*right*). (In neither case was the character of the radiation to which the population was exposed the same as that which would be involved in a reactor accident, but the Nagasaki event was much closer than the Hiroshima one.) In both cases the incidence of fatal cancer at zero radiation dose is not very different from that observed today in the U.S., where the probability of dying of cancer is currently between 15 and 20 percent. The key question is to what extent the cancer-mortality rate increases with increasing dose of radiation, and the data available do not clearly support either linearity or nonlinearity. Although theoretical considerations make it appear extremely unlikely that there is a threshold for the induction of cancer by radiation, there is at present no evidence that radiation doses of less than about 50 rems measurably increase the natural incidence of cancer among human beings. Since it is precisely in this range that most of the radiation exposures due to a putative reactor accident would be expected to fall, estimates of the carcinogenic effects of such an accident differ widely. Most experts accept the linearity hypothesis as a conservative upper limit, but an increasing number regard it as a gross overestimate. In fact, the author points out, "unless major strides in our understanding of carcinogenesis enable us to develop a theoretical basis for our beliefs, we may never understand these small effects better than we do now."

incorporating into reactor-safety lore those day-to-day occurrences that are a way of life in any large industry, and particularly in the nuclear industry. The nuclear industry is very well regulated, so that even minor failures at a reactor are necessarily reported to the NRC and form the body of a system of reports called Licensee Event Reports, which are then filed and distributed. Thousands of these documents are generated each year, most of them quite trivial, but it is interesting that they have included in the past incidents at other plants that are reminiscent of the early stages of the Three Mile Island accident. If there were an institutional means of learning by experience, it too might conceivably have prevented the Three Mile Island accident.

This is a point worth discussing in somewhat more detail. It seems to be a feature of nuclear reactors, and it is certainly implied by the analysis given in the Rasmussen report, that the probability of an accident decreases with the severity of that accident. This is a feature nuclear technology shares with other technologies, for example aviation technology, where minor malfunctions of aircraft happen far more often than minor accidents, which in turn happen more often than major accidents. In effect many potential large accidents are nipped in the bud. In the aircraft case the procedure for learning by experience is institutionalized through the National Transportation Safety Board, whose function it is to determine the probable cause of any accident and to recommend appropriate preventive measures. There is no comparable institution for nuclear reactors, and so the job of regulation is somehow combined with the job of assessing the effectiveness of that regulation, all within the NRC. There also exists an Advisory Committee on Reactor Safeguards (of which I am a member) that can perform this function, and it does so on an ad hoc basis. There certainly is enough information in the operational experience of other reactors to have alerted all of us to the possibility of an accident of the kind that happened at Three Mile Island, but for one reason or another we seem not to have been alerted.

What about the public response to the accident? What are the social lessons to be learned from the experience? There were, in the early stages of the accident, releases of a radioactive isotope of xenon, xenon 133, which has a half-life of approximately five days. The releases were monitored, and the actual exposure of the public is estimated to have been approximately 4,000 man-rems; accordingly the radiation release has the potential for causing the death, by cancer, of less than one person in the next 30 or 40 years. Although this finding is hardly a matter for rejoicing, the response of the press, of radio and television reporters and of the public to the hazard was all out of proportion to the actual damage. In retrospect there was a genuine breakdown of the nation's ability to react responsibly and in proportion to an accident that, although serious and threatening, fell far short of doomsday. Many states have now instituted studies of emergency-response procedures that can draw from the lessons of Three Mile Island.

On the other hand, the Three Mile Island incident illustrates graphically how important it is to quantify both the probability and the consequences of an accident, and to generate some public awareness of these issues. For example, those of us who are alleged to know something about such matters are often asked by friends a question that goes as follows: "Yes, we were lucky things worked out all right, but tell me, what is the worst that could have happened?" I usually reply to the question by saying that the worst that could have happened is that a series of other misadventures could have befallen the reactor—a massive electrical failure, an earthquake, a fire or the like—leading to a core melt. The molten core could then have interacted with the water in the pressure vessel or in the containment building, leading to a steam explosion that could have torn off the roof of the containment building. Then all the radioactivity could have gone into the atmosphere at the very moment a tornado came by to pick it up and proceeded to wander through the Northeast, dropping just the right amount on each city to annihilate its inhabitants. Indeed, this could have happened.

My friends then get angry, but the answer is not evasive and is meant only to illustrate that the question of what could have happened is not a reasonable question unless it is attached to some estimate of the probability of the event. In other words, it is essential to discuss this safety issue and others with some quantitative objective in mind. Hence it is reasonable to ask what could have happened for an event that could occur once in 100 years or once in 1,000 years or once in a million years, but short of events that actually violate the laws of nature it is not reasonable to ask simply what could have happened. This is an issue that goes to the heart of many regulatory and safety discussions, where one must have some measure of the risks one is willing to accept on as quantitative a basis as the expert community can provide.

There is one other point on public response that needs to be mentioned. Many people responded to the Three Mile Island accident with statements such as, "They told us it couldn't happen, but it did!" In fact, no responsible person ever said that it could not happen, because the very business of quantitative risk assessment is to calculate the probability of an accident. No one will calculate a probability if he believes it is zero. What is at stake here is a widespread misunderstanding of the probability of infrequent events, a misunderstanding that is by no means confined to the nonscientific community.

Imagine, for example, a list of a million different events, each of which has a probability of one in a million of happening this year. The list might include the probability of a certain football team's going to the Super Bowl, of the OPEC cartel's deciding to lower oil prices as a goodwill gesture and so forth. If there were literally a million items on the list, and if the probability of each had been correctly calculated as one in a million, then there would be a good chance that one of those things would happen this year. When it did, one can be quite sure people would forget the other 999,999 items and would say that the probability for the event that did in fact happen had been grossly underestimated. People have a tendency to think that anything that actually occurs cannot have had a small probability of occurrence, because their view of the world is inevitably influenced by those things that do occur. Therefore even the NRC is devoting a great effort to making sure the accident that occurred at Three Mile Island will not occur again, with substantially less attention being devoted to perceiving it as a member of a large class of possible events that should not be singled out for having a high probability simply because it happened. The same comment can be made at this stage about the engine pylons on the DC-10.

All of the preceding is intended to illustrate the importance to society of assessing risk in quantitative terms and of making sound interpretations of those risks. Since it is clear that we cannot live in a world without risk, the only alternative to understanding and managing the risk to which we have chosen to expose ourselves is institutional mismanagement and the squandering of resources. Examples of this abound, and it is a luxury we cannot afford.

Finally, then, any reader who has come this far will know better than to ask the meaningless question, "Are reactors safe?" The reader may want to know, however, whether I believe nuclear power is safe enough to supply a large part of our national energy needs. The answer is yes, not because there are no remaining risks and uncertainties in nuclear power, nor because coal is more dangerous (although it is), but because President Carter was right when he declared that the energy crisis in which we find ourselves is "the moral equivalent of war." I see no point in not fighting that war, and nuclear power is an essential weapon in the fight.

The Inner Structure of the Proton

There is something small and hard inside. These objects, which may be the particles called quarks, are seen most clearly when a violent collision of particles gives rise to a "jet" of debris

by Maurice Jacob and Peter Landshoff

In the study of the atom and its parts one of the most influential of all experiments was carried out almost 70 years ago in Ernest Rutherford's laboratory at the University of Manchester. Two of Rutherford's students, Hans Geiger and Ernest Marsden, directed a beam of alpha particles, which are fast-moving helium nuclei, onto a thin foil of gold. With a screen of fluorescent material, which scintillates when it is struck by an alpha particle, they then counted the number of particles scattered at various angles as a result of encounters with the gold atoms. Most of the particles passed straight through the foil or were deflected by only a small angle; the average deflection was less than a degree. Surprisingly, however, a few particles were deflected sharply. About one in 20,000, for example, was deflected by 90 degrees.

It was Rutherford who supplied the interpretation of these findings. Since the foil was many atoms thick, and since most of the alpha particles traversed it unimpeded, he reasoned that an alpha particle must be able to pass through an atom with little disturbance of its trajectory. Hence the atom as a whole must be diffuse, with much empty space. The occasional scattering at wide angles, however, was evidence that there is something hard in the atom, which must be small since only a few of the alpha particles encountered it. Both the violence of the collisions and their rarity could be explained by assuming that the atom has an impenetrable, dense core where all its positive electric charge is concentrated in a small volume. In traversing the foil most of the alpha particles never approached one of these small cores close enough to be strongly influenced by it, but when a collision did take place, the alpha particle could be scattered in any direction, even straight back along its original path.

What Rutherford had discovered, of course, was the atomic nucleus. He had also introduced a method for investigating the constitution of matter, a method whose importance is undiminished today. In the decades following Rutherford's experiment it became apparent that the nucleus itself has a structure: it is made up of protons and neutrons. Now there is compelling evidence that the component protons and neutrons are not elementary objects; like Rutherford's atoms they are mostly empty space, but embedded within them are small, hard constituents. The constituents have been given different names in different contexts: they can be called either partons or quarks.

The internal structure of the proton is being explored today through experiments that are almost identical in form with Rutherford's. Collisions are arranged between various kinds of particles, and instruments measure the angular distribution of the scattered fragments. Again it is the particles emerging at large angles to the direction of the original beam that convey information about the finest details of the internal structure.

The modern experiments differ from Rutherford's chiefly in scale. The projectiles employed are not alpha particles emitted during the radioactive decay of a nucleus but electrons or protons raised to high energy by an accelerator. Secondary beams of other particles, such as neutrinos or pions, can also be created. The most energetic collisions come about when two beams of accelerated particles are made to collide head on. At high energy the particles do not merely bounce apart; instead much of their energy goes into creating new particles and antiparticles, often dozens of them, which fly away from the point of impact like debris from an explosion. The instruments that detect these particles are not simple fluorescent screens (although that principle is still in use) but elaborate electronic "counters," which not only register the direction a particle takes but also measure its energy, momentum and electric charge. There is a difference of scale in another sense as well. With energies several thousand times greater, the modern experiments can reveal structural features several thousand times smaller. Indeed, the resolving power of the highest-energy experiments is now about 10^{-16} centimeter, which is roughly a thousandth the diameter of the proton.

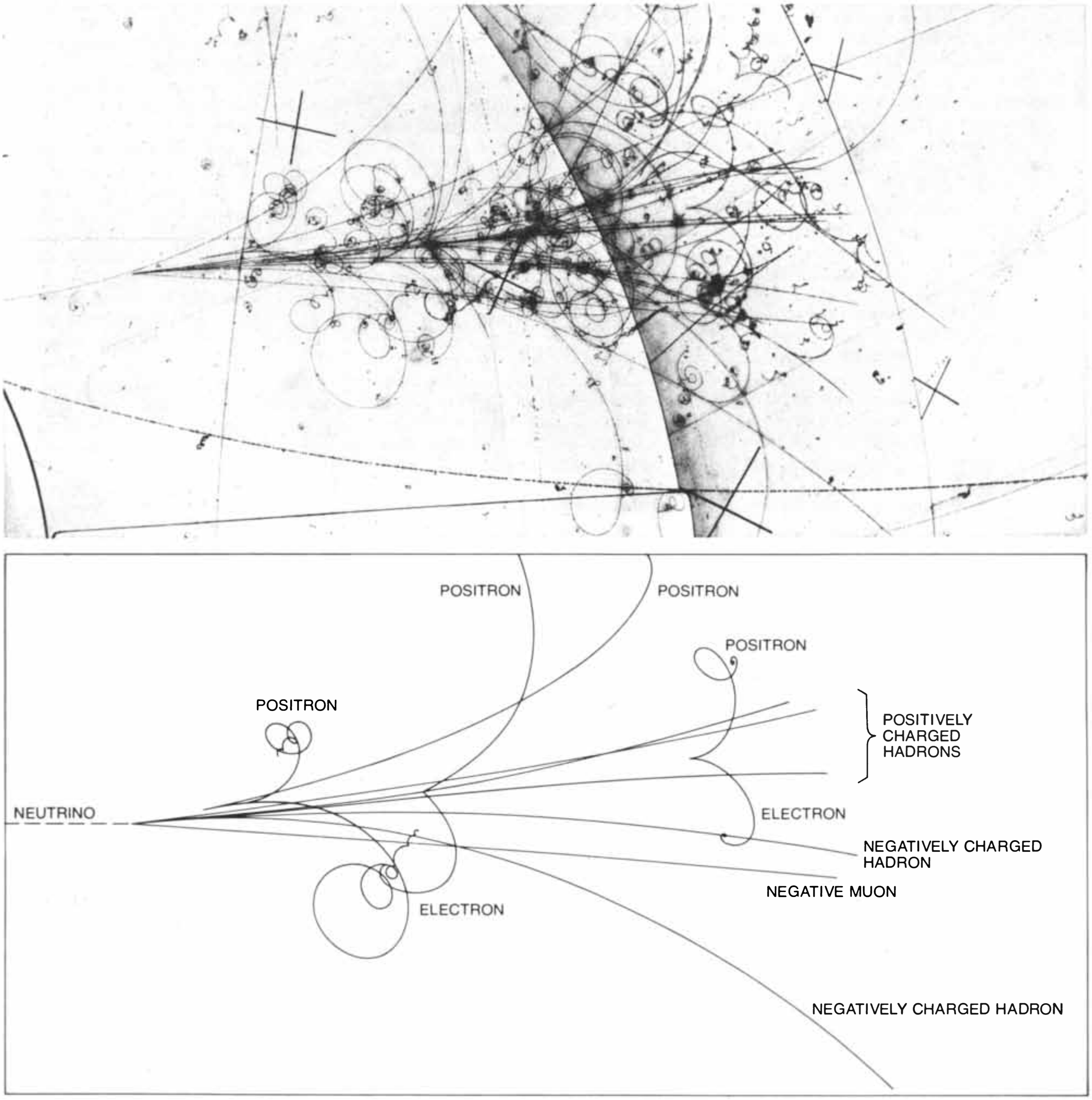
This fine structure becomes visible only in those collisions where some of the energetic fragments emerge at a large angle to the beam direction. As in the earlier atomic experiments, such "hard-scattering" events are comparatively rare. When two protons collide head on, for example, the emitted particles are almost always confined to two narrow cones centered on the axis defined by the two colliding beams. Occasionally, however, particles emerge from the point of impact roughly perpendicular to the beam axis. If one such particle is detected, at least several more usually accompany it. What is most intriguing is that when a fragment is shot to the side in this way, the particles are not scattered randomly in all directions; instead they are generally organized into well-collimated spurts of particles, which have been named jets. The wide-angle jets have the same significance for the structure of the proton as the wide-angle scattering of alpha particles had for the structure of the atom. They are evidence for something small and hard in the proton.

It has been known for some time that the proton is not a pointlike particle. It has a finite size, a diameter of about 10^{-13} centimeter. Although that is very small—indeed, it is smaller than an atom by a factor of about 100,000—it is still measurable. The same cannot be said of certain other particles, most notably the electron. If the electron has any extension, it has not yet been detected, and for now the electron can be regarded as a mathematical point.

In 1970 an experiment at the Stanford

Linear Accelerator Center (SLAC) provided the first direct evidence that the proton has not only size but also structure. In the two-mile linear accelerator at SLAC electrons were raised to an energy of some 20 billion electron volts. (One electron volt is the energy imparted to an electron, or to any other particle with one unit of electric charge, when it is accelerated through a potential difference of one volt. A billion electron volts is abbreviated GeV, the *G* standing for the prefix giga-.) The accelerated electrons struck protons and neutrons in the atoms of a stationary target. Instruments monitored the angular distribution of the scattered electrons and of other particles created in the collisions.

Although most of the electrons passed through the target with little change in direction, the number of widely scattered particles was greater than expected. It was greater than would be predicted if the proton were diffuse and homo-



JET OF PARTICLES emerges from a proton struck by a high-energy neutrino. The event is recorded in trails of bubbles, which form in superheated hydrogen along the path of a charged particle. The neutrino, which leaves no track because it has no charge, is transformed by the collision into a negatively charged muon, which can be observed. At the same time a stream of particles moves off in another direction. They are hadrons, a class of particles (such as the proton and the pion) that are thought to be made up of the more fundamental entities called quarks. From the curvature of the tracks in the magnetic field that permeates the bubble chamber it can be deduced that three of the hadrons carry a positive charge and two have a negative charge. In addition at least one neutral pion is emitted; it cannot be seen, but the products of its decay are pairs of electrons and antielectrons, or positrons, which leave distinctive spiral tracks. In the frame of reference in which the neutrino and the target proton collide with equal but opposite momentum, the scattered muon and the jet of hadrons would appear to emerge almost back to back. Such wide-angle scattering signals a violent process. The event can be explained by the hypothesis that the neutrino collides with a hard constituent of the proton, such as a quark; the quark is ejected, but as it escapes several other quarks and antiquarks materialize, creating the jet of hadrons. The photograph was made with the Big European Bubble Chamber at the European Organization for Nuclear Research (CERN) near Geneva. Some of the particle tracks are identified in the map below.

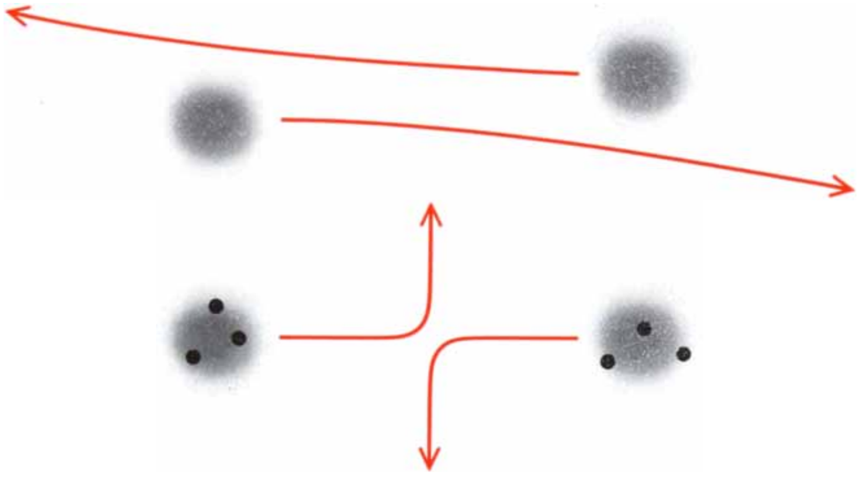
geneous. The excess of widely scattered particles implied that the proton has embedded within it objects whose diameter is no more than a fiftieth that of the proton as a whole. Richard P. Feynman of the California Institute of Technology supplied a name for these constituent objects: partons.

What was revealed in the SLAC experiments was the internal structure of the proton as illuminated by electrons. Since then similar studies have been done in which the target is illuminated by a beam of muons (which are much like electrons but have a mass 200 times as great) or by a beam of neutrinos (which are particles related to the electron and the muon but lacking all mass and electric charge). Electrons, muons and neutrinos are collectively called leptons, and they make excellent probes in physics experiments because they themselves seem to be pointlike and without structure. Deep-scattering experiments with all three kinds of lepton have given consistent results: occasional wide-angle scattering can be explained by collisions between the incident leptons and some hard constituent of the proton.

The scattering of leptons by protons gave the first experimental indication that the proton has definite structural constituents. Interactions among those constituents were first observed clearly in another series of experiments, begun in 1972, in which protons were scattered by protons. The experiments were carried out by three groups working at the Intersecting Storage Rings (ISR) of the European Organization for Nuclear Research (CERN) near Geneva. Collisions of protons with protons gave rise to infrequent events in which energetic particles appeared at a wide angle to the axis of the beams. These results were interpreted as evidence for the scattering of a constituent object in one proton by a constituent of the other proton.

Several years before the discovery of the parton and before the ISR experiments began, a structure had been proposed for the proton entirely on theoretical grounds. The proton and the neutron are members of the large family of particles called hadrons, which are distinguished from the leptons in that they are susceptible to the strong, or nuclear, force. It is the strong force that binds protons and neutrons together to form atomic nuclei, but the strong force has no effect on leptons; they simply do not "feel" it, much as an electrically neutral particle does not respond to an electric field. The proton and the neutron were the first hadrons known; in the 1940's another was discovered: the pion. In the 1950's a number of powerful accelerators began operating, and an unexpected multitude of new hadrons came to attention. It was this multiplicity of hadrons that stood in need of explanation; it seemed unlikely that all these particles could be equally elementary.

An explanation was proposed in 1963 by Murray Gell-Mann and by George Zweig, both of Cal Tech, who worked independently but reached similar conclusions at about the same time. They pointed out that all the known hadrons could be explained as combinations of just three kinds of more fundamental particles, which Gell-Mann named quarks. Some of the hadrons, including the proton and the neutron, were to be made up of three quarks; others, such as the pion, consist of one quark and one antiquark. The properties associated with the hadron as a whole are given simply by adding up the corresponding properties of the component quarks. In this way all the known hadrons could be accounted for as combinations of quarks. What is more, every allowed combination of quarks, with one exception, corresponded to a known hadron; the exception described a particle designated omega minus, which was discovered in 1964.



WIDE-ANGLE SCATTERING is interpreted as evidence that particles have a grainy structure, or hard constituents. When large, diffuse particles collide, they are little deflected from their paths. Such glancing collisions are also the most likely for particles that have hard constituents, but in the rare instances when the hard objects meet head on, they ricochet sharply.

The quark model was formulated to explain the diversity of the hadrons; it says nothing explicitly about the internal structure of any particle. Nevertheless, when partons were discovered, there was a natural tendency to identify them with the hypothetical quarks. Several properties of the partons, such as their intrinsic spin angular momentum, have been measured and are consistent with the predictions of the quark model. What is more, the quark model itself has become more secure.

The three "flavors," or kinds, of quark proposed in 1963 were enough to construct all the hadrons then known. It was soon suggested, however, that there should be a fourth flavor, distinguished by a new property of matter called charm. The discovery in 1974 of the hadron designated *J* or psi provided strong evidence for the charmed quark, and a rich spectrum of other charmed hadrons was subsequently discovered. Since then particles that carry still another flavor have turned up. They are thought to incorporate a fifth flavor of quark; because the other four quarks seem to be organized in pairs it is assumed there is also a sixth flavor. All these new hadrons follow the pattern specified by the quark model. Each hadron seems to consist either of three quarks or of one quark and one antiquark, drawn from the set of five or six possible flavors. No particle that would require some other combination has been observed.

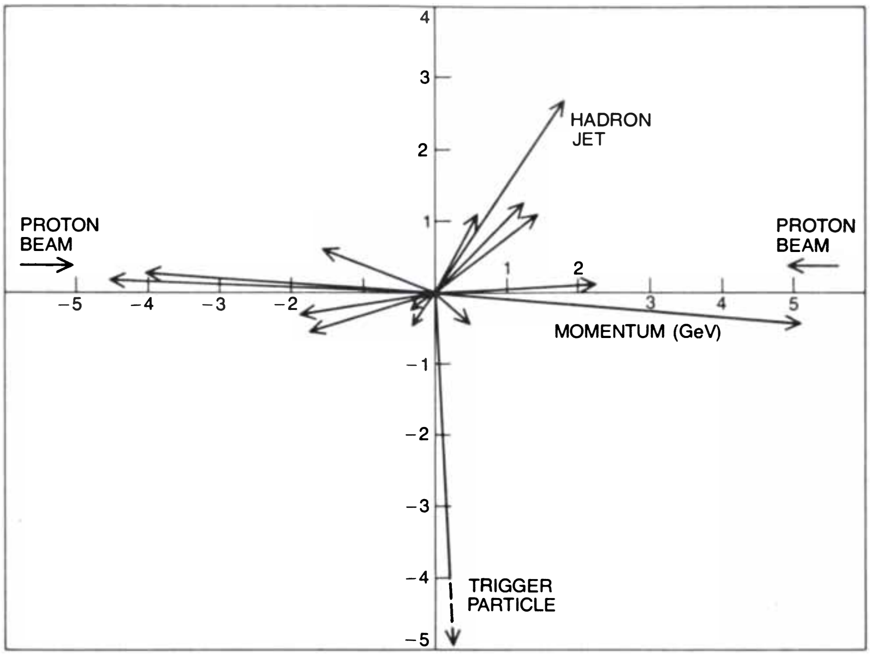
In addition to their flavors each of the quarks bears another distinctive property, which in the spirit of whimsy that characterizes the quark nomenclature has been given the name color. It is the colors of quarks that govern their binding together to form hadrons. There are three colors, and only certain combinations of them seem to be possible.

The role of color in binding together the quarks in a hadron is analogous to the role of electric charge in binding together the particles that make up an atom. A precise and well-tested theory describes the latter interaction: quantum electrodynamics. It depicts the attraction or repulsion between two charged particles as being communicated by the exchange of photons, or quanta of electromagnetic radiation. A theory constructed and named on the model of quantum electrodynamics has been formulated to describe interactions between colored quarks; it is called quantum chromodynamics. Here the force between the quarks is mediated by the exchange of gluons, hypothetical particles that "glue" the quarks together. Differences between electromagnetism and the strong interactions of quarks result largely from differences between the photon and the gluons. In the first place, whereas there is only one kind of photon, there are eight kinds of gluon. Furthermore, the photon communicates electromagnetic forces between charged particles but itself carries no electric charge; as a result a particle can emit or absorb a photon without changing its charge. The gluons, on the other hand, are themselves colored particles, and so they are subject to the very forces they transmit. Quantum chromodynamics has made a number of successful predictions, but it is a difficult theory with which to calculate precise results and it has not yet been confirmed with a precision even approaching that of quantum electrodynamics.

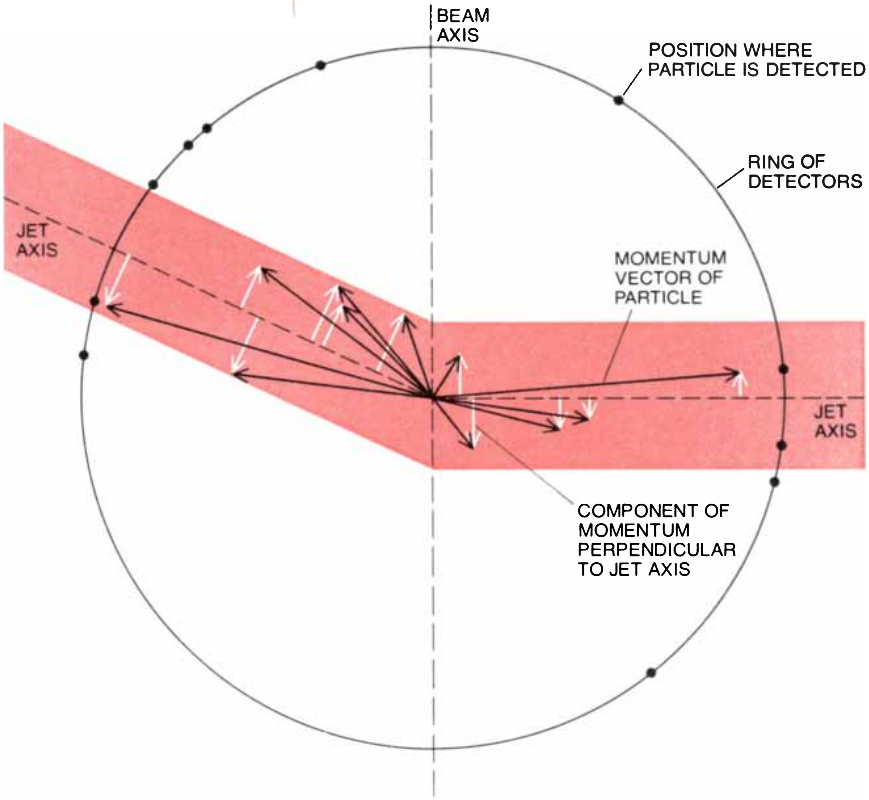
The existence of several hundred hadrons that correspond to allowed combinations of quarks, and the failure to observe even one hadron that cannot be explained as such a combination, represent powerful evidence for the quark model. Nevertheless, what might be considered the most direct and most compelling confirmation of the theory is still lacking: no one has yet isolated a quark. This failure is all the more puzzling in that deep-scattering experiments show the quarks within hadrons as moving about freely, as if they were only weakly bound together. It seems it should be easy to knock one out. When that is attempted, however, by bombarding a hadron with high-energy particles, the fragments that emerge are not quarks but ordinary hadrons, constituted of the standard combinations of quarks.

A possible explanation of this paradoxical behavior has been proposed in the context of quantum chromodynamics. It is hypothesized that the effective strength of the force between quarks is small at close range but grows much larger when the quarks are separated by more than about the diameter of a proton. This force law is just the opposite of the one that governs the more familiar forces of electromagnetism and gravitation, where the forces become weaker as the bodies recede from one another. Because of the peculiar form of the color force the quarks are little constrained inside a hadron, but the energy needed to extract a quark grows without limit as the separation increases.

So far it has not been proved with the tools provided by quantum chromodynamics that the quarks in a hadron are permanently or absolutely confined. There is still a possibility that experiments at higher energy may release a free quark. For now, however, physicists must live with the consequences of apparent confinement. One of these is that quarks cannot be examined in isolation; they must be studied in situ. Hence our best access to them is through wide-angle-scattering events in which a hard collision between a quark and a probe



HEAD-ON COLLISION OF TWO PROTONS yields several widely scattered hadrons. The protons approach each other with equal speed along the horizontal axis and meet at the center. A number of the emitted particles deviate little from the beam axis, but one particle emerges with high momentum at an angle of almost 90 degrees. The detection of this particle triggered the apparatus with which the event was recorded. The high transverse momentum of the trigger particle is partly balanced by a jet of hadrons. Not all the particles in the jet have necessarily been detected; the apparatus is not sensitive to electrically neutral particles, which generally account for about a third of the jet momentum. Only transverse jets are thought to result from the hard-scattering of quarks. The collision was observed with the Intersecting Storage Rings (ISR) at CERN. The length of each arrow is proportional to the momentum of the particle.

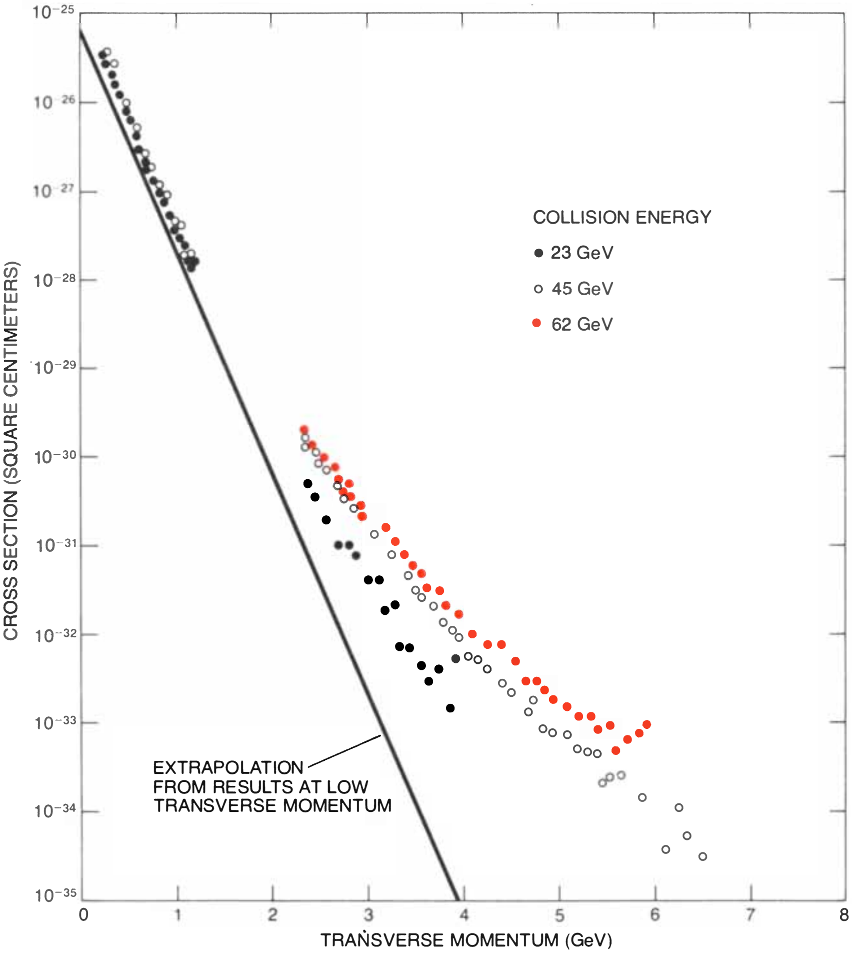


JET IS DEFINED in terms of the momentum of the constituent hadrons. If only the directions of the particles were recorded (by noting where they crossed a ring of detectors), they would be widely distributed. The jet becomes more coherent, however, when it is noted that the component of the momentum of a particle perpendicular to the axis of the jet seldom exceeds a threshold. Thus particles with large momentum are always closely aligned with the jet axis.

particle (which may be another quark or a gluon) gives rise to a jet of hadrons.

Collisions between particles are most easily visualized in the frame of reference where the center of mass of the colliding particles is regarded as being stationary. In this frame of reference the colliding particles approach each other with equal but opposite momentum; if they have the same mass, they collide head on with equal but opposite velocity. Like automobiles that collide head on and come to a dead stop, both particles give up all their kinetic energy.

In experiments where an accelerated particle strikes a stationary target the appearance of the event in the laboratory frame of reference is quite different. The center of mass is not stationary but is swept along in the direction of the beam, even after the collision. As a result the appearance of the event is greatly altered; for example, a jet of particles emitted at 90 degrees to the beam direction in the center-of-mass frame of reference is swept along with the moving particles, so that it appears to diverge from the beam by only a few degrees. In order to see the event in its simplest form one would have to race along parallel to the beam with the same speed as the center of mass. Although that is impractical, there are mathematical transformations that accomplish the same thing: they convert the directions and energies of particles observed in the laboratory into equivalent values in the center-of-mass frame. We shall discuss fixed-target experiments as if such transformations had been carried out.



PARTICLES WITH HIGH TRANSVERSE MOMENTUM are rarely emitted in proton-proton collisions, but at the largest observable values of transverse momentum there is an enhancement in their numbers. The yield of particles is given in terms of a cross section, or effective area, which measures the probability of an interaction. At transverse momenta below about 1 GeV (billion electron volts) the probability of emitting a particle declines steadily as the transverse momentum of the particles increases. At higher values of transverse momentum the probability continues to decline, but not as rapidly as would be predicted from an extrapolation of the results at lower transverse momentum. For example, the probability of observing a particle with a transverse momentum of 4 GeV is roughly 1,000 times greater than would be expected from the extrapolation. Moreover, the probability at low transverse momentum is almost independent of the energy with which the protons collide, whereas at high transverse momentum the collision energy has a strong influence. The anomalously large yields of high-transverse-momentum particles gave the first evidence for the hard-scattering of quarks by quarks. It was reported simultaneously by three groups of experimenters at the CERN ISR.

There is one type of high-energy-physics experiment in which the center of mass actually is stationary and the collisions have their simplest form even as they are observed in the laboratory frame of reference. They are events in which two particles are accelerated to the same momentum and are brought together head on. Such collisions can be arranged with particle storage rings, where beams of particles circulate in opposite directions and pass through each other on each revolution. The energy liberated by the collision is merely the sum of the energies of the two beams.

Collisions between electrons and their antiparticles, the positrons, are brought about in storage rings at a number of laboratories, including SLAC and the German Electron Synchrotron (DESY) near Hamburg. Both of these institutions have been operating electron-positron rings since the early 1970's, with maximum collision energies of roughly 10 GeV; both of them have also undertaken the construction of larger rings, capable of collision energies more than three times as great. The larger ring at DESY, which is called PETRA, has been operating since last spring. Still higher energies can be reached in collisions of protons with protons. The only facility for such collisions that is now operating is the ISR at CERN; it has a maximum energy of 63 GeV, the highest center-of-mass energy that can be reached by any instrument in particle physics.

The result of a head-on particle collision is perhaps easiest to interpret in the case of electron-positron interactions. Because the electron and the positron are particle and antiparticle they are both annihilated when they collide, yielding a state of pure electromagnetic energy. This state can be represented as a high-energy photon, but it is a photon with bizarre and paradoxical properties. A fundamental law of nature states that both energy and momentum must be conserved in all physical processes. In order for energy to be conserved in an electron-positron collision, the photon must carry off the several billion electron volts contributed by the annihilating particles. A photon can do that but, moving at the speed of light, it also has substantial momentum. The net momentum of the electron and positron, however, is zero, since they are moving with the same speed in opposite directions. Therefore the photon must have zero momentum and cannot move at all.

A way out of this quandary is provided by the uncertainty principle of quantum mechanics, which allows momentary fluctuations in the energy and momentum of a particle, provided they do not last too long or extend over too great a distance. Hence the photon can exist briefly even with its energy and momentum out of balance, but it must decay within a finite period into a set of particles that properly conserves energy and momentum. Such a photon is called a virtual particle, to distinguish it from a real photon, whose lifetime is unlimited.

The virtual photon can decay into any assortment of particles that conserves energy and momentum and various other properties that also must remain in balance, such as electric charge. These requirements can be met most easily if the virtual photon decays into a state made up of two particles, one being the antiparticle of the other. Energy can be conserved as long as the combined mass of the pair is no greater than the total energy of the electron and the positron. Momentum is conserved if the particle and the antiparticle move apart at the same speed but in opposite directions (which need not correspond to the axis of the electron and positron beams but can have any orientation in space). Electric charge and similar quantities are also conserved.

At low energy one of the commonest decay schemes for the virtual photon results in the regeneration of another electron and positron, with the same energy as the original pair. Another possible outcome is the creation of two muons, one with a positive electric charge and the other with a negative charge. If the interaction region is surrounded by appropriate instruments, the electron pair or muon pair can be detected, with the characteristic signature of oppositely charged particles moving in opposite directions. A third possible decay sequence is of greater interest here. Provided the energy of the collision is sufficiently large, the virtual photon can decay to yield a quark and an antiquark. Significantly, however, the quark and antiquark do not, in their native state, reach the detectors. What is seen instead are two jets of hadrons, emitted back to back from the point of collision.

Any kind of hadron can appear in a jet, but pions are by far the commonest kind. At the collision energies available today a dozen or more particles can be emitted. Among them, in general, will be both positively charged and negatively charged particles as well as electrically neutral ones. Because most particle detectors rely on the ionization caused by the passage of a moving electric charge, the neutral particles escape detection in some experiments. If the neutral particles can be accounted for, however, it is always found that all conservation laws are obeyed by the complete ensemble of emitted hadrons. For example, the total charge of the hadrons is zero and so is their net momentum.

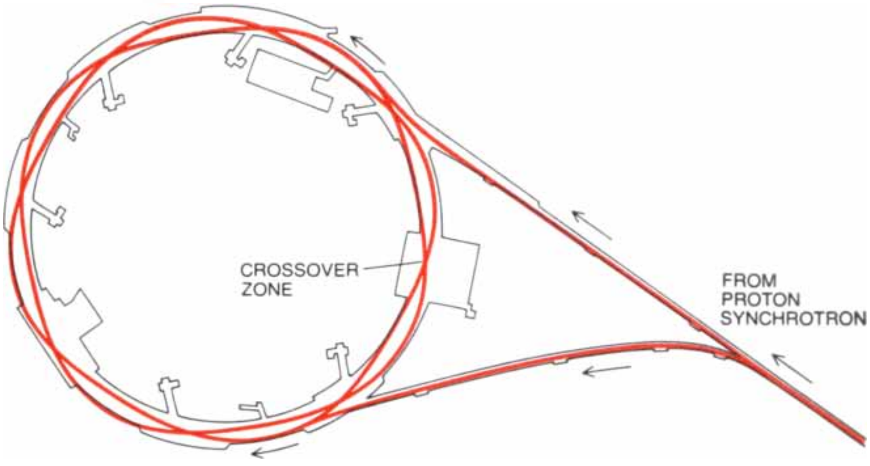
The conversion of a single quark-antiquark pair into a diverse array of hadrons is the most mysterious process in the creation of a jet. It may not be possible to describe it fully until the nature of the color charge is better understood. It is apparent that somehow the naked quark and antiquark "dress" themselves with other quark-antiquark pairs before they emerge to macroscopic distances, where they can be detected. As long as all the particles created in this process include equal quantities of matter and antimatter all conservation laws will be obeyed. Of course, there is still an energy constraint: the total mass of all the created particles cannot exceed the energy brought to the collision by the annihilated electron and positron.

The two kinds of quark that make up all the hadronic constituents of ordinary matter are designated *u* and *d*. Suppose the primordial pair created by the decay of the virtual photon consists of a *u* quark and its corresponding antiquark, which is labeled $\bar{u}$. Before these particles have separated any appreciable distance at least one more pair must be created. Suppose it is made up of a *d* quark and a $\bar{d}$ antiquark. The *u* quark can then become associated with the $\bar{d}$ antiquark, a combination that defines the structure of a positively charged pion. The remaining *d* quark and $\bar{u}$ antiquark constitute a negatively charged pion. In this case the final state would consist of just two particles, but in general there is additional pair creation, leading to a more complicated set of hadrons.

Quark pairs and muon pairs created in electron-positron annihilation seem to arise through the same process (namely through the decay of a virtual photon). It therefore seems reasonable that their average angular distribution, when it is calculated over many events, should also be the same. In testing this hypothesis we are handicapped because we cannot measure the direction taken by the quarks. It is known, however, that the set of all the hadrons descended from a given quark must conserve that quark's momentum. It is therefore possible to add up the momenta of all the hadrons in a jet in order to define the momentum vector for the jet as a whole. The direction along which this vector lies is the axis of the jet, and it should coincide with the direction of motion of the original quark. Experiments at SLAC and at DESY have compared the angular distribution of the jet axes with the distribution of muons, and they are in good agreement.

The total number of events in which muons are created and the number in which hadrons appear should also be related, and their relation should remain unchanged as the energy of the collision increases. In other words, the ratio of hadron events to muon events should approach a constant value regardless of the collision energy. The expected value of the ratio depends only on the total number of quark types and on their electric charges, and so it can be calculated directly from the quark model. Assuming that there are just the three quarks of the original Gell-Mann model, each of which comes in three colors, the predicted value of the ratio is 2. At energies below about 3 GeV that prediction is confirmed. Above 3 GeV significant numbers of charmed particles are created, so that the fourth, charmed quark must be included in the calculation. Adding the charmed quark (again in three colors) changes the predicted value to 10/3, which has also been confirmed experimentally. This remarkable accord between theory and observation has been found again on the next energy plateau, where another pair of quarks is introduced.

A jet of particles does not always look much like a jet at first glance. If the point of annihilation were surrounded by a spherical detector that would merely indicate the position of each hadron as it crossed the spherical surface, the particles making up each of the two jets might well be spread out over a wide



INTERSECTING STORAGE RINGS at CERN provide head-on collisions between protons in two counter-rotating beams. Protons supplied by a synchrotron are injected clockwise into one of the rings and counterclockwise into the other; they can then be maintained in a stable orbit for many hours. Each beam has a maximum energy of 31.5 GeV, so that the total collision energy is 63 GeV. Collisions take place in eight regions where the interlaced rings cross over.

area. The configuration of the jet becomes more coherent, however, if not only the direction but also the momentum of each particle is indicated. In general it turns out that the particles with the highest total momentum are closely aligned with the jet axis. The more widely scattered particles carry little momentum. Indeed, the jet can be defined in terms of this relation. A particle is considered to be part of a jet if the component of its momentum perpendicular to the jet axis is below a certain threshold. Under this rule a fast-moving, high-momentum particle must nearly coincide with the jet axis for it to be included, but for a slow-moving particle the direction is less critical.

The tendency for the particle momentum to be concentrated along the jet axis becomes more pronounced as the total momentum of the jet increases. This relation could be deduced from the simple observation that the number of particles in a jet increases more slowly than the total jet momentum. If the total momentum is, say, doubled, the number of particles will rise, but by a factor of less than 2. It follows that the average momentum per particle must be higher. If the perpendicular component of the momentum is not to exceed a threshold, then the momentum vectors of the particles must be more closely aligned, that is, they must bend closer to the jet axis.

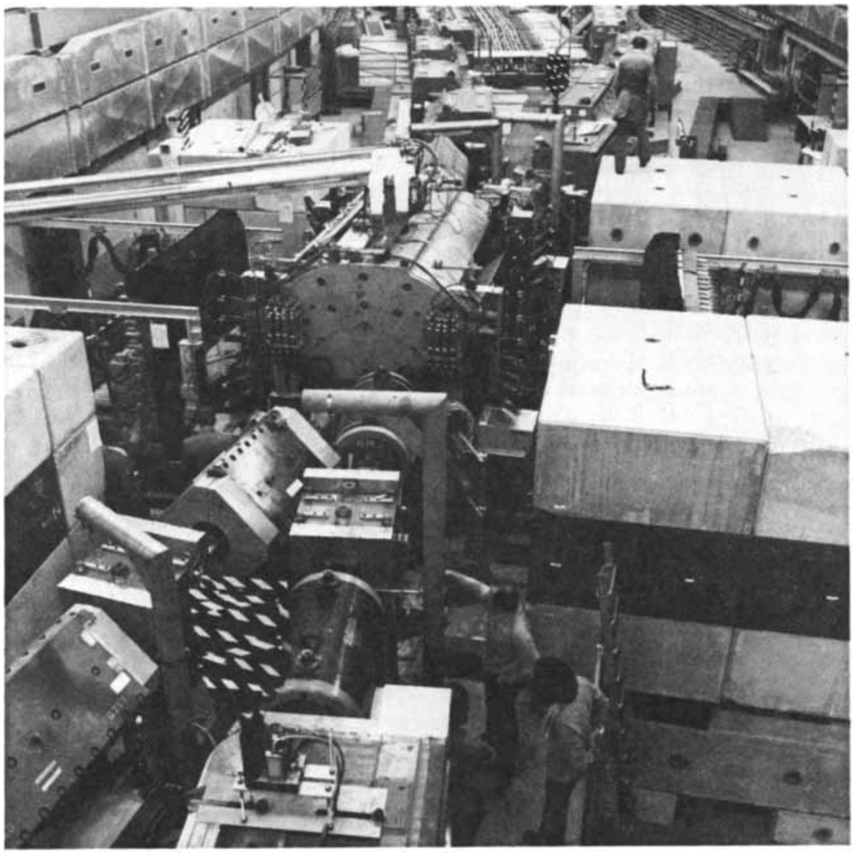
As it turns out, the average perpendicular momentum of the particles in a jet remains limited to about .3 GeV regardless of the total jet momentum. Although such a limit may seem mysteriously arbitrary, there is a plausible explanation for it: the perpendicular component of the momentum and the component parallel to the jet axis originate in different processes, which are largely independent of each other. The small, perpendicular component apparently results from interactions whose characteristic scale of length is comparable to the size of the hadron as a whole. The larger parallel component is associated with direct interactions of the pointlike quarks. This distinction becomes clearer in jets produced by proton-proton collisions, where both the quarks and the hadrons are present from the start.

So far we have been concerned mainly with experiments in which hadrons are bombarded by leptons or in which hadrons are created by the annihilation of leptons. It stands to reason that the quark structure of the hadrons should also be evident when the colliding particles are themselves hadrons. A jet of particles emerging from such a collision with high momentum transverse to the beam axis would then signal a direct, close-range interaction of two quarks. The most obvious interpretation of such events is that one constituent is expelled from each proton and subsequently gives rise to a jet of hadrons.

Precisely because hadrons have an internal structure, proton-proton experiments are more difficult to carry out and more difficult to interpret than experiments with leptons. When an electron is employed as a probe of the structure of the proton, at least the projectile is simple, apparently pointlike and well understood. A precise theory, quantum electrodynamics, describes its interactions. In proton-proton collisions both the probe and the target are complicated objects and the theory that describes them, quantum chromodynamics, is itself under test. In spite of these difficulties hadron jets in proton-proton collisions have been investigated in a long series of experiments over the past several years. In fixed-target experiments they have been studied with the large proton synchrotron at the Fermi National Accelerator Laboratory near Chicago. The most violent collisions have been observed with the ISR at CERN.

Given ideal apparatus an experiment with head-on proton collisions might not be too difficult. Detectors could be made to surround the interaction zone completely, so that every particle leaving the region would be intercepted. Every particle would be identified, including both the charged particles and the neutral ones, and their energy and momenta would be measured. What is more, every collision, no matter what its outcome, would be documented in this way, so that the interesting events could be picked out later for detailed analysis.

Real apparatus requires a number of compromises. The detector cannot encompass the entire solid angle surrounding the interaction zone and it cannot identify every particle, and so the reconstruction of events is often incomplete. Furthermore, it is not practical to record the outcome of every collision and to sort the results for interesting events after the fact. Even if the detector and the computers with which it communicates were capable of recording data at the necessary rate, years of labor would be required to sift the few hard-scattering events from the millions or billions of glancing collisions. Instead some criterion must be established for identifying a hard-scattering event as it happens. Then the detector is triggered only for those events that meet the criterion and



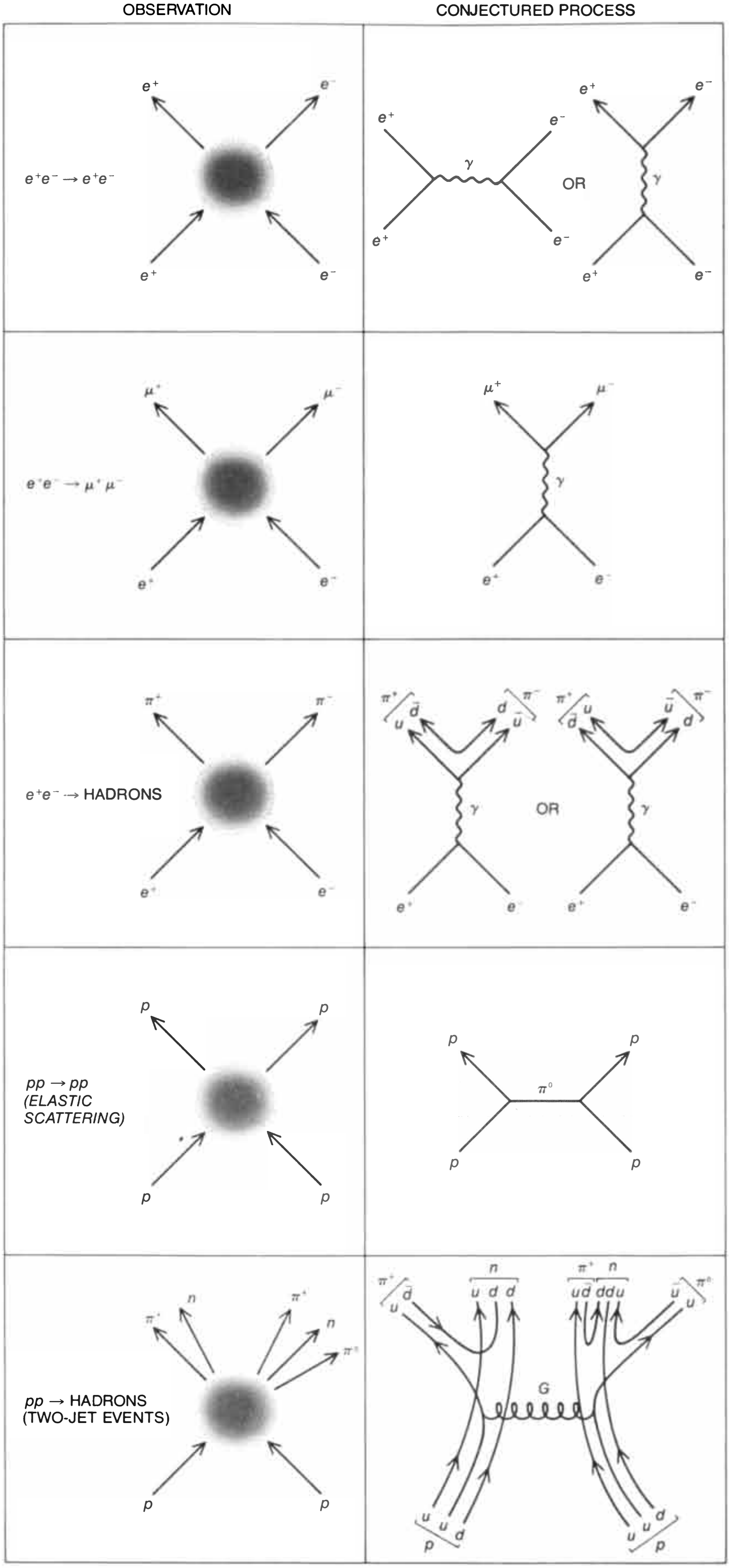
CROSSOVER ZONE at the ISR is instrumented with a large system of detectors for particles with high transverse momentum. The two proton beams circulate in pipes that are obscured by the magnets required to bend and focus the beams. The crossover itself is inside a larger magnet that makes up part of the detector system. The magnet bends the trajectories of the emitted particles so that their momentum can be measured. Electronic detectors bristle from the sides of the magnet and, at a greater distance, two large slabs of glass draped in black cloth serve as triggering detectors. Blocks of concrete and lead provide radiation shielding when the rings are operating. The experiment is being done by physicists from CERN and three universities.

all others are ignored. In most of the experiments conducted so far the triggering event has been the emergence of at least one particle with high momentum transverse to the beam axis. If the trigger threshold is set at 3.5 GeV, a few events per million are selected. Raising the threshold to 6 GeV reduces the fraction to a few per billion.

One drawback of such a triggering mechanism is that it rejects not only the glancing collisions but also a substantial number of head-on ones. If the threshold is set at 6 GeV, a jet with a total momentum of 6 GeV will be recorded only in the unlikely circumstance that all the momentum has been invested in a single particle. It is more likely that the momentum would be distributed among several particles (for example, three hadrons might have 2 GeV each), but none of these particles would be energetic enough to trigger the detector. The result is a bias in the data toward unusual events in which a single particle gets a major share of the total momentum.

Another form of trigger has recently been developed, first at Fermilab and then at CERN. It employs a type of detector called a calorimeter, which issues a triggering signal not when a single particle exceeds a certain momentum but when the total energy deposited in the calorimeter exceeds a preset value. By this means the rate at which acceptable events are recorded is increased by two or three orders of magnitude.

Although the study of jets is more



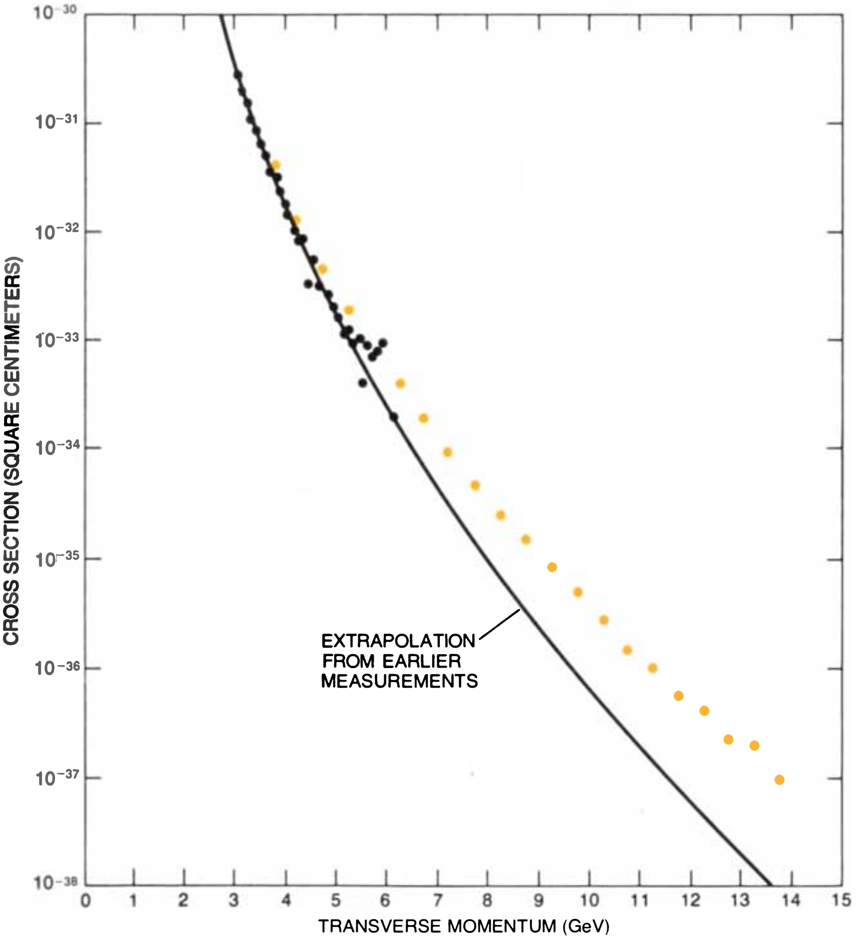
e^-	ELECTRON	n	NEUTRON
e^+	POSITRON	γ	PHOTON
$\mu^-\ \mu^+$	MUONS	$u\ d$	QUARKS
$\pi^-\ \pi^+\ \pi^0$	PIONS	$\bar{u}\ \bar{d}$	ANTIQUARKS
p	PROTON	G	GLUON

VIRTUAL PARTICLES serve as intermediaries between scattered quarks and other particles. Because virtual particles cannot survive long enough or travel far enough to be detected, their role must be deduced from the products of the interaction observed at long range. When an electron and a positron collide (*a*), they can merely bounce apart by exchanging a virtual photon. Alternatively the electron and the positron can annihilate each other, yielding a virtual photon that can then decay into a new electron-positron pair or into a positive and a negative muon (*b*). The virtual photon can also yield a quark and an antiquark (*c*), but unlike the electrons and the muons the quarks are never observed at long range. What are seen instead are pions or other hadrons; somehow the quark and the antiquark "dress" themselves in other quark-antiquark pairs. Collisions between protons are also mediated by virtual particles. If the collision is a glancing one (*d*), the exchanged particle might be a virtual pion. In hard-scattering events, however, the quarks themselves rather than the proton as a whole interact, and the quantum exchanged is called a gluon. Again pairs of quarks and antiquarks are created, giving rise to jets of hadrons (*e*). Symbols for the particles are identified in the key above.

straightforward in electron-positron annihilations than it is in hadron collisions, it is important that both kinds of experiment be carried out. In the first place there is great interest in cataloguing the similarities and differences between the jets produced by these very different reactions. The hadron collisions are of special interest because they provide a direct view of the interactions between quarks and gluons. For now the electron-positron storage rings yield jets of higher energy, but that lead should soon pass to experiments in which protons and antiprotons are brought into collision at energies roughly 10 times greater than those of the proton-proton collisions at the ISR.

Even after a high-transverse-momentum jet has been detected in the wake of a proton-proton collision it is not an easy matter to reconstruct the events that gave rise to the jet. The interaction itself is much more complicated than that of an electron and a positron. More particles are generally emitted: an average of about 16 at the highest energies employed with the ISR. The two jets do not necessarily appear back to back, even in the frame of reference defined by the center of mass of the two colliding protons. The reason is that the quarks are able to move almost independently inside the proton, and so a given quark does not carry a fixed, or even a predictable, fraction of the proton's total momentum.

The most disturbing influence on the interpretation of the proton-proton data is that the production of a transverse jet is not the only process going on in the collision. When an electron and a positron come together, the collision is either glancing or hard; when two protons collide, on the other hand, the collision can be both things at once! Glancing collisions are of course the commonest type. They result from interactions that involve only the diffuse, large-scale structure of the proton, and they give rise to particles whose momentum deviates little from that of the original, colliding particles. In other words, they give rise to longitudinal jets, which remain in close alignment with the beam axis. Hard-scattering events are thought to result from the direct collision of a quark in one proton with a quark in the other proton; a gluon may also collide with another gluon or with a quark. When quarks or gluons collide, however, the more diffuse parts of the protons still interact. As a result the transverse jets appear in addition to the longitudinal ones rather than instead of them. It is not always easy to decide which process gave rise to a given scattered particle.



ENHANCED PRODUCTION of high-transverse-momentum particles has been found in recent experiments at the ISR to continue increasing at still larger values of transverse momentum. The earlier results are shown in black; the new data, in color, depart significantly from the rate of production extrapolated from the measurements at lower transverse momentum. The further anomaly could indicate that hard-scattering of quarks and gluons has become the dominant component of the proton-proton interaction. The data were recorded with the detector shown on page 72. The effect has been observed by two other groups working at the ISR.

At the lower collision energies and the lower transverse momenta prevalent until a few years ago, the existence of jets could be demonstrated only by a statistical technique: by analyzing the correlations of hadrons appearing on opposite sides of the beam axis. With higher energies and with detector triggers set at higher momenta the analysis has become much simpler. It is possible to see a jet merely by looking at a diagram of the event. There is certainly no longer any doubt that transverse jets exist, both in electron-positron annihilations and in proton-proton collisions.

Analysis of the transverse jets observed at the ISR suggests that quark collisions have a number of similarities to lepton collisions. For the particles that make up the transverse jets (but not for those in the longitudinal jets) the allocation of momentum to components parallel to the jet axis and perpendicular to it is similar in lepton and in proton collisions. This finding suggests that the process whereby separated quarks dress themselves in quark-antiquark pairs may be the same in the two kinds of experiment. Further work will be needed, however, to confirm this conjecture.

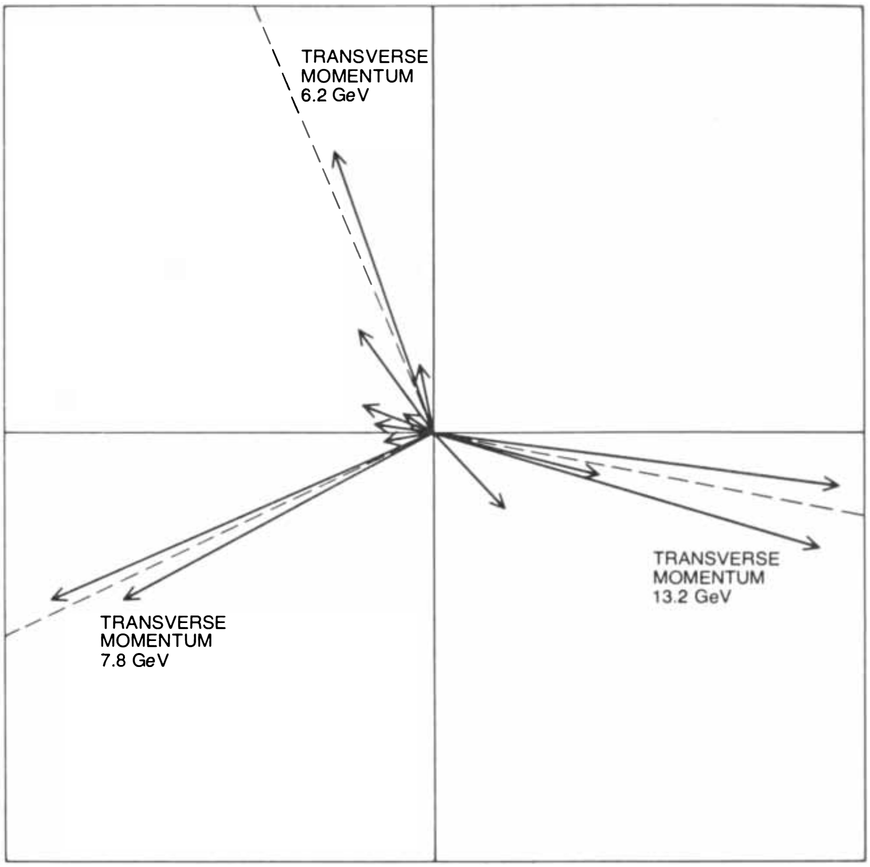
The findings of the several experimental groups at the ISR have already provided strong evidence supporting a much earlier conjecture, called Feynman scaling (after Richard Feynman). The scaling hypothesis holds that on the average each hadron in a transverse jet should carry a fixed proportion of the total jet momentum (rather than a fixed quantity of momentum) as the total jet momentum increases. Thus the basic form of the jet and the way it breaks up into fragments should not vary with the momentum.

Now that hadron jets are well established, it is the nature of the constituents that give rise to the jets and the theory needed to describe those constituents that have become the focus of interest and controversy. Among theorists there is some disagreement over whether the results of the proton-proton experiments are in accord with the predictions of quantum chromodynamics.

It seems fair to say that the events seen so far are not in exact agreement with any detailed calculations that can be done today in quantum chromodynamics. The discrepancy may result, however, not from a defect in the theory but from the limitations of available mathematical procedures. The strong forces that operate between quarks make it difficult to calculate exactly the behavior of a quark in many circumstances, even though that behavior is determined in principle by the theory. Detailed calculations are practical only in the special case of quarks that are very close together, where the color forces become weak. Collisions in which jets are emitted with high transverse momentum probe the quark structure at close range, but it remains to be seen whether the range achieved so far is small enough to be described by the theory.

In essence the experimental results observed up to now are more complicated than would be expected for the simplest possible interactions of pointlike constituents. Some theorists think nonetheless that the events represent collisions of individual quarks and gluons and that the form of the jets will become simpler when events are observed at higher transverse momentum. Other theorists have suggested that the departures from theory have a more fundamental cause and that the jets observed so far reflect interactions of some more extended structures inside the proton, such as a bound system of a quark and an antiquark.

Where the two factions are in agreement is in their confidence that the form of the jets will become simpler at higher transverse momentum. Hints of such a simplification have already been observed in recent proton-proton experiments at the ISR, where the maximum transverse momentum has been pushed up to almost 14 GeV. For pions of the highest transverse momentum (greater than 6 GeV) the production rate was found to be enhanced slightly over the rate extrapolated from earlier results. This finding is consistent with the theoretical model in which the scattering of individual quarks and gluons obeys quantum chromodynamics in its simplest form.



THREE-JET EVENT was observed in electron-positron collisions at the PETRA storage ring near Hamburg. Two of the jets consist of five detected particles; the third has six tracks. Broken lines indicate the axes of the jets, defined by the average momentum of the detected particles. Like the two-jet events, the trijets are thought to originate with the creation of a quark and an antiquark. One of these particles then emits a real gluon, which decays to yield another quark-antiquark pair and hence another jet of hadrons. The event was recorded by physicists operating the TASSO detector; other groups at PETRA have also observed trijets.

The ultimate test of quantum chromodynamics will require experiments with jets of still higher transverse momentum; producing those jets will in turn require particle beams of still higher energy. New storage rings being planned or built now will provide the more energetic beams. At both CERN and Fermilab plans have been made to store counter-rotating beams of protons and antiprotons, with energies of from 250 GeV to 1,000 GeV, in large synchrotrons. A set of interlaced rings for proton-proton collisions, similar to the ISR in design but larger in scale, is under construction at the Brookhaven National Laboratory; it will have a maximum center-of-mass energy of 800 GeV, more than 10 times that of the ISR. A still grander project being considered in Europe is an electron-positron storage ring, to be called LEP, with a circumference of some 30 kilometers and a maximum center-of-mass energy of about 200 GeV.

In the meantime the PETRA storage ring commissioned last year at the DESY center has turned up the first few specimens of a new kind of hadron jet. Four groups of experimenters at PETRA, each working independently and with a different system of detectors, have observed electron-positron annihilations that give rise to three jets instead of the usual two. Quantum chromodynamics offers a possible explanation of such trijets. As in other lepton-induced events, a virtual photon decays to yield a quark and an antiquark, but one of these particles reduces its energy by spontaneously emitting a real gluon. The three particles then continue to separate, and each of them acquires its own escort of quarks and antiquarks, eventually forming a jet of hadrons.

In the 1950's the hope was that higher energy would make the physics of strong interactions simple. All the complicating effects that can now be attributed to the finite size of the hadrons would fall away, and the strong force would be as easily comprehended as electromagnetism. In terms of the objectives of the 1950's higher energy is here now, but the great simplification has not arrived in the way that was expected. It is only in those collisions where a large quantity of momentum is transferred from one particle to another that simplicity has emerged. These are also the collisions in which the structure of matter is probed at the smallest distances. Further progress will require still higher energies.

In the pursuit of this receding horizon, however, much has already been learned about the interactions, however complicated they may be, observed at energies accessible today. A new level in the structure of matter has been discovered. Hadron jets, together with other phenomena, have made us rich in experimental data. Quantum chromodynamics, even if it is only a theory in the making, has added a wealth of testable predictions. Enthusiasm runs high at the prospect that the two lines of work may soon converge.

Eburacum, Jorvik, York

These three names refer to the same city of northern England through Roman, Viking, medieval and modern times. A major archaeological campaign is uncovering material evidence of its 2,000-year history

by Peter V. Addyman

The city of York, witness to 2,000 years of British history, is a repository of that history in the form of archaeological strata as much as nine meters deep. This wealth of material evidence is the result of two accidents, one geological and one economic. The geological accident is that the settlement which became the city was built on impervious glacial clays, so that a few inches down the soil is permanently wet, oxygen-poor and acid. This combination of conditions acts as an excellent medium of preservation for perishable organic materials such as wood, leather and cloth and metallic materials such as bronze and iron. The economic accident is that the fortunes of the city have declined in recent centuries, with the result that the remains of hundreds of buildings of many ages have survived, undisturbed by the digging of foundations and basements that has destroyed the archaeological record in other cities of ancient origin.

Preserved under the city is a record of its development since the year of its founding in A.D. 71 as a strongpoint for the Roman Ninth Legion, commanded by Petillius Cerealis. The principal remains at York can be assigned to the Roman period and later ones as follows.

Over some 350 years of Roman rule the 50-acre legionary fortress, initially built of timber and earth, was rebuilt in stone and later reorganized several times. The garrison town that grew up around the fortress walls was called Eburacum. Early in the third century A.D. the town was rebuilt on a new site, across the River Ouse from the north bank where the fortress stood. When the Roman province of Britain was divided in two at the end of the second century, the new town was named the capital of Lower Britain; by the fourth century it had become the seat of one of Britain's first bishops, who is known to have crossed the English Channel in A.D. 314 to attend a church council at Arles.

The period of Roman withdrawal from Britain in about A.D. 400 coincides with a generally impoverished chapter in the archaeological record of York. The buried history recommences, so to speak, when the town and its surroundings emerged as the Anglian kingdom of Deira in A.D. 560–80. By the end of the sixth century this pagan realm had grown and was known as Northumbria. In 627 its ruler, Edwin, was converted to Christianity and was baptized in the town on Easter Day. A century later the town was made an archbishopric, one of only two in all England.

In 866, a century and a half later, the town was captured by the Great Army, a Viking force that had harried France and the Lowlands for decades. A part of the Great Army decided to settle there, and by A.D. 876 the town was renamed Jorvik. The Anglo-Scandinavian town, a community of craftsmen and traders, flourished under Scandinavian kings and later under English earls for almost two centuries. Then in the year following the Norman victory at Hastings it felt the hand of new masters. A Norman castle, built at the confluence of the Ouse and the River Foss, dominated the town's defenses. The Normans also rebuilt the cathedral in a new location: within the bounds of the original Roman fortress, where it stands today.

Thereafter the town grew steadily, reaching its medieval apogee in the 13th and 14th centuries. Notable among the great buildings added in this period was the College of the Vicars Choral in 1252. The archaeological record continued to accumulate with each succeeding century, so that today evidence is found of events as recent as the 1644 siege of the city in the Civil War.

The city of York now has a major program of urban redevelopment of the kind that has obliterated the archaeology of other early urban sites in Britain. As a result for the past eight years a large team of rescue archaeologists has been at work under the sponsorship of a specially formed charity, the York Archaeological Trust. It is my purpose here, as director of excavation and research for the York Trust, to outline its program and objectives and to describe what has been accomplished so far in salvaging the buried record of the city's long past.

Our research program has several aims. The first is to determine the pattern of land use in the area before the first settlement was established and to reconstruct the preurban topography of the settlement site itself. Because the Roman fortress and its garrison town are heritages that still influence the modern city plan, our second aim is to determine both the original Roman plan and the steps whereby the city grew to its present size and character.

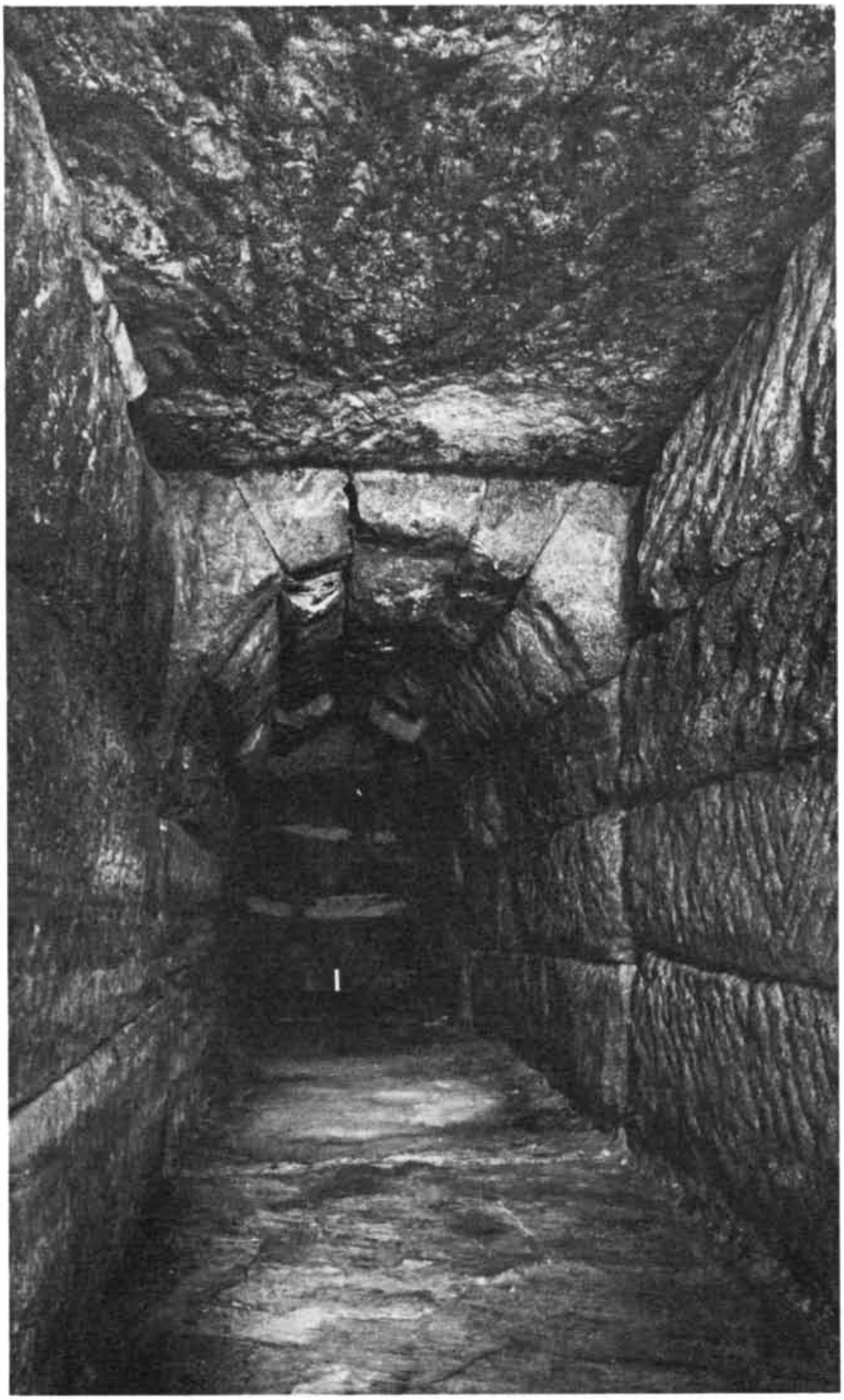
The city's soil holds such an abundance of archaeological evidence that our research program has to be very selective. As a minimum we have decided that when any building of a unique character in the various periods of the city's past is threatened with destruction, it will be excavated. The Roman amphitheater would be one such building, if it is ever found. The York Trust also aims to excavate, as opportunities present themselves, a representative series of commoner buildings: temples, shops and warehouses in the Roman town, churches and wharves of the Viking period and guildhalls, colleges, friaries and hospitals in the medieval city.

Beyond this a few extensive excavations will be undertaken in areas representative of entire districts in the past: part of the Roman garrison town, part of a street at the heart of the Viking capital and three or four blocks that should illustrate different aspects of

CORE OF HISTORIC YORK is defined by the confluence of the River Ouse, at left, and the River Foss, a smaller meandering stream, at the bottom of the vertical aerial photograph on the opposite page. York Minster, the cathedral built by the Normans within the old Roman fortification, is the cruciform building at the center. Clifford's Tower, just above the medieval castle near the rivers' confluence, and Old Baile, a similar structure on the west bank of the Ouse, are the two Norman fortifications that overlooked Anglo-Scandinavian York in 1068.

the life of the medieval city. Running through the entire program are the additional objectives of showing the impact of urban man on his environment, the environmental conditions in the city throughout its history, man's exploitation of the natural and man-made resources of a continually expanding hinterland and man's dependence on trade to supply the needs of what must surely have seemed in Roman, in Anglo-Scandinavian and in medieval times to be a large and exceptional city.

In the eight years since we started our work England has happened to have several exceptionally dry summers. Aerial photography during the dry spells has revealed numerous markings in patterns of crop growth on the glacial ridges that run across the low-lying Vale of York near the city. These markings where disturbed soil underlies plowed ground have revealed long-vanished ditches, the foundations of ancient farms, the patterns of field systems and the lines of ancient paths and roads. Some of these traces of human activity may belong to the Roman period. Many, however, are older and indicate that the legionary fortress was set down in a mature inhabited landscape.



ROMAN MASONRY, complete with its supporting arch, lined the sewer that drained the great legionary bath building within the fortress at York. The debris collected in the excavation of the sewer included pollens that identify the source of the water supply for the bath.

Although no traces of pre-Roman occupation have yet been found within the bounds of the city itself, it is likely that some exist. This is both because such traces are ubiquitous in the surrounding area and because the Roman settlement was at the natural crossing point of the Ouse: on the spur of land between the river and its tributary the Foss, where the two streams had cut through the glacial ridges.

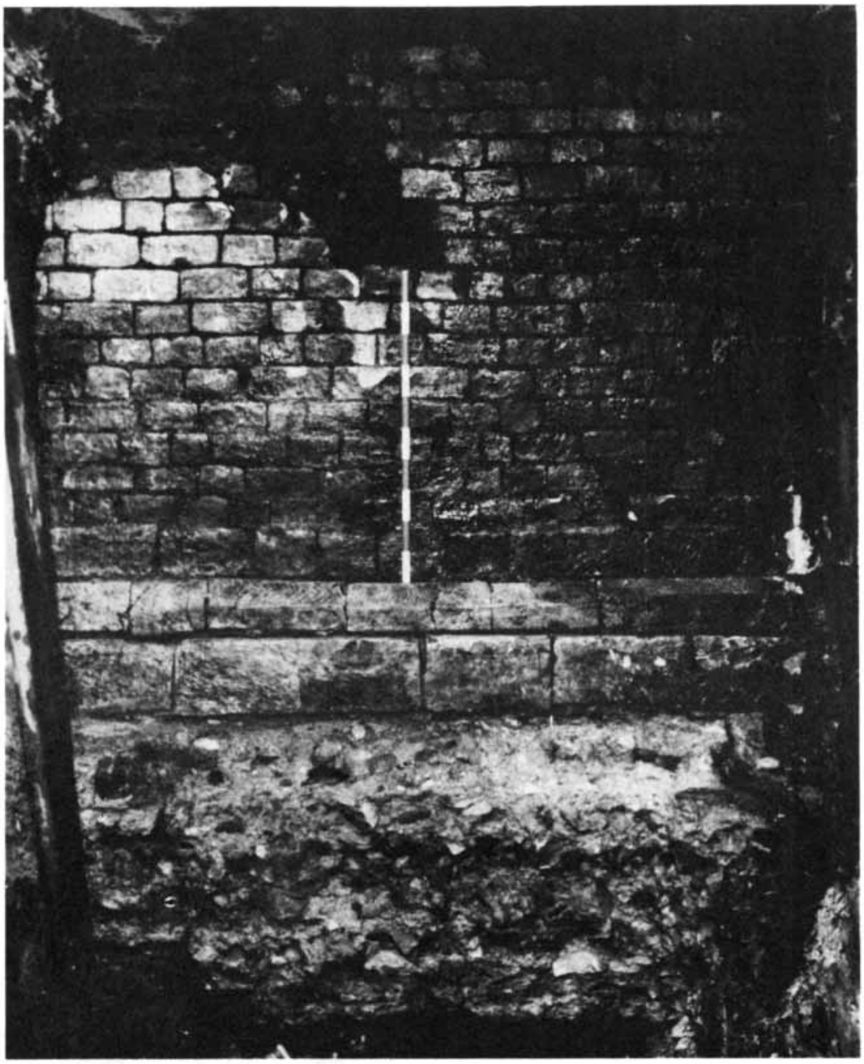
The location of the fortress chose itself. The correlation of data from commercial boreholes, from trenches dug for the laying of pipe and from our own excavations shows that what is now a relatively level city center was once a plateau with steep scarps running down to the two rivers. The Romans placed their fortress on that plateau. The military base had not only its natural defenses but also a natural overland link with the rest of Yorkshire by way of the glacial ridges crossing the Vale of York and by way of the navigable Ouse, which gave access to the sea some 50 miles to the east.

Some of the defenses of the Roman fortress remain aboveground; the best-known is a fourth-century multiangled tower at the west corner. Elsewhere the defenses, although well preserved, are buried deep below the debris of later ages. One objective of our excavation has been to reexamine the defensive system. Close study of commercial excavations has helped toward this end. For example, one deep sewer trench in the city center exposed a section of the masonry fortress wall that still stood 16 courses high above a finely chiseled plinth supported by deep mortar-and-cobble foundations and a substructure of squared oak pilings.

We cut a trench elsewhere across this line of wall at a point where the original fortress earthworks were well preserved. It was possible to trace the timber strapwork that supported the piled earth, the root-filled turf cuttings used to strengthen the ramparts and the stonework with which these were resurfaced, perhaps during the reign of the emperor Trajan. At another point we examined the ditch systems that flanked the fortress walls. We uncovered the remains of a timber defensive tower and its monumental fourth-century masonry replacement, a projecting multiangled tower. Also uncovered were certain of the civilian buildings and streets that lay outside the Roman defenses at various periods.

Several opportunities to excavate within the fortress have arisen in recent years. Its buildings seem to have been at first constructed of timber and then rebuilt in stone, on a new layout but within the same defense line, early in the second century. The site was already a permanent base by the time the Ninth Legion was withdrawn from Britain in about A.D. 110. The Ninth Legion was replaced by the Sixth, which had garrisoned and helped to build the Roman northern defense: Hadrian's Wall.

Parts of the fortress barracks have been investigated along with a section of one of the houses provided for the five military tribunes, important legionary officers. A complex tunneling operation has also exposed the monumental Roman sewer system that served the great legionary baths. In addition to revealing the sophisticated engineering of the Roman system, the York Trust team recovered a series of artifacts eloquent of life in the fortress: glass bottles for the oil with which the bathers anointed themselves, gold amulets lost by the bathers and gaming counters that are evidence of the social function of the baths. Organic remains from the sewer include beetles and other insects, seeds and pollen. They indicate the purposes served by adjacent buildings, the environment of the fortress and even the source of supply for the water of the baths. The excavation suggests that the great bath building itself must have covered a square block measuring some 85 meters on a side.



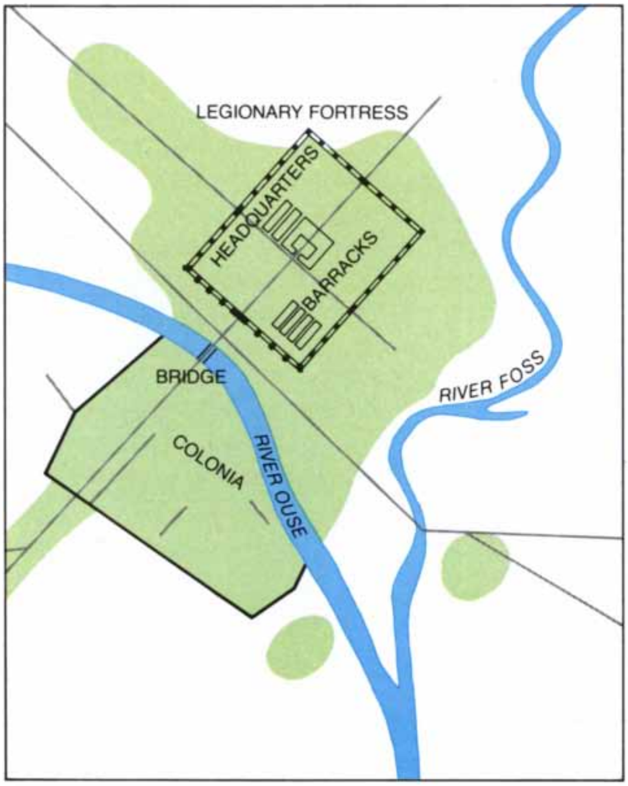
FORTRESS WALL, standing 16 masonry courses high above a chiseled plinth that is supported by a mortar-and-cobble foundation resting on oak piles, is another relic of Roman York uncovered by chance during commercial excavation for a deep sewer in the center of the city.

Two excavations have been made in the civilian settlement outside the fortress walls and a third is about to begin. In one area small-scale industry had grown up along blocks defined by a street system that became established soon after construction of the fortress itself. The industries seem to have been both official and unofficial. In the first category were pottery and tile making. The kilns produced stamped tiles for the Ninth Legion and pottery characteristic of that found here and in other British legionary fortresses in the first and second centuries. (The York variant is now known as Eburacum ware.) By the third century a highly unofficial industry also existed: the counterfeiting of denarii, Roman silver coins, for which we found a variety of casting molds.

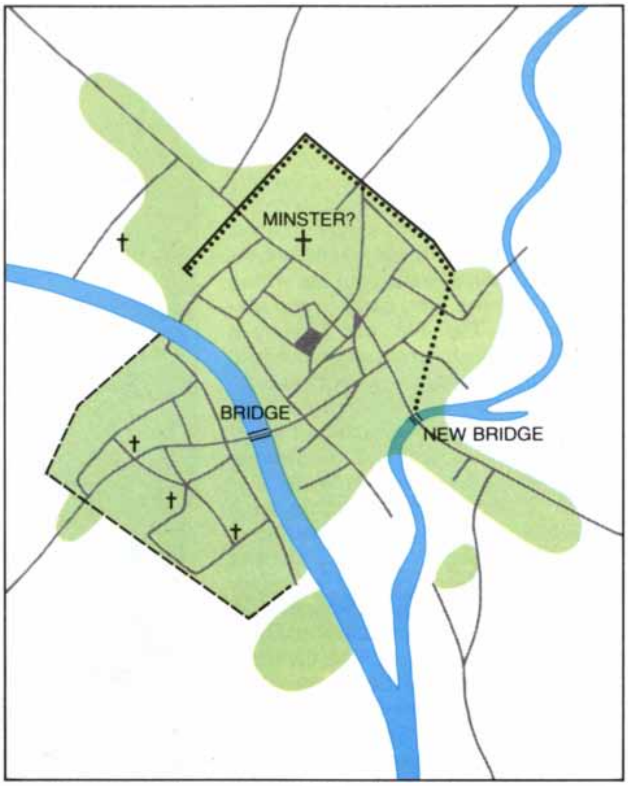
In another area, by the banks of the Ouse, we have uncovered warehouses that were already in service by A.D. 75, doubtless housing supplies for the Ninth Legion. Here we found evidence of their use for grain storage and also of a disaster that soon struck one of them. In the older of the two warehouses we excavated we found no evidence of grain but we did uncover a thick layer of carbonized grain beetles, millions of them per square meter. The structure had clearly burned down. Its ruins were then buried under a layer of clay, and a similar warehouse was built over them. The second warehouse contained few grain beetles and ample evidence of grain storage, including some grain of nonlocal origin (indicated by the weed seeds it contained). Evidently a massive infestation of grain beetles had been dealt with by the deliberate burning of the first building. The reconstruction of this dramatic story exemplifies the usefulness of two fast-growing archaeological disciplines: paleoentomology and paleobotany.

The York Trust has selected two areas of the later Roman town for excavation. In one area the development of riverside roads was investigated. The roads were established late in the first century or early in the second century on land that had recently been cleared of brush by the simple slash-and-burn method. Interestingly, the land showed little sign of the flooding that nowadays affects central York almost every year. The modern flooding problem may therefore stem almost entirely from later works of man that have narrowed the river valley and increased the rate of upstream runoff by deforestation and "improvements" to drainage. Near the riverside roads and on the natural river terrace above them stood the fine residences of the Roman capital. Parts of several have now been excavated.

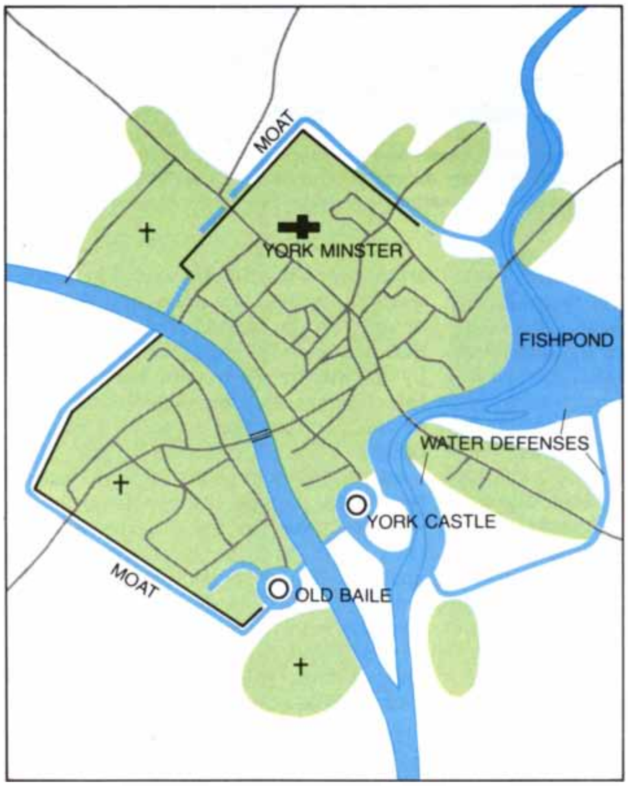
A feature of one of these houses was a sophisticated water supply. A deep well had been sunk; its shaft was supported by elaborate shoring as a square timber lining was inserted. The lining was stepped inward near the base to provide



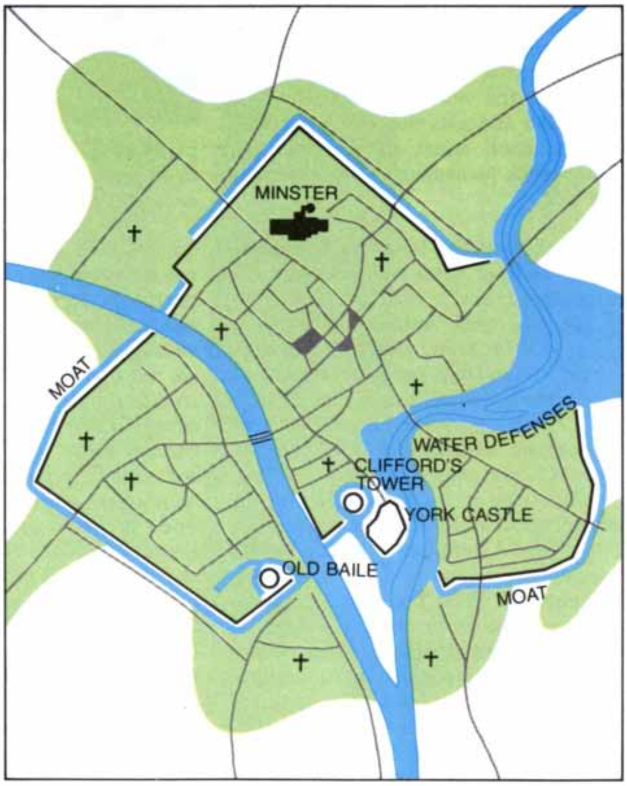
ROMAN YORK consisted of a rectangular fortress, enclosing 50 acres, on a natural plateau between the Ouse and the Foss. The civilian settlement, Eburacum, once clustered around the fortress walls but then was relocated across the Ouse early in the third century.



VIKING YORK, as it may have appeared in the 11th century, was still largely confined within the old Roman lines. Street grid is conjectural. Excavations of workshops in the heart of Jorvik, as the Vikings called the town, suggest that it was a smelly but lively place.



NORMAN YORK was dominated by two castles on opposite sides of the Ouse: Old Baile and York Castle, now known as Clifford's Tower. The Normans also built the cathedral church, York Minster, on the site within the old Roman fortress that it occupies to this day.



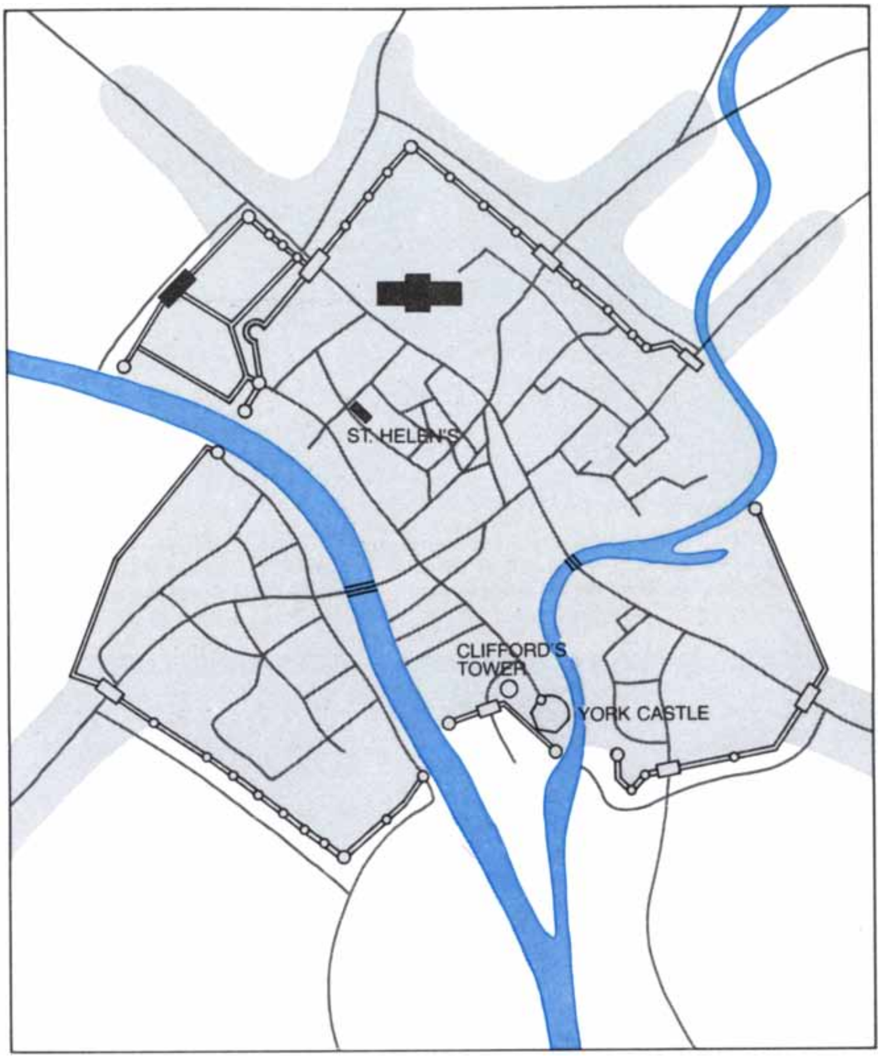
MEDIEVAL YORK was the largest and most prosperous city of all; it reached its apogee, second in rank only to London, in the 13th and 14th centuries. The Minster was enlarged, a new York Castle was constructed and a moated perimeter wall was added on the southeast.

an efficient means of rapidly refilling the well. The lining had braced corners near the top to give horizontal stability and perhaps also to provide access by ladder for cleaning. A variety of normally perishable objects, for example leather shoes, had fallen into the well, which was probably filled in during the fourth century. They were preserved in the waterlogged fill.

Perhaps the most important find, some nine meters below the ground level today, were several specimens of the black rat, *Rattus rattus.* This species is notorious as a carrier of the primary vector of the bubonic plague: the flea *Xenopsylla cheopsis.* Black rats had not heretofore been recorded in England earlier than the later Middle Ages. Doubtless these specimens came ashore from some ship of Mediterranean origin that had called at the late Roman town.

The town houses of the civilian community flourished to the end of the Roman period. The York Trust's excavations have revealed buildings with mosaic floors, elaborately painted plasterwork and fine contents, along with evidence that additions were being made to the structures late in the fourth century. It was a time when the town may well have been not only the provincial administrative headquarters but also headquarters for the Dux Britanniarum himself, the supreme commander charged with the defense of Roman Britain. It is therefore surprising that so little has been found, either in our excavations or in the century of earlier investigations at York, indicating occupation in the period immediately afterward: the fifth and sixth centuries. There were communities of Germanic settlers nearby, as the discovery of their cemeteries demonstrates, but evidently no large population remained in the town.

The new techniques of environmental archaeology are beginning to confirm that this period was a low ebb in the town's history. The findings hint at an ecology of the kind one might expect in decaying buildings, streets covered with weeds and little in the way of urban activity. Such evidence of occupation as there is bespeaks breakdown: thick layers of dirt and rubbish overlying formerly well-kept Roman streets, and squatter occupation of dwellings, with rough hearths cut into the Roman floor mosaics. Even so, some buildings were kept in good repair. Evidently the legionary headquarters building collapsed only in the ninth or the 10th century, and it is conceivable that the town at this period was the administrative center of a British kingdom, perhaps maintained at first by Germanic mercenaries, that eventually served as the nucleus for the Germanic successors who formed the Anglian kingdom of Deira and eventually Northumbria.

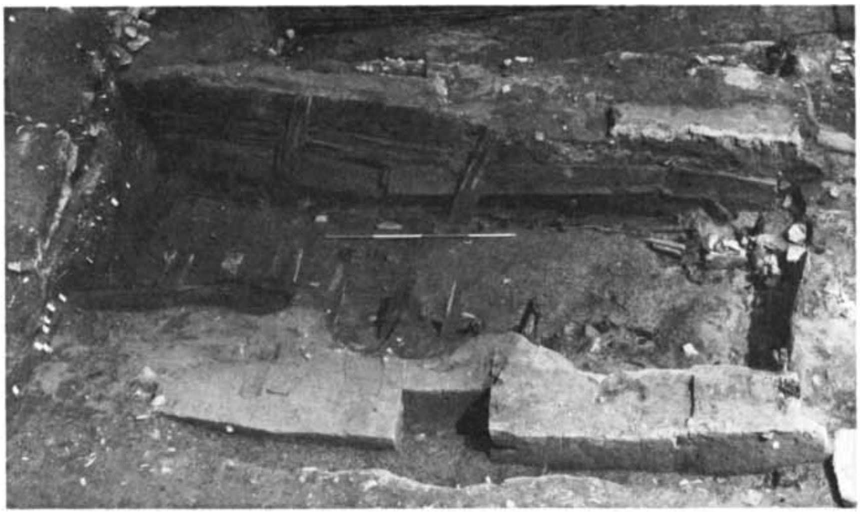


SEVENTEENTH-CENTURY YORK was a city in decline. It was heavily defended, as is indicated by this moat-and-wall plan taken from John Speed's map of 1611. In the Civil War the city was besieged by Cromwellian troops early in 1644 and finally surrendered in July. The absence of much industrial and commercial development in the 18th and 19th centuries has preserved many aspects of the city's earlier history from obliteration during urban renewal.

The town was certainly playing such a role by the seventh century. It was here that the missionary Paulinus found and converted the Northumbrian king, Edwin, here that Edwin was baptized in 627 in a "little wooden church dedicated to St. Peter," here that the refounded church flourished until in 735 it became an archbishopric, as it is today. Alcuin, an eighth-century alumnus of the town's cathedral school and a scholar at Charlemagne's court in Aachen, wrote a poem of praise that described the town as one of fine buildings, many Roman in origin, and of great churches. By implication the town was populous and rich, as numerous archaeological finds in the past century have indicated. Alcuin also bemoaned early raids by the Vikings, but the town seems not to have suffered from them.

The town was nonetheless the key to northern England, and when Viking aims changed from raiding to conquest, it was to here that the Great Army turned. In a well-documented attack the town was captured in 866. In 876 the Danish warriors decided to settle in Northumbria. They called their colony "the kingdom dependent on Jorvik." Archaeological confirmation of the Viking takeover comes from the large number of coins dating to about 866 that have been found in coin hoards in the city over the past century.

Evidence of the Viking's exploitation of their great prize has been seen increasingly in the excavations of recent years. The walls of the town were built higher and were topped by timber palisades that may have extended along them for several kilometers. Apparently by this time the decayed Roman bridge across the Ouse had been replaced by one at a different place, and a new town street plan had formed around the roads leading to the new bridge. York streets still bear names of Scandinavian origin,



WORKSHOP IN VIKING YORK is one of several excavated along Coppergate, as the woodworkers' street was called. The wet subsoil has preserved the 1,000-year-old timber walls of the shop by saturation. Here the excavators found lathe-turned wood bowls and waste cores.

ADJACENT VIKING STRUCTURES of the ninth century were separated from each other by wattle-and-timber fences. The trace of one such fence lies midway between the structure at the bottom and the structure at the center. These fence lines lie deep under the lines of modern walls, evidence that modern property patterns are artifacts of Anglo-Scandinavian York.

many with the suffix "gate," from the Old Norse *gata,* meaning path or street. The new plan meant that the business center of the town shifted downstream nearer the confluence of the two rivers, perhaps to take advantage of the good wharfage facilities. For modern archaeology the move was a blessing: it took the town into wet areas where the conditions for preservation were excellent. It is therefore in this part of York that the York Trust's recent efforts have been concentrated. Here for the first time in England a large part of a Viking town has been exposed.

The initiative for the work came after some nine meters of archaeological deposits were encountered as a city bank began constructing new vaults under its splendid 18th-century premises. In the course of the excavation the York Trust recovered 10 successive timber buildings of the Viking age: the Anglo-Scandinavian period, to use the archaeological terminology employed at York. The occupants of each building seem to have been engaged in leatherworking, either tanning leather, making shoes and garments or simply cobbling, that is, mending shoes. The presence of seeds, other plant remains and insects vividly demonstrates the conditions under which the craftsmen worked: damp, smelly, fly-ridden and rubbish-laden. It is a picture that corroborates one contemporary description of the town: a "dank demesne."

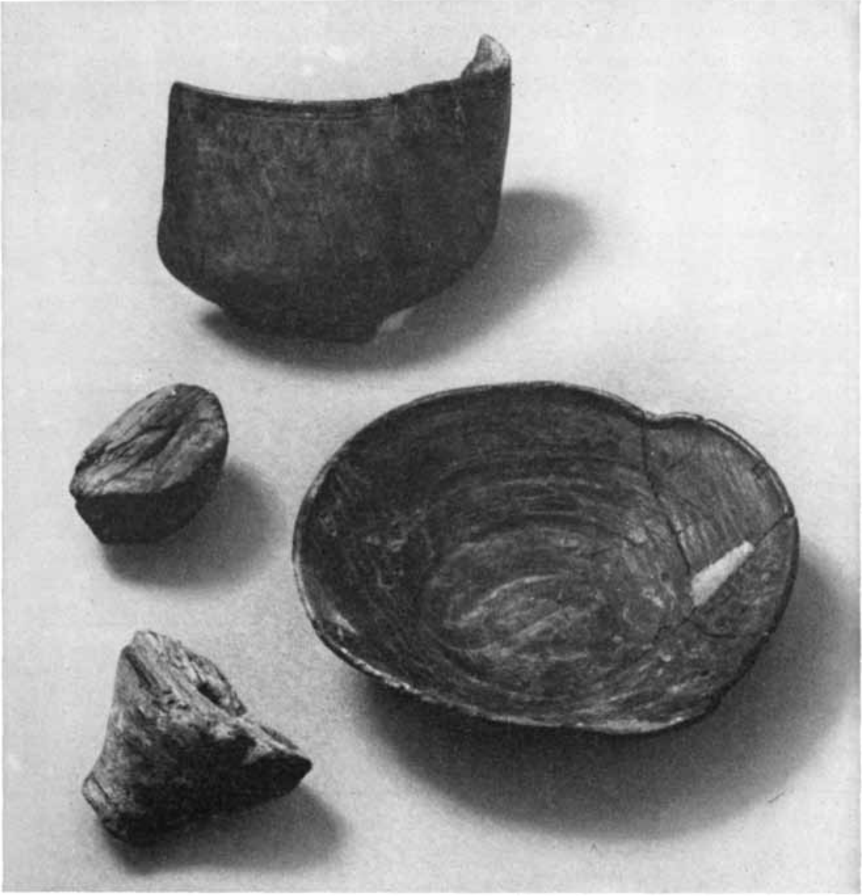
York is now preparing a major development scheme for a four-acre area not a stone's throw from the site of the bank-vault excavation. Over the past four years the York Trust has been excavating half an acre of this huge and archaeologically vital area before new building destroys it. Our salvage work has taken place in what is called Coppergate: the Scandinavian name for street of the coopers, or woodworkers. Here we have excavated four of the long, narrow properties that ran back from the ancient street front in this part of the town. The modern properties prove to follow the lines of plots laid out 1,000 years ago. The excavation has exposed the wattle-and-timber fences of Viking age that lay deep under the lines of modern walls. With this knowledge we are able to interpret other isolated stretches of fence, noted in commercial excavations on nearby properties, as evidence that a large part of the property pattern in modern York is an artifact of the Viking period: a fossil record of the ancient town plan.

Within the properties excavated in Coppergate were timber buildings, set gable end to the street and built back down the slope from Coppergate to the banks of the nearby River Foss. Several of these buildings were partially sunk into the sloping ground, like half cellars. This had ensured the survival of their timbers in excellent condition. We found the walls, made of horizontal planks set behind squared oak posts, preserved to a height of 1.7 meters. Also well-preserved were the internal fittings, including doorways, plank-lined drains and (in the buildings on the street front) hearths. Evidently there was a difference in function between the street-front buildings and the buildings back of them. The front buildings may have been shops and living quarters; the back ones seem more likely to have been workshops. One of the back buildings was filled with wood chips and shavings and the discarded cores of wood bowls and cups turned on a pole lathe. Woodworking tools too were evidence of the profession that gave its name to the street.

The neighboring property may have accommodated jewelers; it yielded much amber and jet in the form of finished articles such as pendants and beads and of unworked materials and by-products. One jeweler seems also to have been a die-cutter in the employ of coinmakers. This is suggested by a strip of lead that bears trial strikings from fresh obverse and reverse dies of a coin of the English king Edwig minted by the moneyer Frothric. The dies were cut between 955 and 959.

These excavations and others in the center of York show that a multiplicity of trades and crafts were pursued in the Anglo-Scandinavian town. Workers in bone and antler produced pins and composite combs of the hog-backed Viking type; we found some of them still in their case. Glassworking was another activity, mainly for the production of beads and rings. Other craftsmen worked in iron, bronze and lead. Brooches made of lead alloy seem to have been a popular product in the town's markets. Our recovery of the mold for a fine trefoil brooch demonstrates that local craftsmen also made cast bronzes of the Scandinavian type.

Jorvik therefore emerges from the excavations as a large town of tightly packed wood buildings, with craftsmen of all kinds turning out the requirements not only of the town itself but of the Viking kingdom it served. Moreover, the town provided its inhabitants with products other than local ones. Our excavations have turned up numerous artifacts of foreign origin. Honing stones made of mica schist, imported from Eidsborg in the Telemark district of Norway, are common finds at York. Presumably they were shipped here in boats like one recently found at Klåstad in Norway, which was loaded with Eidsborg honing stones. Bowls of soapstone also arrived in the town, perhaps from Shetland, and so did millstones of lava from the Mayen region of the Rhineland and wine in Rhenish amphoras. Silk

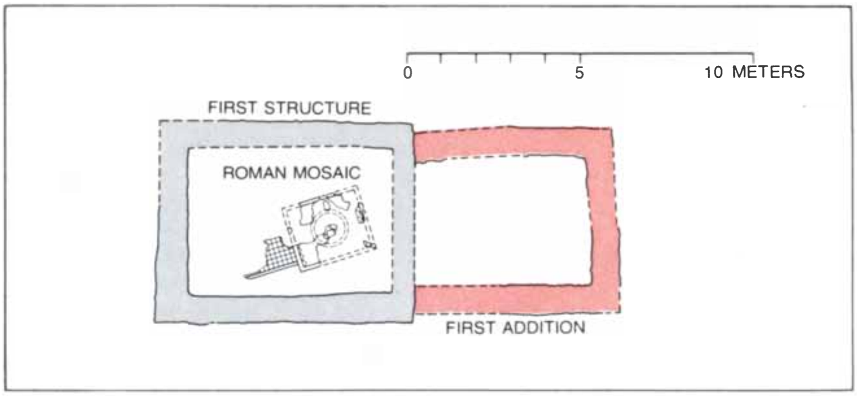


WOODWORKERS' PRODUCTS, these bowls were turned by means of a pole lathe, a spring device that rotates the workpiece. Top-shaped objects at the left are two of the waste cores.

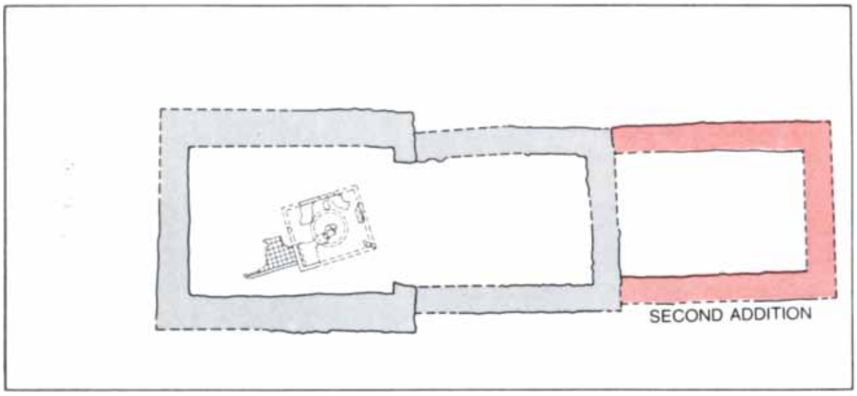
AMBER JEWELRY was another product of Anglo-Scandinavian Jorvik. At top are pendants (one pierced for suspension), a bead and a ring fragment. Below them are bits of raw amber.

came to the cloth markets of the Viking town from even farther afield to compete with the homelier woolen fabrics we have found in great variety in our excavations.

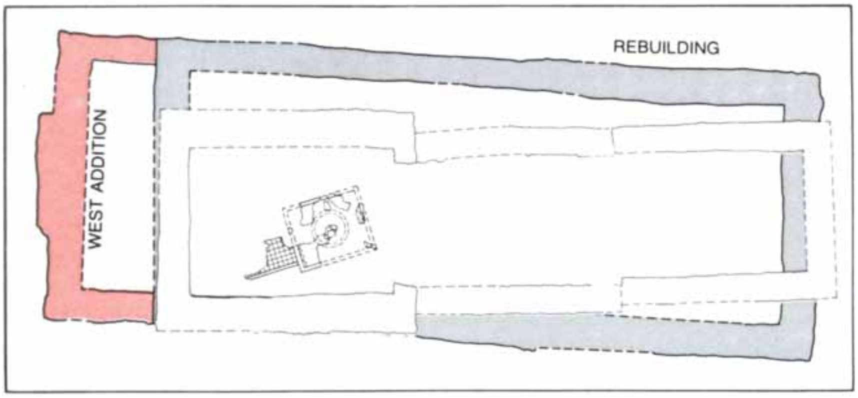
Other commodities, from the town's own hinterland, were also for sale. Pottery was brought down the River Trent and up the Ouse from Lincolnshire. Fish, oysters and other seafoods were brought up the Ouse in vast quantities from the North Sea fisheries, a minimum of 50 miles away, to help feed the 10,000 inhabitants (at a conservative estimate) of this rich trading, manufacturing and administrative town, the royal and archiepiscopal center of its day.



GROWTH OF A CHURCH, St. Helen-on-the-Walls, is traced in this series of plans. The first two phases were the construction of a small chapel over an abandoned Roman mosaic floor in the 10th century (*black*) and the addition of a chancel (*color*) in the 12th century.



THIRD PHASE of construction, in the 12th or 13th century, consisted in a lengthening of the recently added Norman chancel. The additional construction made St. Helen-on-the-Walls excessively long and narrow, which proved inconvenient for its medieval congregation.



FINAL PHASES of construction took place in the 14th century, when St. Helen-on-the-Walls was almost entirely rebuilt. The reconstruction placed the building on a new alignment (*black*). The work was further extended in the 15th century by an addition to the west (*color*).

Such a flourishing locality was inevitably important during the Norman conquest of England. Indeed, the troubles that William the Conqueror encountered after building a castle in York in 1068, garrisoned by 500 picked knights, were so severe that he ordered the construction of a second castle the following spring. In that year a combined Anglo-Danish force destroyed both Norman strongholds. William responded by spending Christmas of 1069 here, rebuilding both castles and ravaging the town and the countryside so thoroughly that his campaign is known in history as the Harrying of the North. In the process approximately half of the town's residences were destroyed or left derelict. Norman builders meanwhile erected York Minster, the cathedral, on its present site, added monasteries and a mill and replanned part of the town center. The town's ancient prosperity soon returned. It reached its apogee in the 13th and 14th centuries.

The York Trust intends to examine something of this great period, and several large areas of the city center have been selected for detailed study. For example, at Skeldergate near the wharves of the Ouse a pair of riverside properties have already been surveyed. At Coppergate we have uncovered fine town houses built of timber and stone and commercial buildings at the heart of the later medieval city. They stood on ancient plots; between them alleys ran steeply down from Coppergate to the Foss.

The floors and rubbish pits of the town houses have yielded a huge number of artifacts. One barrel-lined well contained a bucket and chain in a remarkably good state of preservation. Two latrines were uncovered, complete with hole-in-plank seats. The waterlogged debris included evidence of the commodities brought in to the city for sale and the kind of food available to the medieval citizen. A vivid picture emerges of the environmental conditions in the city center. Standards of hygiene and municipal cleanliness had evidently improved greatly since Viking times, even if contemporary records do complain of York's being the dirtiest city in the kingdom.

We have sampled a third and rather marginal area of the medieval city that proved to have accommodated the smelly pottery and tile industry. Pewterers also worked here. A fourth sample area, flanking an alley off Goodramgate in the shadow of York Minster, accommodated another noxious industry in the form of a bell foundry right in the middle of the city. The main structure of the foundry, rebuilt several times between the 13th and the 15th century, housed a furnace, a fuel store and a barrel-lined well of a type found frequently in the city. Nearby were smaller workshops. On and around the premises and in the street outside were some 13,000 bell-mold fragments. The archaeological evidence demonstrates the practices and technology of an industry hitherto known only from the registration (in the freemen's register of the medieval city) of a bellmaker in each of several successive generations.

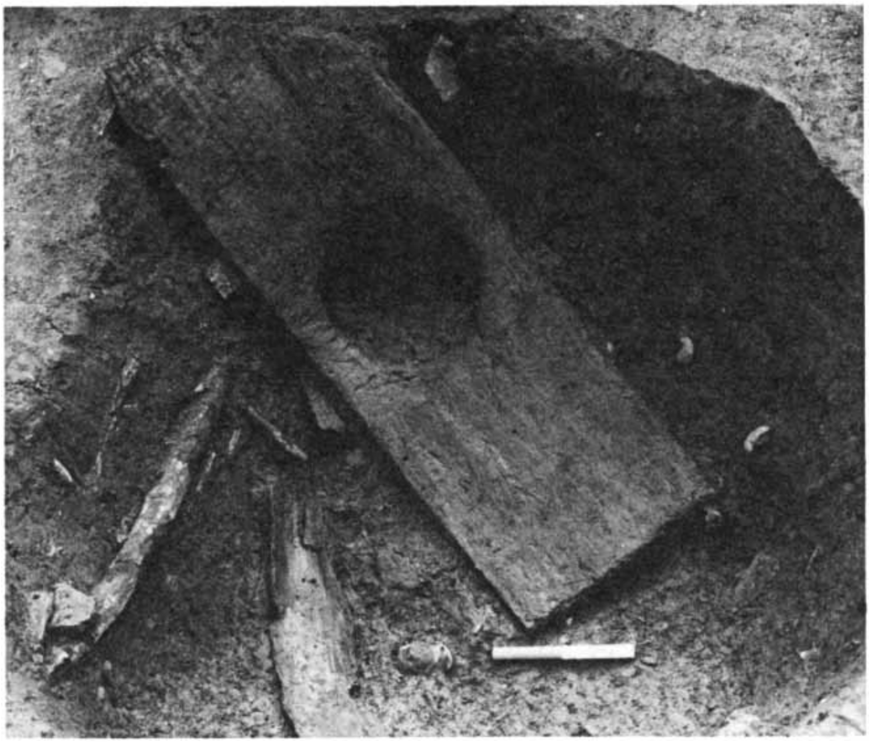
The York Trust has made progress in its aim to excavate individual examples of various common buildings in the medieval city. A hospital at the edge of the city will have to stand for the 23 that existed in medieval York. A small nunnery is similarly representative of the city's eight monastic houses. Of the 44 medieval churches, only one has been excavated in detail: St. Helen-on-the-Walls, named for its being tucked into the city ramparts. That one church, however, tells a remarkable story.

In the 10th century a little stone chapel was built over the mosaic floor of a small Roman town house. In the 12th century it was given a chancel, which was soon lengthened. The church, by now somewhat long and inconvenient, was rebuilt in the 13th or the 14th century and was finally lengthened to the west toward the end of the Middle Ages. The cemetery associated with St. Helen-on-the-Walls developed in a similar way, and more than 1,200 individual burials have now been recovered from it. Studies of these remains are now complete. They reveal the physical characteristics of the people of medieval York and hint at a change in genotype in the 11th or the 12th century. The studies have also provided the first statistics on the incidence of several deficiency diseases, of diseases with an occupational or environmental cause, of various forms of dental disease and of other conditions that leave their mark on the skeleton. Now the York Trust awaits the opportunity to excavate other cemeteries of similar size to get statistically acceptable samples for the Roman, the Anglo-Saxon and the Viking periods. The findings would add importantly to the demographic data obtainable in documentary sources from the 16th century on.

One further great institution of the city has been revealed in perhaps the most comprehensive area excavation ever undertaken in a medieval city. A six-year campaign, now nearing completion, has uncovered almost the entire plan of the College of the Vicars Choral, a group, originally 36 in number, who served as deputies for the cathedral canons. The college was established by Archbishop Walter de Grey, chancellor of England, in 1252. Its 14th-century hall and chapel still survive, and our excavation has shown how the rest of the college developed. Initially there was a large, open collection of buildings, perhaps taking their inspiration from the plan of contemporaneous monasteries. Later these structures were replaced by buildings of a more domestic aspect. In the 15th century the college had a courtyard almost like that of a university, flanked by a hall on one side, a kitchen and brewhouse on another and domestic accommodations on a third. The timber-framed buildings surrounded a garden, and behind them lay orchards. Later the Vicars Choral were accommodated in small individual houses along an adjacent street; each had its own hearth and two or three rooms, and most had a latrine.

Details of a not uncomfortable way of life have been revealed by a study of the contents of the college's rubbish pits. For example, one pit held a large quantity of fig seeds. Adding to this picture is a wide range of personal trinkets and jewelry, among them seal stamps and a gold ring set with sapphires. The excavation gains considerably from having the guidance, on the one hand, of surviving architectural elements of the buildings and, on the other, of a remarkably com-

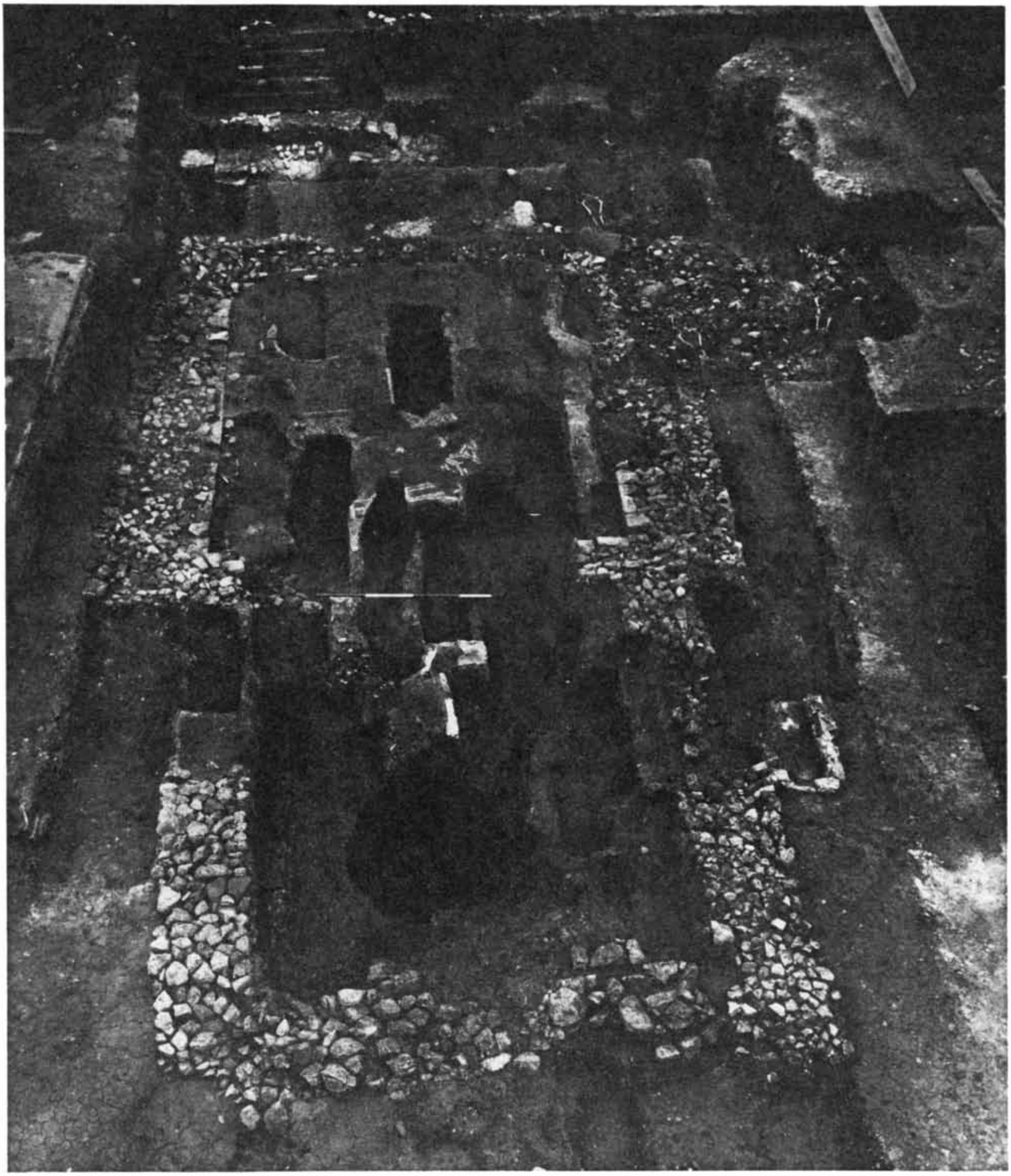
DIE-CUTTING was another craft practiced in Anglo-Scandinavian Jorvik. Seen here are two test strikings for a coin, impressed on a strip of lead. The coin was to be minted for Edwig, a great-grandson of Alfred the Great, who ruled from 955 to 959. His name, spelled Eadwig, appears on the obverse (*left*). The name of the coinmaker, Frothric, is on the reverse (*right*).



LATRINE SEAT of the period after the Norman Conquest was found in situ by the York excavators. The contents of this 12th-century latrine and others have provided paleobotanists and paleoentomologists with data on human diet and parasites at this stage in the city's history.

plete series of medieval building accounts and leases that help to explain the function and rationale of both the excavated and the surviving buildings.

The work of the York Trust since 1972 has added flesh to the bones of the city's 2,000-year history. Perhaps the most significant result of the work is the progress it has brought in the systematic application of the methods of the natural sciences to the solution of the problems confronting the urban archaeologist. Our permanent team includes an entomologist, a zoologist, a botanist, a soil analyst, a physical anthropologist and several conservators in addition to archaeological specialists of the more traditional kind. They normally work in collaboration on common problems, and their joint results create a new expectation that the techniques of archaeology can define and relate the story of that most complex and changeful of human artifacts, a living city.



PRE-CONQUEST CHURCH, St. Helen-on-the-Walls, is seen excavated to the level of its first phase, a small 10th-century chapel. A chancel added in the 12th century appears in the foreground. Remains of a Roman mosaic lie just beyond the measuring rod at the center. Most of the oblong cuts through the mosaic are graves of later periods; several burials outside the church appear at the top right.

Mr. Eastman

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SCIENCE AND THE CITIZEN

Death Takes a Holiday

The death rate in the U.S. for diseases of the heart and blood vessels continues to decrease—and so far no one has been able to establish how much of the decline can be attributed to a reduction in the incidence of cardiovascular disease and how much to better patient care. Participants at a meeting on coronary heart disease held last fall by the National Academy of Science's Institute of Medicine agreed that the reduction in mortality is striking but disagreed about the causes of the decline. Probably both primary prevention and improved treatment have played a part, but their relative roles cannot be determined because there are inadequate data on the nationwide incidence of nonfatal heart attacks and strokes. Meanwhile, however, increasing attention is being called to the fact that the decline in cardiovascular deaths is part of a broader trend: the steady reduction in the overall U.S. mortality rate. Among the major causes of death only cancer, suicide, homicide and a category labeled chronic obstructive pulmonary disease have taken an increasing toll since 1968.

From 1968 to 1978 the age-adjusted mortality rate for cardiovascular disease declined by 24.6 percent; for coronary heart disease the 10-year decline was 25.2 percent and for cerebrovascular disease (stroke) it was 37.7 percent. Why? Better control of hypertension (high blood pressure) is suggested as one important reason, but there are indications that the decline began before moderate hypertension was aggressively treated in otherwise well people. The drop correlates rather well with a reduction since the mid-1960's in the proportion of men who smoke cigarettes, but women's coronary-disease mortality is decreasing faster than men's, and in many age groups more women are smoking now than were smoking 10 years ago. The impact of changes in diet and exercise is similarly uncertain.

The death rate from cancer increased over the 10 years by 3.1 percent. As Lester Breslow of the School of Public Health of the University of California at Los Angeles has pointed out, however, that is largely owing to the sharp increase in respiratory (mostly lung) cancer: "If it were not for lung cancer, mortality from cancer as a whole would be falling." The death rate for respiratory cancer rose by 31.2 percent in the 10 years, whereas the overall rate for all other cancers has fallen by 4.1 percent, The lung-cancer death rate among men has been increasing for several decades, a rise that is generally attributed to the large increase in men's cigarette smoking after about 1920; women began smoking in large numbers later, and now their lung-cancer death rate is rising steeply. Breslow noted that a reduction in cigarette smoking appears to be reflected more quickly in lower coronary-disease mortality than it is in lower lung-cancer mortality, so that the long-term lung-cancer increase and the recent heart-disease decrease are consistent with a role for cigarette smoking in both diseases. The increase in a broad group of chronic lung conditions that includes emphysema might also be attributable to the long-term increase in smoking.

The U.S. mortality rate from all causes appeared to have reached a plateau in the 1950's and early 1960's. Then it began to fall again at an appreciable rate; the overall decline in the age-adjusted death rate was 18.6 percent from 1968 to 1978. That, of course, raises a new question: Why is the country generally so much healthier? General economic improvement and better access to medical care may be among the major reasons. The possibility is supported by the fact that the reduction in the overall mortality rate, and particularly in the infant-mortality rate, is significantly less for blacks than it is for the population as a whole.

Vanishing Point

The idea of the mathematical point, a point with no size or extension, is a long-standing challenge to the imagination. The challenge is all the greater when the point represents not a mathematical abstraction but a physical object, such as an elementary particle of matter. In mathematics a point has only one attribute: position. A physical particle, on the other hand, can have properties such as mass, electric charge and intrinsic angular momentum, all of which must somehow be embodied in a region of zero volume.

As a conceptual device the point particle has long been useful in physics because a number of fundamental laws have their simplest form when forces act at a point. Celestial mechanics, for example, is greatly simplified if the planets are treated as though they were pointlike. This description is obviously contrary to fact, and so calculations based on it give only approximate results. At least one class of physical objects, however, seem to be truly pointlike: they are the leptons, the family of elementary particles that includes the electron. In the theory that describes electromagnetic interactions of the leptons—quantum electrodynamics—it is assumed explicitly that the electric charge of a lepton is confined to a dimensionless point. If that assumption is only an approximation, it must be a quite good one, because quantum electrodynamics has been verified to greater accuracy than any other physical theory. All experimental tests of it carried out so far indicate that it is an exact theory of the leptons.

The electron is the only lepton familiar as a constituent of ordinary matter. "Lepton" derives from a Greek word meaning "small" or "light in weight," and the electron fits that specification well. Its mass (expressed in energy units) is about 500,000 electron volts; the other constituents of the atom, the proton and the neutron, are almost 2,000 times heavier. A second kind of lepton, the muon, was first observed 40 years ago in cosmic rays; with a mass of about 100 million electron volts, it also qualifies as a comparatively light particle. The third lepton, however, which was discovered five years ago, has made nonsense of the classification of particles according to mass. The new lepton, designated tau, has a mass of 1.8 billion electron volts, which is almost twice that of the proton. Indeed, the tau has been given the oxymoronic label "heavy lepton."

The electron, the muon and the tau can each have an electric charge of either $+1$ or -1. (The positively charged electron is often called a positron.) There are also three electrically neutral leptons, or neutrinos, each associated with one of the charged leptons. The neutrinos are the most ephemeral of all particles. It seems they lack not only all size and electric charge but also mass; they are the great nonentities of the subatomic realm. Nevertheless, the neutrinos clearly do exist, and each kind of neutrino can readily be distinguished from the others.

All six of the leptons are thought to be pointlike. It should be emphasized that the same cannot be said of many other particles. The proton and the neutron, for example, have a diameter of some 10^{-13} centimeter. Although that is very small (smaller than the diameter of an atom by a factor of 100,000), it is definitely greater than zero, and it can be measured. The proton and the neutron are not elementary particles but instead have a complex internal structure. They are thought to be composites of the more fundamental particles called quarks, which may be pointlike.

In order to measure the size of a particle it is necessary to bring a probe particle within close range of it. Forcing two particles together in this way requires that they approach each other with high energy. For this reason the lower limit that can be set on the size of the leptons depends on the energy available for accelerating them. In the past year a new device for causing leptons to collide at high energy has begun operating:


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the PETRA storage ring at the German Electron Synchrotron (DESY) near Hamburg. A series of measurements setting a new limit on the lepton radius was recently completed there by 57 physicists from West Germany, the U.S., the Netherlands and China. Their findings are published in *Physical Review Letters.*

In the PETRA storage ring electrons and positrons collide head on, annihilating each other and thereby giving rise to other particles. Among the many possible outcomes of such a collision three are of interest in the measurement of the lepton radius: the energy of the annihilated particles can rematerialize as another electron and positron, as a pair of muons with opposite charges or as a pair of tau leptons, again with opposite charges. Each of these reactions has a different probability, and the probabilities change with the energy of the colliding particles. The probabilities and their dependence on the collision energy can be calculated in quantum electrodynamics, making use of the assumption that the leptons have zero radius. If the leptons actually have some size greater than zero, then the observed reaction rates should depart from the predictions of quantum electrodynamics. The discrepancy would be detected only when the collision energy reached a level high enough to bring the particles within a few diameters of each other. Hence the plan of the experiment is simply to measure the rates at which electrons, muons and tau leptons are emitted at various energies and to compare the results with the predictions of quantum electrodynamics.

Certain experimental difficulties are encountered in such a measurement. Although the region where the electron and the positron collide is surrounded by a dense array of electronic detectors, not all particles emitted in the aftermath of a collision can always be registered. Moreover, not all the particles detected at any moment necessarily derive from the same collision. In the case of the tau there is an additional complication: the tau survives too briefly for it to reach the detectors, and so it must be identified by its decay products. Similar problems arise in many other experiments in high-energy physics, and techniques have been developed for overcoming them.

The PETRA measurements extended to an energy of 31.6 billion electron volts, roughly three times the maximum that could be reached with earlier instruments. At that energy the distribution of the electric field surrounding a lepton is examined at a scale of about 10^{-16} centimeter. No departures from the predictions of quantum electrodynamics were detected. Thus if any of the charged leptons has a size greater than zero, it cannot be greater than 10^{-16} centimeter. That is a thousandth the diameter of the proton. All the data are consistent with the hypothesis that the leptons are perfectly pointlike.

Warmed-over Chips

The silicon chip of a microelectronic device must be selectively "doped" with a relatively small number of atoms of other elements if its various areas are to have the appropriate electrical properties. One of the best ways to accomplish the doping is by ion implantation: driving the dopant atoms into the silicon with an ion accelerator. A drawback of ion implantation is that the energetic ions frequently disrupt the orderly three-dimensional lattice of the silicon crystal and spoil its electrical properties. Therefore after ion implantation the silicon is usually annealed, or reheated, to restore the lattice. The annealing itself, however, tends to move the dopant atoms out of an optimal configuration. It now appears that if the silicon is annealed not in a furnace but by having only its surface heated with a laser or electron beam, this considerable drawback is overcome: not only is the three-dimensional lattice restored but also the dopant atoms take up an even more optimal configuration than before.

Annealing with a pulsed laser beam was introduced in 1974 by two Russian groups, one at the Kazan Physical-Technical Institute, the other at the Institute of Semiconductor Physics in Novosibirsk. More recently a group at Stanford University including James F. Gibbons, Fabian Pease and Thomas Sigmon has worked with both laser light and electrons, supplied not in pulses but by a continuous finely focused beam that scans the surface of the silicon wafer out of which chips are cut. The energy of the scanning beam can be made high enough to excite strong vibrations among the atoms in the disrupted surface without actually melting it. The crystal lattice reconstitutes itself in the pattern of the undisrupted lattice under it. The vibrations also tend to shake the dopant atoms out of what are called interstitial sites to sites where they substitute for atoms of silicon. Here they can play their part in the electrical behavior of the semiconductor.

The laser or electron annealing enhances the advantages of ion implantation over an older method, in which the wafer is heated in the presence of a vapor of a dopant so that the atoms of the dopant can diffuse into it. In the course of ion implantation the wafer can be metered for charge in order to monitor the total amount of the doping. This cannot be done in a furnace. Moreover, ion implantation can be confined to particular parts of the surface by masking, and the effects of the masking are precise. In the diffusion method atoms that have diffused into a wafer can also diffuse sideways under a mask.

Such annealing has other uses. For

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example, the Stanford group has found that heating a surface consisting not of a disrupted crystal lattice but of numerous small crystals transforms the small crystals into larger ones. Semiconductor devices fabricated on these polycrystalline surfaces have properties similar to those of devices made on single-crystal material. Furthermore, "islands" of single-crystal material in the polycrystalline surface have dimensions suitable for the fabrication of high-density microelectronic devices. The implantation of dopants with suitable masking would make an island a transistor. Repeating the process with layers of silicon laid down on top of the first layer might make it possible to fabricate a microelectronic device in three dimensions instead of the usual two.

Voices in the Light

For nearly 20 years the Bell System has been working to develop the technology of optical communication, in which information is transmitted at the frequencies of light (instead of at the much lower frequencies of electrical and radio waves) over thin, highly transparent glass fibers (instead of metal wires or radio beams). The optical system offers the advantages of a far greater carrying capacity and less interference. Bell tested an optical telephone system successfully in Atlanta in 1976 and in Chicago from 1977 to 1979. Now the Bell System is preparing to start up the first standard commercial installation, which later this year will link three central offices in Atlanta. The plans are described in *Bell Laboratories Record* by Ira Jacobs, director of the Wideband Transmission Facilities Laboratory at Bell Laboratories in Holmdel, N.J.

The Atlanta installation will be digital. In a digital light-wave system the light source, which is either a small laser or a light-emitting diode, emits pulses of light of equal intensity rather than a steady beam of varying intensity. Each second is divided into 44.7 million segments, and the light source inserts one bit of information into each time slot by either flashing on or remaining off. The receiver, a small photodetector, senses in each time slot either a pulse or the absence of one. If it senses a pulse, it registers a 1; if it senses the absence of a pulse, it registers a 0. Eight such bits of information make up a digital word (for example 11010010), and from a series of such words other elements of the transmission system can reconstruct the original voice signal.

A person making a telephone call is typically connected to a central office by a single pair of wires called a loop. At the central office the call is dispatched (along with many other calls) over high-capacity transmission links to the central office serving the recipient. It is this communication among central offices that will be achieved by the light-wave installation in Atlanta, which will serve alongside (and as an expansion of) the conventional cable network that links the three offices now.

One of the problems in developing the technology of light-wave communication was that the glass had to be made transparent enough to carry a strong signal over a considerable distance without the need of repeaters to regenerate the pulses. The technology has now advanced to the point where the fibers can maintain an adequate signal for several miles. Since most central offices are closer together than that, glass-fiber cables can serve them without repeaters. Although the first standard light-wave installations will serve central offices, the Bell System plans to expand the concept to include short-haul and long-haul trunk lines and submarine cables.

From Reckoning to Writing

What gave rise to writing on clay tablets, the earliest writing known? A leading hypothesis is that both the form and the meaning of the characters on the tablets evolved from special counters, or "tokens," used in keeping records in the ancient Near East (see "The Earliest Precursor of Writing," by Denise Schmandt-Besserat; SCIENTIFIC AMERICAN, June, 1978). The hypothesis has now been strengthened by the clarification of another puzzle related to the origin of writing. The puzzle had its beginnings at the turn of the century with the discovery at Susa, an ancient proto-Elamite city site in southwestern Iran, of what remain the earliest inscribed clay tablets known. The tablets bear various kinds of crude impressions that are neither pictographs nor writing such as cuneiform. Work at Uruk, a nearby Sumerian city site, in the 1930's uncovered similar impressed tablets. Their discoverer, the German archaeologist Julius Jordan, interpreted the impressions as being numerical notations. Since then such impressed tablets have been unearthed at seven other sites in Iran, Iraq and Syria; 183 of them, complete or fragmentary, are now known.

Recently Jöran Friberg of the University of Göteborg, who has been studying early Sumerian and proto-Elamite mathematics, found that both of these peoples had different systems for enumerating different categories of commodities. One system was used to keep track of grain, another to deal with livestock and a third to enumerate landholdings. Friberg's discovery of this three-way division of quantitative systems was immediately suggestive to Denise Schmandt-Besserat of the University of Texas at Austin.

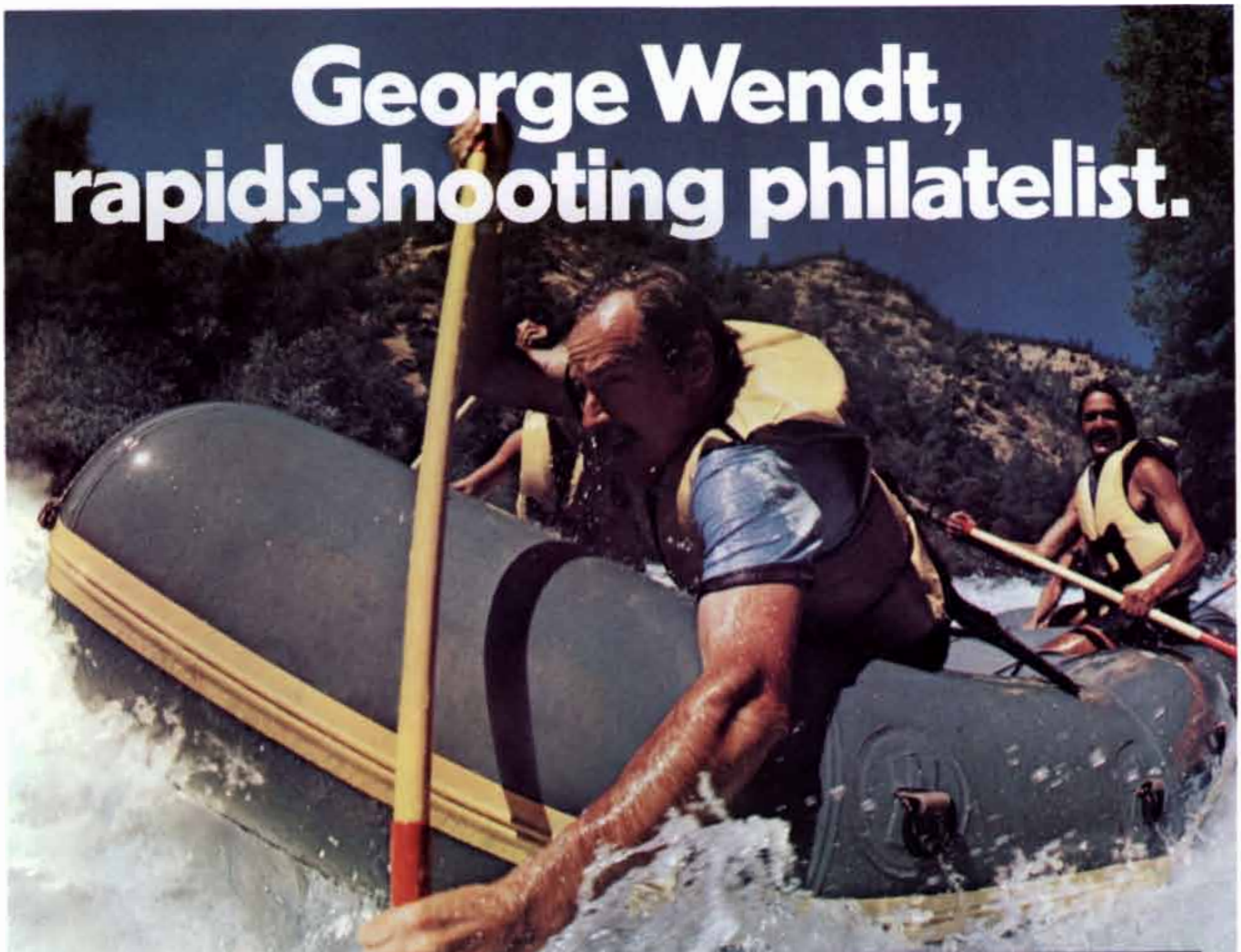
A student of prehistoric and early historic clay artifacts in Southwest Asia, Schmandt-Besserat had just begun to analyze the repertory of impressions appearing on the early tablets. She did so because of their similarity to certain Sumerian efforts to reproduce, by impressing and inscribing, the distinctive three-dimensional shapes of the tokens then widely used for record keeping. She found that the impressed tablets included 18 different kinds of signs that resemble seven categories of three-dimensional tokens. For example, she equated deep circular punch marks with spherical tokens. Larger, shallower punch marks she equated with disk-shaped tokens, long wedge-shaped marks with cylindrical tokens and short wedge-shaped marks with cone-shaped tokens.

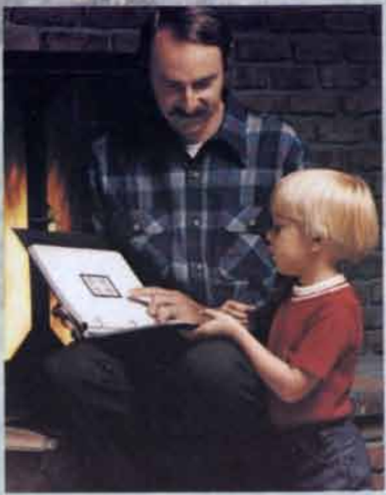
The commonest impressions are those equated with cones and spheres. Deep circular punches (spheres) appear on 88 tablets and short wedges (cones) appear on 69. Next most frequent are long wedges (cylinders) and broad shallow punches (disks); they respectively appear on 30 and 15 tablets. Less frequent are impressions equated with such tokens as triangles, ovoids and cones attached vertex to vertex.

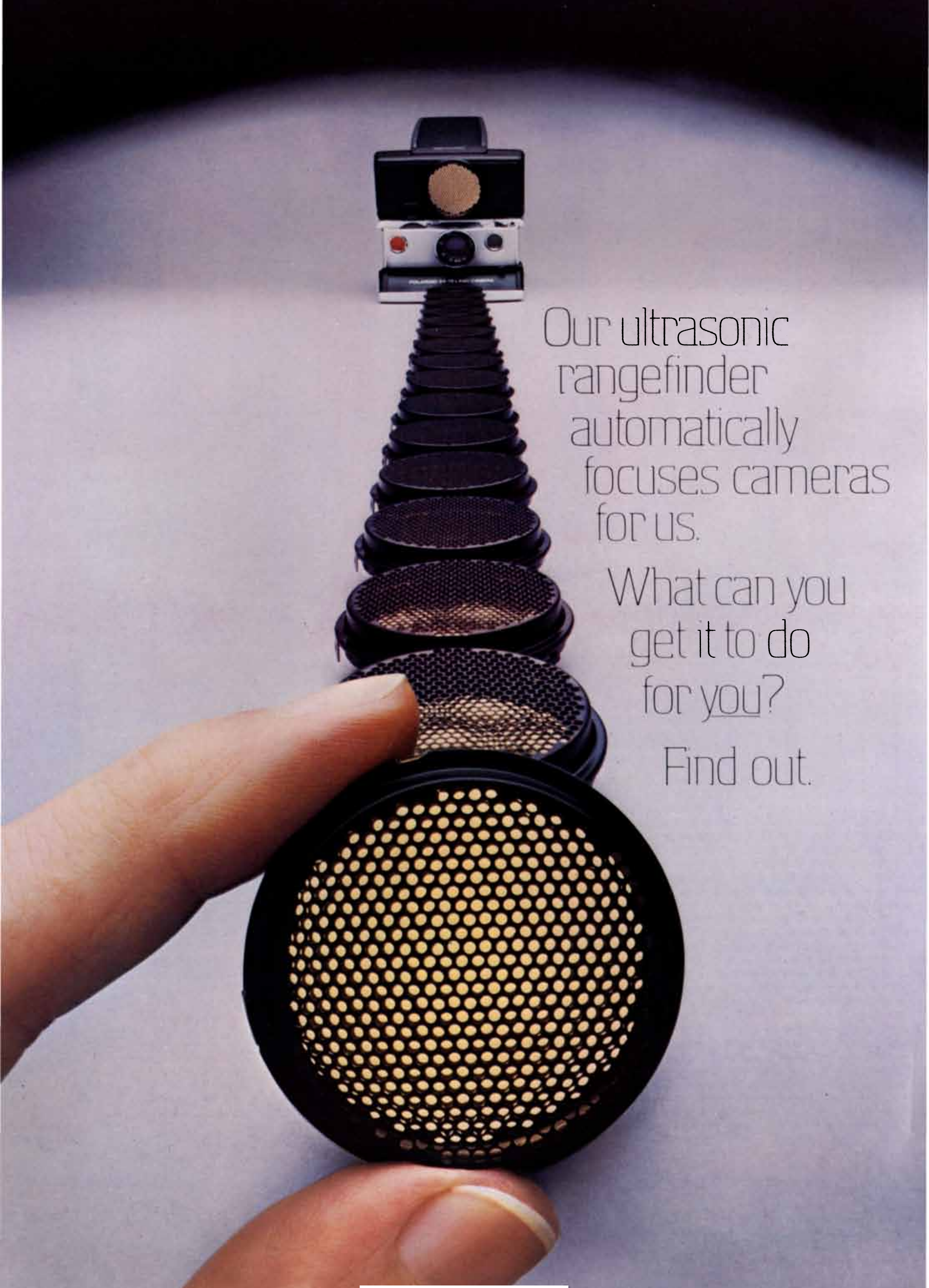
Proposing a five-step series for Friberg's barley measures, symbolized by the successive punch signs for a triangle, a small cone, a sphere, a large sphere and a large cone, Schmandt-Besserat has assigned to the second punch sign the Sumerian unit (a *ban*) equivalent to six liters and to the third punch sign the Sumerian unit (a *barriga*) equivalent to 36 liters. This enables her to offer a reading for an impressed tablet from Tepe Sialk, a site in Iran, that shows one row of six sphere signs above a second row of three small-cone signs. Schmandt-Besserat's reading is "six *barriga*s and three *ban*s [234 liters] of barley."

Schmandt-Besserat has further proposed a three-step series for Friberg's livestock counts, symbolized by the successive punch signs for a cylinder (with the value of 1), a disk (with the value of 10) and a pair of cones attached vertex to vertex (with the value of 100). On this basis she offers a reading for one impressed tablet from Susa ("21 sheep") and for another ("four sheep"). Finally, with respect to a five-step series proposed for land measurements she reads a fragmentary tablet from the Iranian site of Tall-i-Ghazir as "10 *bur*s and four *iku*s [648,072 square meters]."

At a recent meeting of the Archaeological Institute of America, Schmandt-Besserat suggested that the impressed tablets are further evidence of the shift from reckoning to writing in the fourth millennium B.C. This, she pointed out, is in agreement with the evolutionary sequence leading to literacy proposed by Jordan on the basis of the stratigraphic sequence at Uruk: first, impressed tablets; second, incised pictographs; third, a shift to phonetic values, and last, the acquisition of full syntax.



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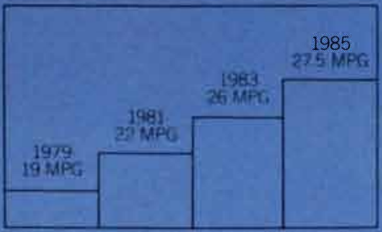

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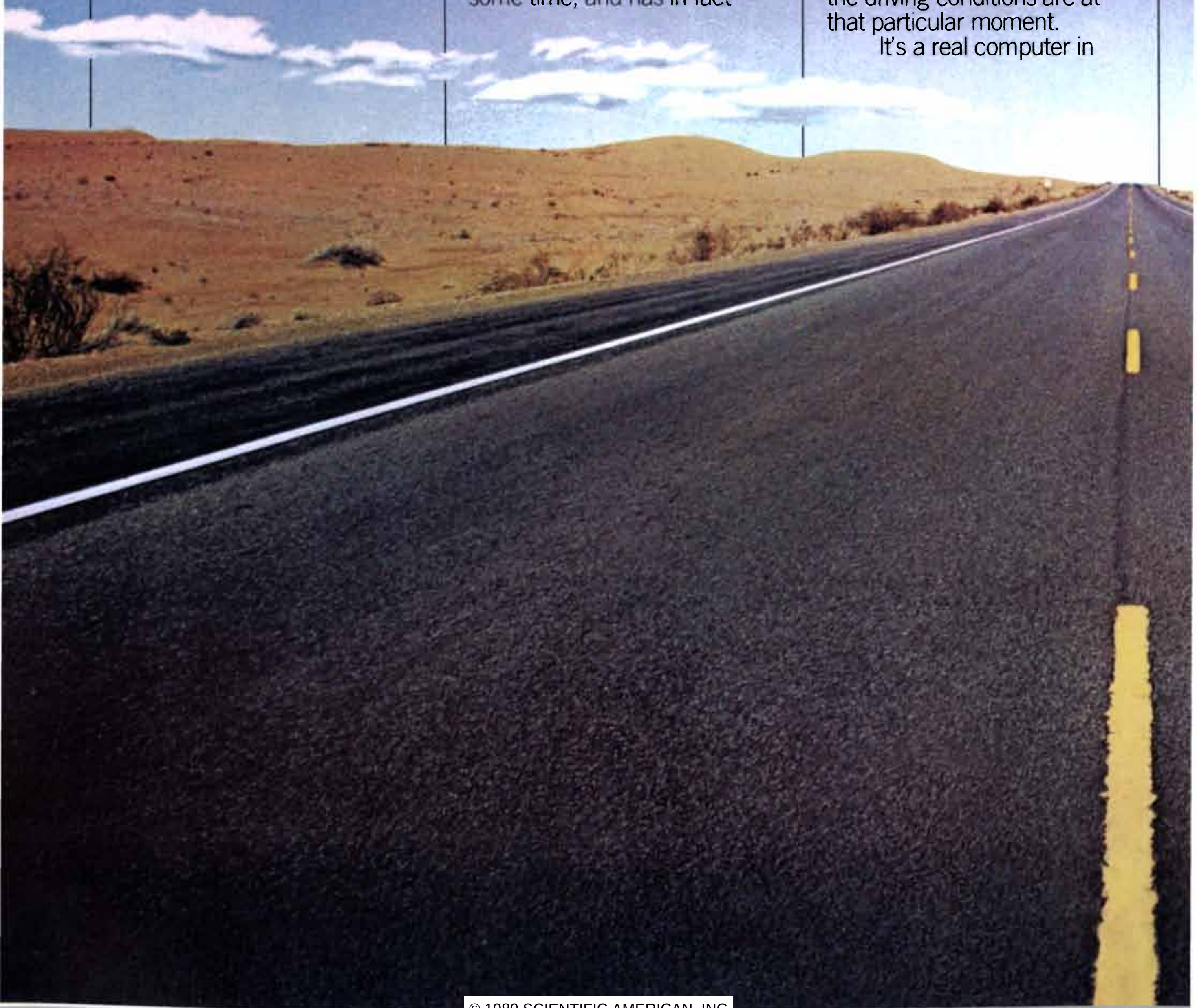

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miniature, with a memory and the ability to manipulate what it learns in terms of what it already knows. It works so well that car and heavy-duty-equipment manufacturers in America and Europe plan to use it, some as early as the 1980 model year.

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Diseases Caused by Impaired Communication among Cells

The activities of the cells of the body are integrated by mediator substances that interact with specific receptors. It appears that many diseases are attributable to errors in such communication

by Edward Rubenstein

In medicine it is both clinically useful and intellectually satisfying when the mechanism underlying a mystifying disease or group of diseases is revealed. Recently it has become apparent that a number of human diseases, among them such diverse disorders as cholera, hyperthyroidism, myasthenia gravis and certain types of diabetes, arise from a common mechanism: faulty communication among cells. The recognition of this mechanism has led to the formulation of important new concepts about a system involved in the self-government of the body. The principal components of this system are chemical signals, called mediators, and the cellular structures with which they interact, called receptors.

Cells communicate with one another by releasing mediators that travel various distances, sometimes only to an adjacent cell and at other times through long journeys in the bloodstream to other parts of the body. The messages are picked up by the receptors, which relay the information to structures within the cell where the incoming signal triggers a biochemical response.

When the mediators are steroid hormones, the information they carry travels in most instances directly to the nucleus of a cell in the target tissue, where interaction with the genetic material of the cell gives rise to the synthesis of new proteins. This process of interaction and synthesis takes a certain amount of time. When the mediators are peptide hormones or catecholamines, the information they carry leads to the modification of previously assembled proteins stored in the cytoplasm of the target cell. This process does not take much time and the biological response can be quick. In many such systems the relay signal is cyclic adenosine monophosphate (cyclic AMP), which is produced when two of three phosphate groups are cleaved from its ubiquitous precursor, adenosine triphosphate (ATP), by the enzyme adenylate cyclase. The free end of the remaining phosphate group combines with carbon atom No. 3 in the ribose (five-carbon sugar) of the ATP to form a ring, hence the term cyclic. The concentration of cyclic AMP is increased by the level of adenylate cyclase and decreased by the level of the enzyme phosphodiesterase.

The diverse effects of cyclic AMP are attributed to its ability to convert certain inert proteins into functioning ones known as kinases. The kinases modulate the metabolism of the cell. They switch systems on or off by activating or deactivating enzymes through the process of phosphorylation. For the discovery of cyclic AMP and the elucidation of its central role in the metabolism of cells the Nobel prize in medicine was awarded in 1971 to Earl W. Sutherland, Jr., of the Vanderbilt University School of Medicine.

More recent studies have indicated that receptors on the cell's outer membrane communicate with adenylate cyclase through an intermediary protein binding guanosine triphosphate (GTP). This protein not only activates the cyclase but also may diminish the affinity of the receptor for the mediator. Such a mechanism would partly explain the fact that high levels of mediators tend to reduce the response of their receptors. For example, the administration of certain adrenergic drugs to patients with asthma reduces the number of adrenergic receptors on their white blood cells. Insulin has a similar diminishing effect on its receptor, whereas estrogen increases the number of receptors for progesterone and thyroid hormone increases the number of beta-adrenergic receptors in some tissues.

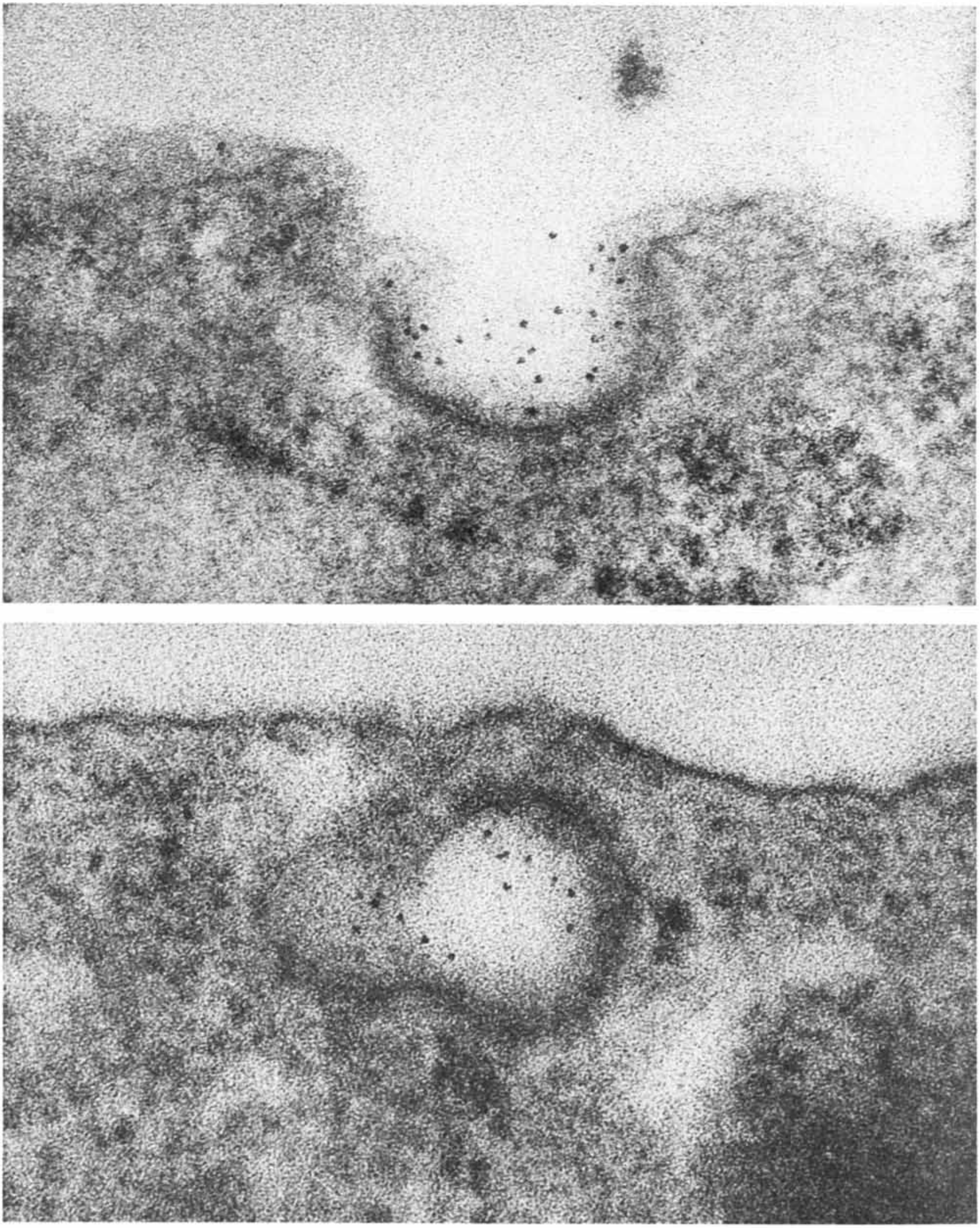
The initial mediator is sometimes called a first messenger and cyclic AMP and other relay substances, which shuttle from the vicinity of the receptor to other sites in the cell, are called second messengers. The terminology is somewhat misleading, because most first messengers are not initiators in the strict sense. They are released in response to prior orders, many of which originate in the central nervous system as a consequence of processes ranging from the perception of a sensory stimulus to the dawning of an idea. The concept is a major extension of the field of neuroendocrinology, with some unexpected twists.

Mediators, Receptors and Membranes

The mediators are molecules ranging in size and complexity from amino acids (consisting of from 10 to 27 atoms) to insulin (consisting of some 925 atoms). The receptors are huge aggregates of many molecules, arranged in an assembly that gives each kind of receptor a unique structure. In general hydrophilic (water-soluble) chemical mediators cannot diffuse across the cell membrane to enter the interior of the cell; their receptors are on the cell surface. Hydrophobic (fat-soluble) compounds seem to diffuse across the cell membrane; their receptors are inside the cell.

One therefore sees that the cell membrane is an important component in the system of communication among cells. The membrane consists of a double layer of phospholipid molecules, arranged so that water-soluble groups point outward toward the exterior and interior of the cell and fatty-acid chains point inward from the water-soluble groups. Interspersed among the phospholipid molecules are flat, rigid molecules of cholesterol, which are aligned with the fatty-acid chains.

Assemblages of protein molecules, many of which are thought to be receptors, float in or are attached to the membrane. Some of them extend across the thickness of the membrane; others are on the inner or outer surface. A few of the latter proteins are probably gated conduits through which fat-insoluble substances gain entrance to the interior of the cell. Fat-soluble compounds, such as androgens, estrogens, corticosteroid

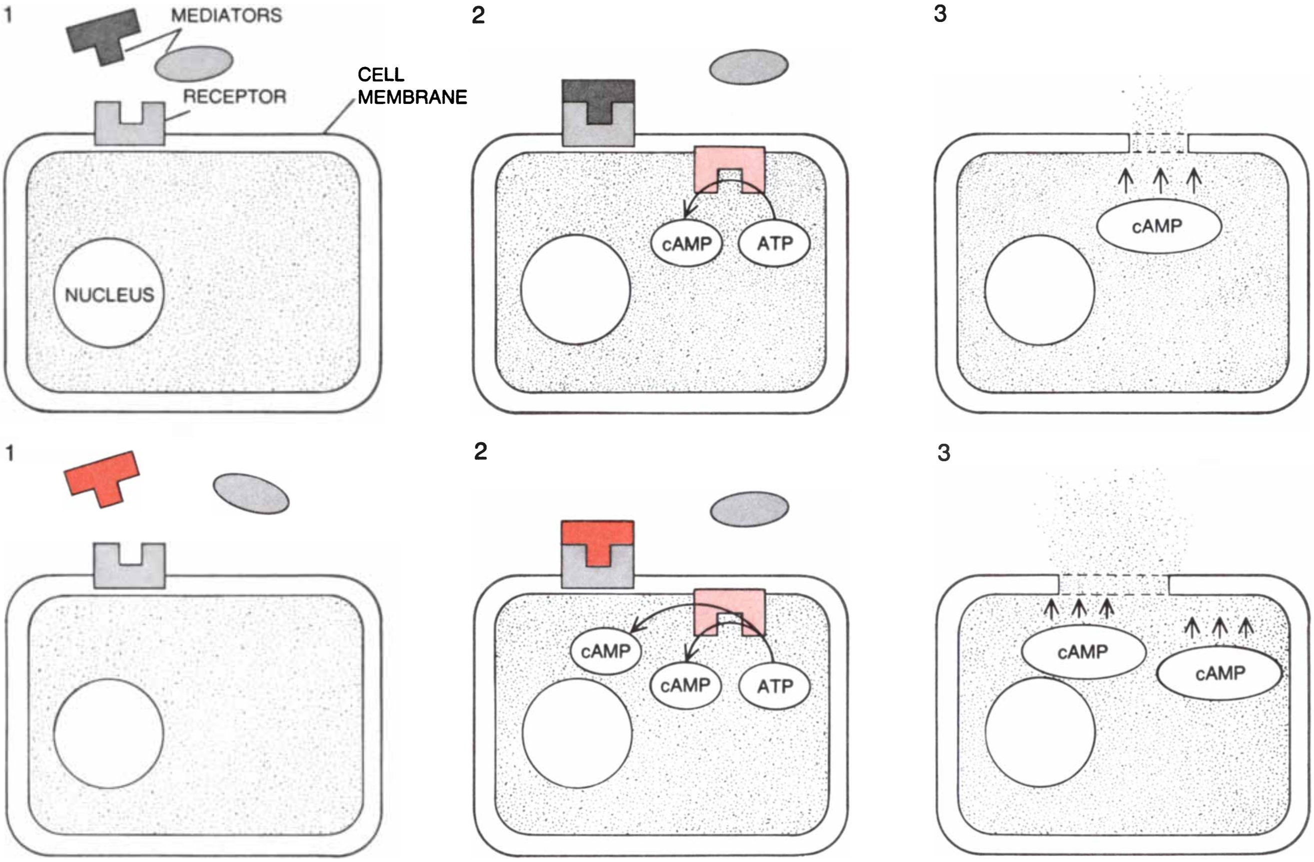


A CELL-COMMUNICATION MECHANISM is evident in these electron micrographs made by Richard G. W. Anderson, Joseph L. Goldstein and Michael S. Brown of the University of Texas Health Science Center at Dallas. The upper micrograph shows a pit in the membrane of a human fibroblast, a cell of the connective tissue. The pit is lined with receptors for low-density lipoprotein, a large molecule that is manufactured in the liver and circulates in the blood carrying cholesterol, which cells need to maintain the structure of their membranes. The black spots above the surface of the pit are particles of low-density lipoprotein bound to the protein ferritin, which is dense in electrons and so enhances the visibility of the particles in the micrograph. The lower picture shows such a pit closed over the particles, forming a vesicle that is delivered to the interior of the cell, where the cholesterol is put to use. A failure of this mechanism is responsible for familial hypercholesterolemia, an inherited disorder in which cell membranes do not have enough receptors for low-density lipoprotein. The victim therefore suffers the pathological effects of excess cholesterol in the blood. The enlargement is about 227,000 diameters.

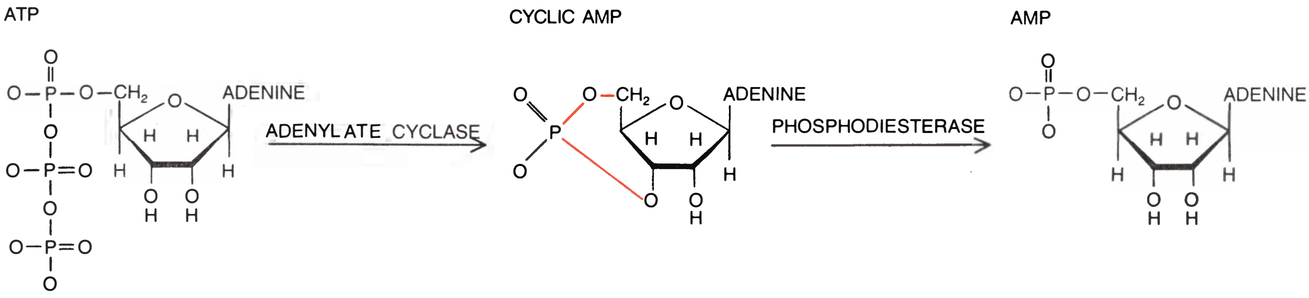
hormones and fat-soluble vitamins, are believed to diffuse across the fatty membrane of the cell and to encounter their specific receptors in the cytoplasm. The receptor for thyroid hormone is probably in the cell nucleus.

Water-soluble compounds, such as the protein hormone insulin, cannot passively cross the hydrophobic barrier, and therefore their receptors are situated in the cell membrane. Recent studies have shown that the membrane-bound receptors for insulin and other hormones enter the cell after they have combined with their mediators and then move in a nonrandom manner to target locations, such as the membrane of the cell nucleus, where they probably exert long-term effects by regulating the expression of genes. Perhaps such effects are initiated by the receptor rather than by the mediator, which may serve only to activate the receptor and to trigger its movement from the cell membrane to a particular site within the cell.

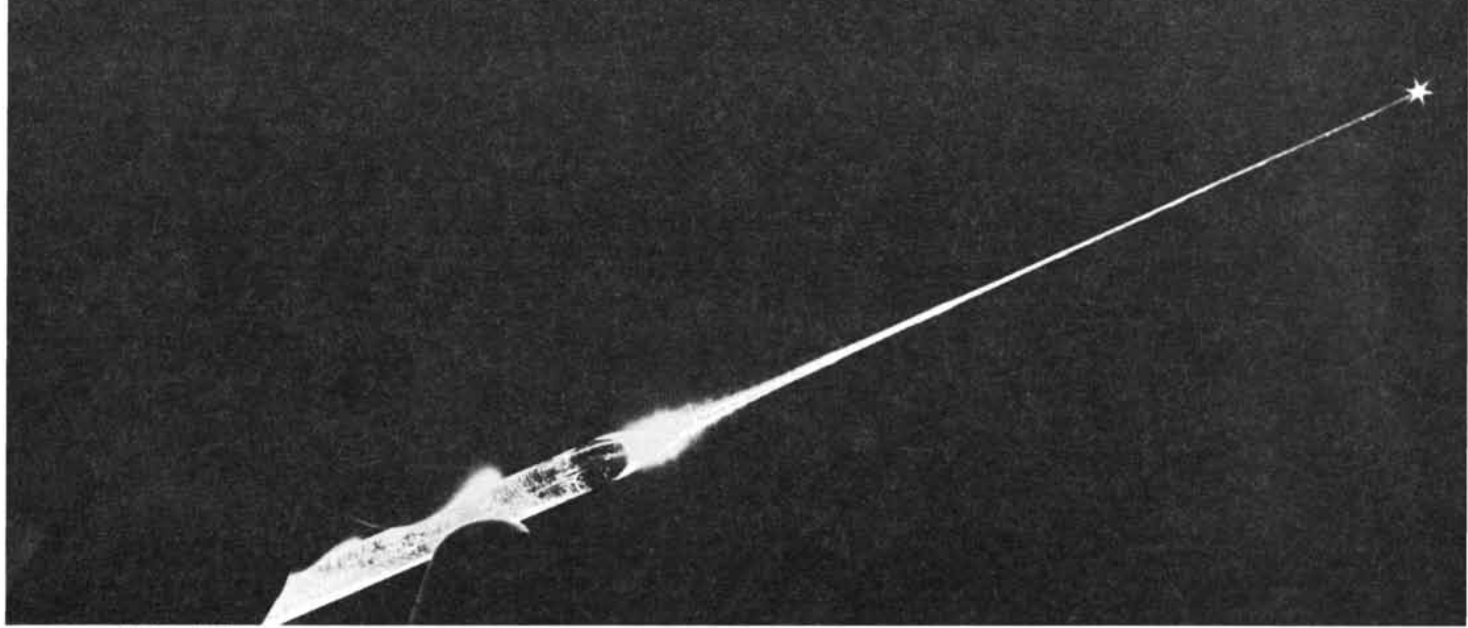
The interaction between the mediator molecule and its receptor is highly specific. It results from the fact that active regions on each of them have complementary contours and distributions of



CELL COMMUNICATION of a normal type (*top*) and of an abnormal one in cholera (*bottom*) is depicted schematically for a cell of the small intestine. In normal communication a receptor, which is situated in the membrane of the cell, encounters many kinds of mediators, or cell-communication substances, flowing past it in the bloodstream. It responds only to a specific mediator released when food is delivered to the small intestine from the stomach. The interaction of the mediator and the receptor activates a relay system consisting of cyclic adenosine monophosphate (*cAMP*), which is manufactured in the cell from adenosine triphosphate (*ATP*). The cyclic AMP in turn activates an enzyme that causes the cell to discharge into the intestinal canal an alkaline fluid that enhances the activity of the digestive enzymes. Later the digestive tract reabsorbs the fluid. In cholera the normal mediator is mimicked by a toxin released by the cholera bacillus. When the toxin binds to the receptor, the cyclic-AMP system is overstimulated, causing the cell to release large amounts of fluid into the intestinal canal. When many such cells are overstimulated, far more fluid is produced than the digestive tract can reabsorb. A person suffering from the disease therefore loses large amounts of fluid through vomiting and diarrhea, often with fatal consequences.



CYCLIC AMP is formed and degraded as is shown here. Its precursor, adenosine triphosphate (*ATP*), loses two of its three phosphate groups (*P*) through cleavage by the enzyme adenylate cyclase. The free end of the remaining phosphate group combines with a carbon atom in a cyclic, or ring, configuration. Cyclic AMP is inactivated by the enzyme phosphodiesterase, which opens the ring and converts the cyclic AMP into an inert form of AMP. Cyclic AMP is in many instances the "second messenger" that responds within a cell to a mediator, such as a hormone, that has arrived from another cell. The mediator molecules bind to specific receptors in the cell membrane.



Why this one-of-a-kind invention didn't end up as the only one of its kind.

Every new invention needs another new invention—the one that can mass-produce it at an affordable cost.

For example, Bell Labs invented a process for making the glass rods from which hair-thin fibers used in lightwave communications can be drawn. The fibers have far greater capacity than conventional copper wires, so they'll help keep costs down. In fact, they've been carrying voice, data, and video signals under city streets for about two years in a Bell System demonstration.

But standard lightwave systems will require *miles* of the fiber, produced at low cost and to specifications nothing short of microscopic.

That's where Western Electric's Engineering Research Center comes in.

A Unique Center

The Center is devoted exclusively to manufacturing research.

Here, a highly trained team of scientists and engineers probe fundamental questions about materials and processes. They provide Western Electric factories with pre-tested, proven ways to manufacture products based on the latest technology coming out of the laboratory.

For example, while Bell Labs scientists were inventing new glass fibers, Western Electric engineers and scientists were tackling the manufacturing problems involved.

The fibers had to be drawn from molten glass at high speeds, with less than a 1% deviation in diameter.

But how do you control a "thread" of glass being spun at rates up to 15 feet per second?

Scientists and engineers at the Center discovered that laser light beamed onto the fiber cast a characteristic pattern. By correlating the pattern to the fiber's diameter, they were able to build a monitoring system into the fiber drawing machinery. It measures the fiber 1000 times per second, automatically adjusting production to keep the diameter constant.

The system works so well that in all the miles of fiber produced by Western Electric, the diameter varies by no more than 30-millionths of an inch.

The Key to the Future

In the Bell System, technology is the key to keeping costs down. It is the key to constantly improving your phone service.

And Western Electric's Engineering Research Center is an essential link between the ideas of the laboratory and the realities of the factory.

So your Bell Telephone Company can make the best one-of-a-kind inventions a part of your phone service.

Keeping your communications system the best in the world.

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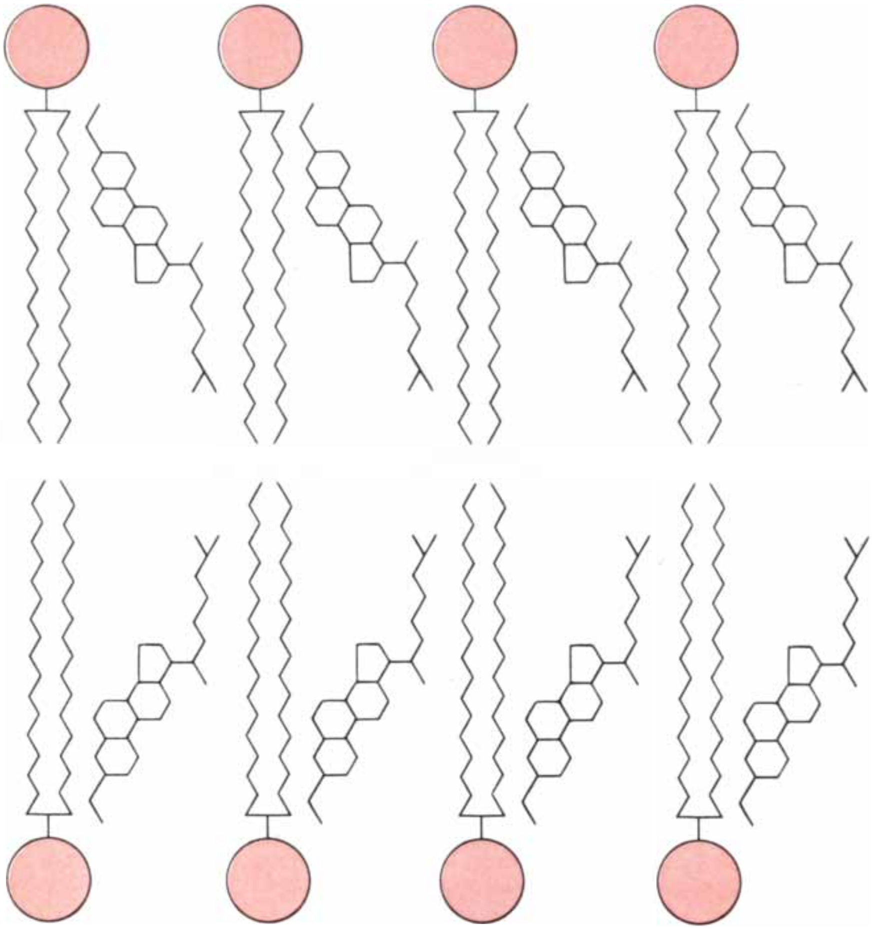
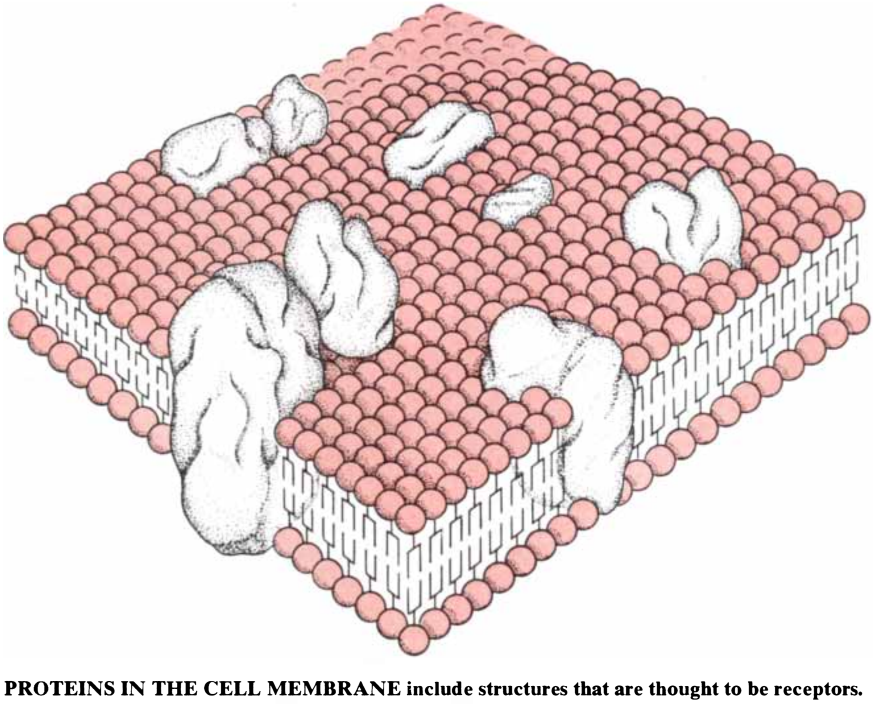


CELL MEMBRANE is a key component of the system of communication among cells. Because of its structure water-soluble and fat-soluble mediators enter the cell in different ways. The membrane consists of a double layer of phospholipid molecules, arranged so that their water-soluble groups (*colored spheres*) point both outward and inward and their chains of fatty acids point inward. Also interspersed among the phospholipid molecules are flat, rigid molecules of cholesterol, shown here as pentagonal structures to the right of the fatty-acid chains.



PROTEINS IN THE CELL MEMBRANE include structures that are thought to be receptors. Some of the proteins, called integral proteins, go entirely through the membrane; others, called peripheral proteins, are on the inner or outer surface of the membrane and are bound to integral proteins. Some of the proteins probably form conduits through which fat-insoluble mediators enter the cell. Fat-soluble mediators probably diffuse across the cell's fatty envelope.

electric charge, enabling the mediator to come into such close contact with the receptor that the two are chemically bonded. The interaction gives rise to a sequence of biochemical reactions that produce a biological effect.

Under normal circumstances the receptor interacts only with the appropriate mediator. Hundreds of other kinds of chemical compounds may come in contact with the receptor, but they bounce off and nothing further happens. The high degree of specificity between the mediator and the receptor is demonstrated by the hormones oxytocin and vasopressin. Each is a simple peptide compound consisting of nine amino acids; they differ from each other only in the amino acid units at the third and the eighth position. The hormones are almost identical in size, shape and the distribution of electric charge on their surface, but the subtle distinctions between them account for the fact that they have entirely different biological effects. Oxytocin activates receptors in the smooth-muscle cells of the wall of the uterus, initiating the contraction of the uterus in labor. Vasopressin activates receptors in epithelial cells that line the collecting tubules of the kidney, causing the tubules to become more permeable and thereby allowing the kidney to reabsorb large amounts of water. (The result is a reduction in the volume of urine.) Vasopressin does not act on the uterus and oxytocin does not act on the kidney.

Although that specificity is exceedingly high, it is not complete. A receptor may on occasion react with an inappropriate compound if the electron clouds of the compound resemble those on the active region of the proper mediator molecule. The receptor then responds to the wrong signal. An example is the action of the drug carbachol on synapses in the autonomic nervous system, which controls such largely involuntary functions as blood pressure and contractions of the intestine.

Where two neurons, or nerve cells, meet at a synapse they are separated by a space filled with fluid. At the terminal of the presynaptic neuron are membrane-enclosed vesicles that contain the neurotransmitter acetylcholine. When a nerve impulse reaches the nerve ending, the molecules of acetylcholine are released in a burst; they diffuse across the narrow gap between the cells and plug into the socketlike cavities of the acetylcholine receptors that cover the surface of the postsynaptic membrane.

The drug carbachol is similar enough to acetylcholine to substitute for it and so to act as a synthetic neurotransmitter. The receptor responds to a false signal, which in this instance is a compound employed as a drug. In other instances faulty communication is the result of a physiological defect involving either the mediator or the receptor.

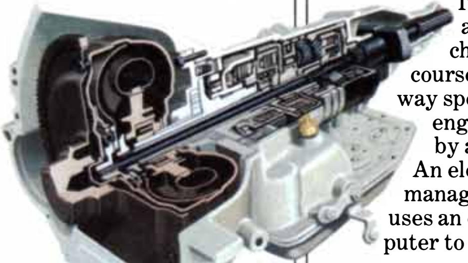
These comparatively simple new con-

LINCOLN CONTINENTAL: QUITE POSSIBLY THE MOST INTELLIGENT CHOICE AMONG ALL THE FINE CARS AVAILABLE TODAY.

Even the most discriminating buyers will find good cause to choose the Lincoln Continental for 1980.

This is the first totally new Lincoln in a decade, a fine car that is appropriate to today's driving needs.

With the help of computers and finite element modeling techniques, our engineers were able to remove excess bulk and weight and to make it fourteen inches shorter than its predecessor—and at the same time to preserve all the Lincoln virtues: the classic styling; the sumptuous ride; ample room for six adults; and a deep-well luggage compartment of 22-cubic-foot capacity.



Lincoln offers as standard equipment an automatic overdrive transmission that is the first of its kind to be made in America. It improves highway mileage by reducing engine speed in relation to road speed.

EPA Estimated miles per gallon has increased a dramatic 41% over last year.* In fact, Lincoln Continental gives you better mileage ratings than any gasoline-engine Cadillac.

Lincoln offers a new automatic overdrive transmission, the first of its kind to be made in America.

It provides fully automatic gear-changing, of course—but at highway speed, it reduces engine revolutions by about 33%.

An electronic engine management system uses an on-board computer to regulate engine timing, fuel injection and other vital engine functions. The computer operates continuously while the engine is running and can make 1200 decisions each second. Your Lincoln is designed to help you use as little fuel as is consistent with the way you are driving at every moment.

Electronic fuel injection meters fuel uniformly into the engine more accurately than a conventional carburetor.

These and other sophisticated engineering details put the Lincoln Continental miles ahead of last year's model in fuel efficiency. Its uncompromised luxury is a subjective pleasure which we invite you to experience yourself.

41% *Improvement in EPA and Highway fuel efficiency ratings over 1979.

17 **EPA EST. MPG 24 EST. HWY. MPG

*Based on comparison of standard engines.
**Compare this estimate to the estimated MPG of other cars. You may get different mileage depending on speed, weather conditions and trip length. Actual highway mileage will probably be less than the estimated highway fuel economy. California estimates and percentages are different.

1. Front headroom	39.0″	5. Rear headroom	38.0″
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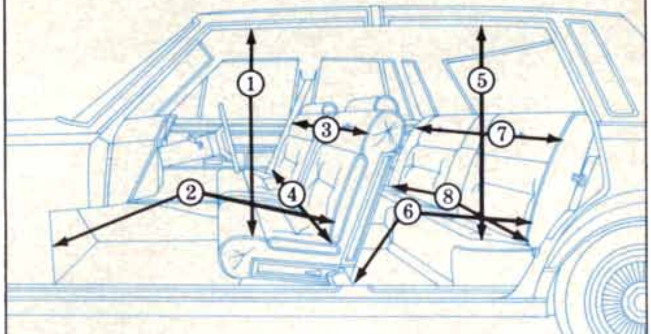
4. Front hiproom	56.5″	8. Rear hiproom	57.8″



Because true efficiency should deliver comfortable miles per gallon, Lincoln's six-passenger interior is even roomier than last year.

LINCOLN CONTINENTAL

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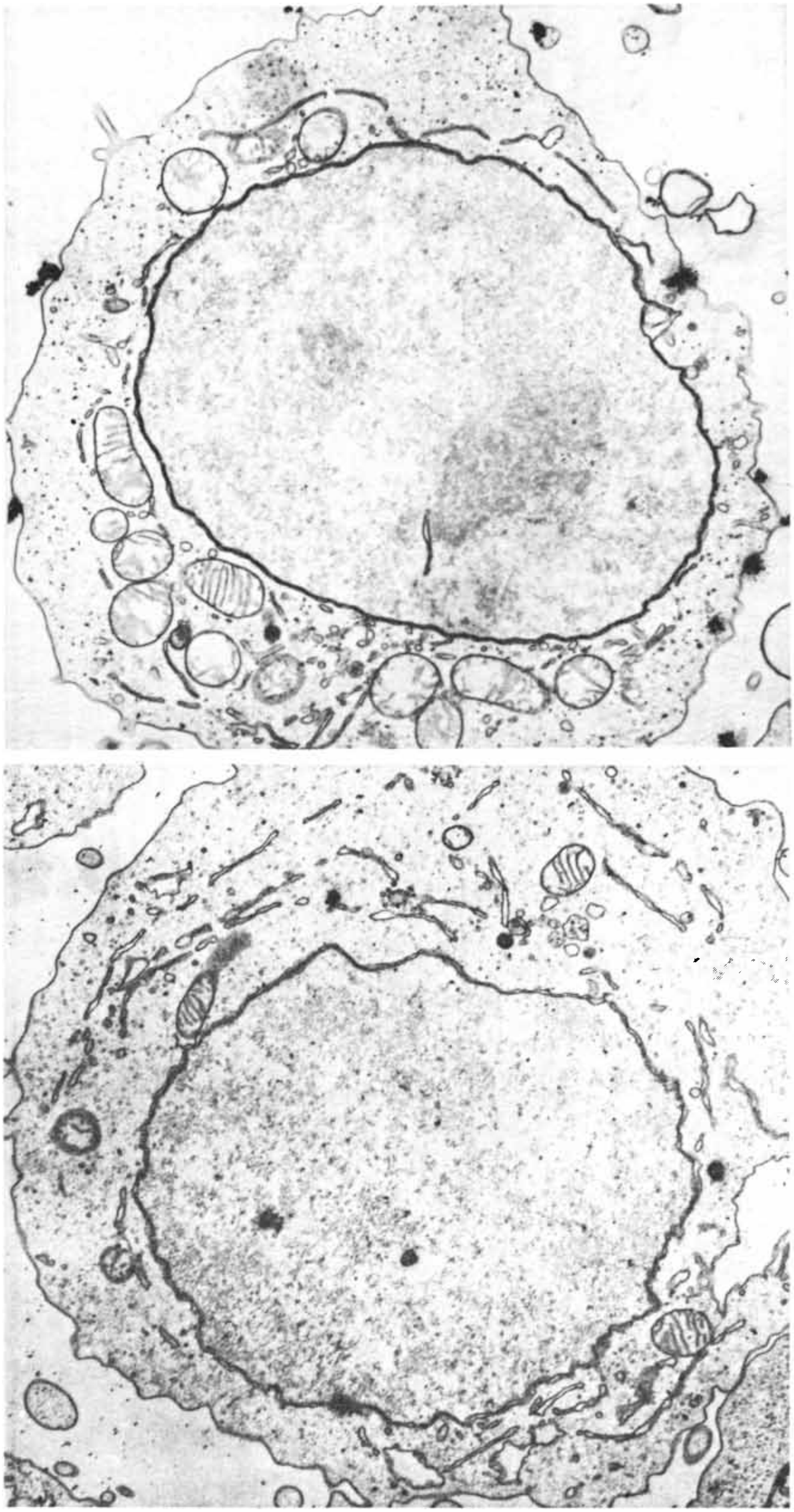
cepts of cell physiology are revolutionizing concepts of many common disease processes. An example is cholera, one of mankind's worst scourges. Although cholera has for years been known to be caused by the ingestion of large numbers of the bacillus *Vibrio cholerae,* the disease itself is not an infection. The microorganism does not invade the tissues; it merely colonizes the intestinal canal for a few days. It cannot penetrate or burrow between the cells that line the gut, it is incapable of gaining access to the lymph channels and it does not enter the bloodstream. There is no microscopic evidence that it damages any tissue. The entire disease process, which kills half of its untreated victims, is the result of the fact that cells in the intestine respond to a chemical substance released by the bacteria as if it were a normal regulatory signal.

Error in Cholera

The principal functions of the small intestine are the digestion and absorption of food. These processes are carried out by the degradation of proteins, carbohydrates and fats by specific enzymes secreted in the small intestine and the pancreas. The enzymes work best in an alkaline fluid. Hence when food is delivered from the stomach to the small intestine, a chemical signal (of uncertain origin) interacts with receptors on the cells of the small intestine and stimulates an adenylate cyclase system that leads to the pumping of about two liters of alkaline fluid into the intestinal canal. The fluid provides a medium for the digestion of food and then is reabsorbed farther along in the small intestine and in the colon.

The work of many investigators has led to the current recognition that a dysfunction of receptors is the key to cholera. W. E. van Heyningen and his colleagues at the University of Oxford and the Johns Hopkins University School of Medicine demonstrated that the toxin produced by cholera bacteria binds to receptor sites on cells lining the small intestine. Two groups at the Harvard Medical School (Daniel V. Kimberg, Michael Field and their associates and Geoffrey W. Sharp and Sixtus Hynie) established that the toxin of cholera bacteria causes the secretion of fluid by the small intestine by increasing the activity of adenylate cyclase in cells of the intestinal mucosa.

The molecule of the cholera toxin consists of two subunits. One binds with a patch on the surface of the receptor. The other, which is held in place by the first, stimulates the adenylate cyclase system into such overactivity that the cells pump from 20 to 30 liters of water into the small intestine. Because fluid cannot be reabsorbed at that rate massive amounts of it are lost through vomiting and diarrhea. These huge losses



MOVEMENT OF MEDIATOR, in this case insulin, is shown in these electron micrographs of cultured human lymphocytes, or lymph cells. The cells were incubated with radioactively labeled insulin and then autoradiographs were made; the insulin appears as black spots of irregular shape. In the upper micrograph, made after 30 seconds, all the insulin is around the perimeter of the cell. In the lower micrograph, made after 30 minutes, the insulin has penetrated the cell and some of it appears to be inside the nucleus. Presumably the insulin was bound to receptors that are specific for it and that cause it to be moved inside the cell. Micrographs, enlarged 13,300 diameters, were made by I. D. Goldfine of the University of California at San Francisco.

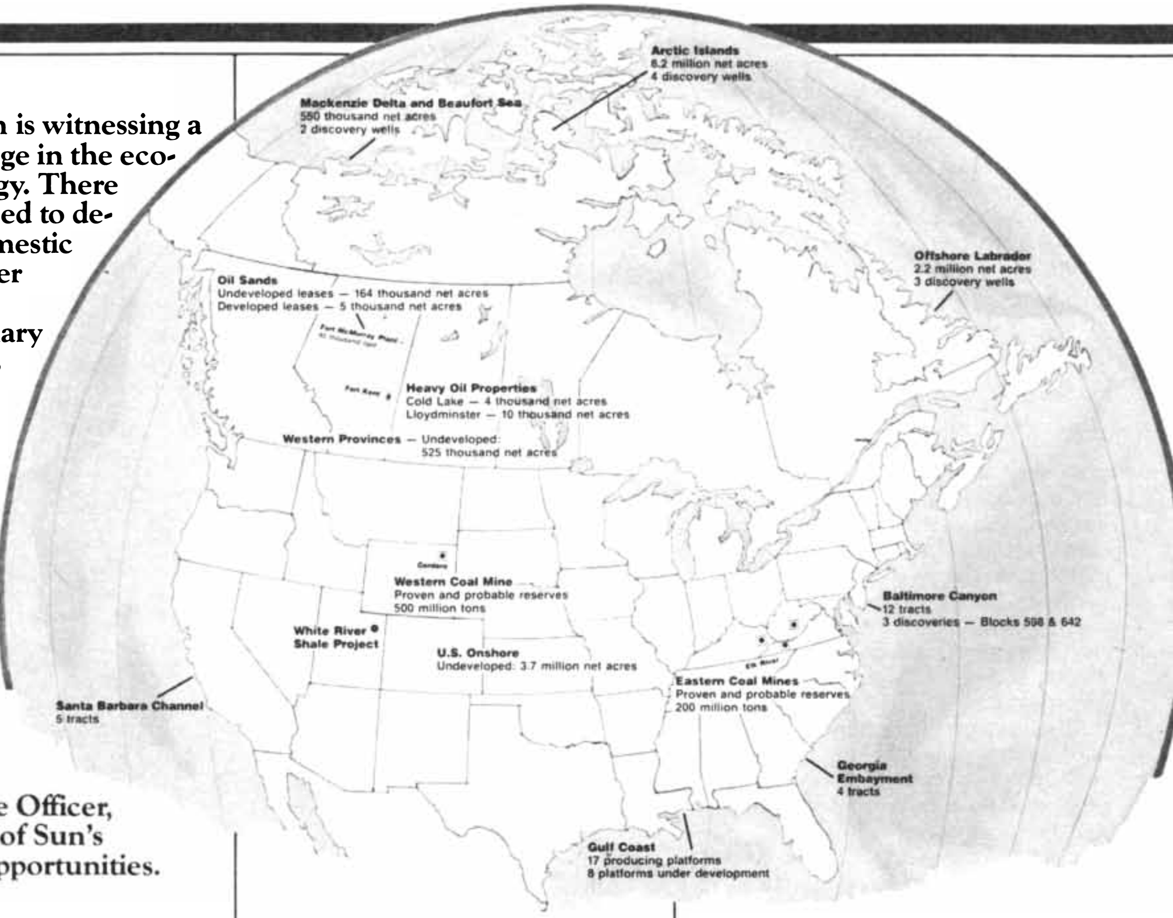
A SUN COMPANY

North American E

The nation is witnessing a structural change in the economics of energy. There is an intense need to develop more domestic energy than ever before.

Sun's primary response to this challenge will be to increase capital spending in the energy areas, and to develop more energy on the North American continent.

Here Theodore A. Burtis, Sun Chairman and Chief Executive Officer, discusses some of Sun's activities and opportunities.



Sun and other oil companies have been earning record profits. How does Sun plan to use the additional income?

For the next three years, Sun Company plans a capital program (including acquisitions) averaging $1.2 billion per year. Together with $1.1 billion for 1979, this nearly doubles Sun's average yearly capital spending for the 1976-78 period.

Sun's major focus in 1980 through 1982 will be on North American energy development, with approximately 60 percent — $730 million per year — allocated for oil and natural gas, oil sands, coal, and alternate energy development.

Are higher prices stimulating an increase in development of Sun's oil and gas producing properties?

Yes. Relative to other long-time producers, Sun has a large volume of lower tier production — from oil fields developed before 1973. Decontrol provided the economic incentive to improve production on these properties. But it now appears that the "windfall profits tax" will reduce that incentive and prevent us from maximizing production from these existing fields. Nonetheless, current drilling and development activities have been stepped up substantially.

Drilling activity is also up sharply to enhance natural gas production. Onshore areas will receive major emphasis, including our expanding program in Western "tight" gas sands.

Overall, Sun plans to drill a yearly average of some 500 net development wells during 1980-82. This represents a 25 percent increase over 1979 activity.

What is the status of Sun's domestic offshore exploration activities?

Sun is active in all the prospective areas, including the Baltimore Canyon, Georgia Embayment and the Santa Barbara Channel.

You're staying with the Baltimore Canyon?

Yes, we are optimistic about our holdings there. The industry as a whole has spent some $2 billion for lease bonuses and 20 exploration wells there. Sun, fortunately, has an interest in each of the three discoveries to date. We have a 16 percent interest in Block 598, where the first discovery was made in 1978. We recently acquired 20 percent of Block 642 (directly south of 598) on which there have been two discovery wells. All three wells have indicated natural gas potential. A fourth well is being drilled to further delineate the structure.

What about onshore?

In 1979, Sun participated in 16 successful wells in 68 exploratory completions in the United States.

Of particular interest are recent discoveries in the Williston Basin of Northeastern Montana. Currently, we have 650,000 net acres in the Basin.

ROGRESS REPORT:
nergy Development

In addition, Sun has 200,000 net acres in the Rocky Mountain Overthrust Belt.

What's the outlook for Sun in Canada?

Two related events in Canada in 1979 have greatly enhanced Sun's position in North American energy development. The first, in April, was the attainment of world prices for synthetic crude in connection with previously announced plans to expand oil sands capacity.

The second event was the amalgamation of Great Canadian Oil Sands Limited with Sun Oil Company Limited, consummated in August. The product of this amalgamation is our new subsidiary, Suncor Inc.

How big is Suncor?

Suncor Inc. is the fifth largest integrated oil company in Canada. It has a broad and extensive land position in all the prospective areas, and sufficient cash flow generated by existing operations to fund aggressive exploration and development of its acreage.

Exploration and production spending in Canada over the 1980-82 period will exceed $340 million (Canadian). This sum includes exploration and production in the Western Provinces, exploration in the frontier areas, and further investment in heavy oil development.

Work is also in progress on a $185 million (Canadian) project to expand oil sands capacity by 13,000 barrels per day.

Suncor is involved in all the major petroleum developments occurring in Canada. This was one important reason for the amalgamation — to bring together a company with a balance of near-term and long-range potential.

What is Sun's position in coal today?

We're very active in coal, and intend to be an aggressive competitor in both the Western and Eastern coal markets.

Sun's Cordero Mine near Gillette, Wyoming, is one of the country's largest mines, with proven and probable reserves of over 500 million tons. We have entered the first phase of a program to double the mine capacity. A coal storage barn under construction will allow the mine to load its fully permitted capacity of 24 million tons a year.

Recently, Sun acquired Elk River Resources, an Eastern coal company, for $300 million in Sun common stock. In 1979, Elk River's mining and coking operations in Kentucky, West Virginia and Virginia produced 4 million tons of coal and 470,000 tons of coke. The Elk River acquisition gives Sun an additional 200 million tons of proven and probable reserves of Eastern coal.

The combination of Sun's output from Cordero and Elk River operations is expected to be 11 million tons per year in 1980 and 14-15 million tons by 1982.

What will this increased spending mean in terms of Sun's production?

Our North American energy output on a BTU equivalent basis will increase by approximately 20 percent between now and the end of 1982. We intend to moderate the decline of our oil and gas production in the early 1980's. Sun's increases in synthetic crude and coal production will more than offset our declines in oil and gas on a BTU equivalent basis.

Do you see any growth opportunities downstream?

In the area of terminalling, we see major growth. Sun plans to invest about $50 million per year to expand existing terminalling business over the next three years.

At this time, 13 percent of all crude oil brought into the U.S. comes over Sun's Gulf Coast docks. Throughput has increased strongly over the past three years, as has profitability. Today 95 percent of our terminalling business is for third parties.

What about financial resources?

In the uncertain environment of the 1980's, Sun's strong balance sheet will provide adequate access to financial resources. As a percent of total capitalization, we have a current long-term debt of only 18 percent. Consequently, we will be able to invest well in excess of $1.2 billion per year to capitalize on additional energy development opportunities, depending on whether the government provides a favorable climate.

What about future dividends?

Sun's management recognizes its responsibility to adequately reward shareholders with a competitive dividend payout. To help ensure "fair valuation" of Sun's stock, we feel that working toward a dividend payout in the range of 35 percent of sustainable earnings is appropriate.

Are Sun's earnings sustainable?

Yes, based on our current interpretation of the industry's economic and political environment, we feel that Sun's earning potential has moved to a higher plateau. While some components of Sun's 1979 earnings may not be sustainable, we recognize upside profit potential in several areas — oil and natural gas, oil sands, coal and terminalling. Of course, we are aware that any major legislative setback could alter this outlook as well as inhibit Sun's energy program.

Our capital program of $1.2 billion per year for the early 1980's reflects only those projects we consider highly probable at this time. Given a favorable environment for energy development, we are optimistic that we can develop opportunities over and above that capital spending level. Sun has the technological, organizational, and financial resources to do so, and this course of action would be in the best interests of the nation.

Sun
company

If you would like additional information about Sun, write Ella W. Wright, Director, Shareholder Relations, Sun Company, Inc., 100 Matsonford Road, Radnor, PA 19087.

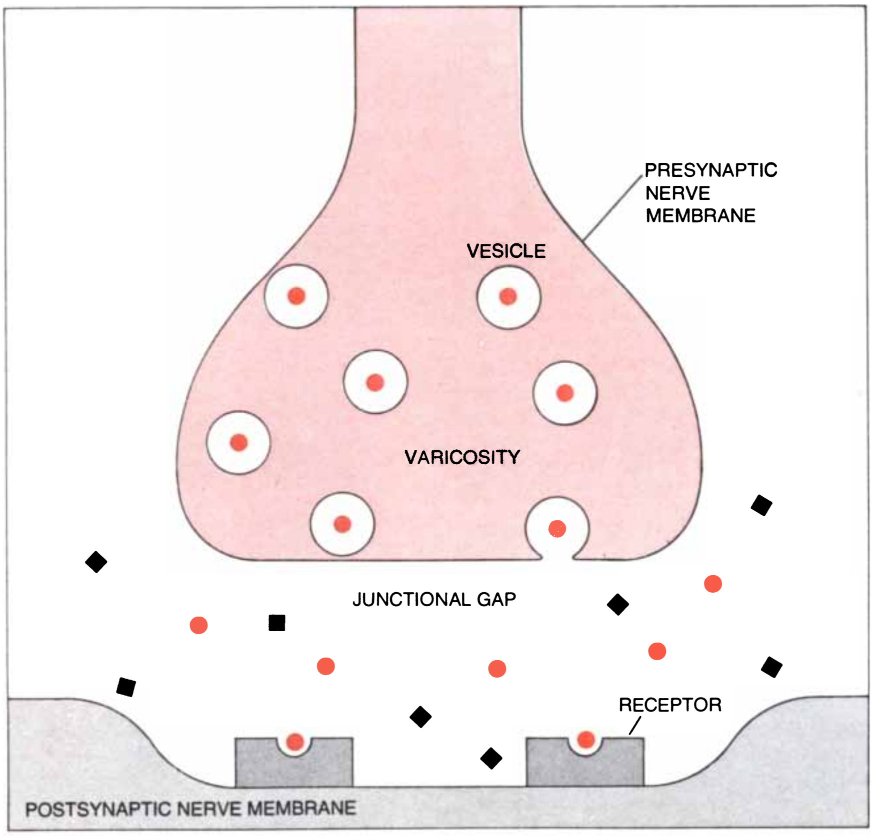
SPECIFICITY OF A CELL-COMMUNICATION SYSTEM is illustrated by the hormones oxytocin and vasopressin. Each of these hormones consists of nine amino acids. They are identical except at positions No. 3 and No. 8, and yet they have entirely different functions and presumably have different receptors. Oxytocin acts on the uterus, vasopressin on the kidney.

of liquid account for the many deaths from cholera. The threat to life can be countered by administering adequate amounts of fluid to the patient. The antibiotic tetracycline also helps, but only to the extent that it shortens the duration of the disease and reduces the likelihood that the patient will become a carrier.

Other Diseases

Graves' disease, a common cause of hyperthyroidism, is characterized by an enlargement of the thyroid gland and a massive overproduction of thyroid hormone. The excess output of the hormone has many adverse effects, largely because of hypermetabolism that is secondary to the inefficient expenditure of cell energy. The patient is likely to exhibit nervousness, tremor, a fast pulse rate, sweating, intolerance of heat, loss of weight and other symptoms.

Ordinarily thyroid-stimulating hormone (TSH), which is manufactured in the pituitary gland, governs the activity of the cells in the thyroid that produce thyroid hormone. Thyroid-stimulating hormone binds with receptors on the cells and then activates adenylate cyclase. The increased levels of cyclic AMP lead to the synthesis of thyroid hormone and its release into the circulation. Thyroid hormone in turn inhibits the release of thyroid-stimulating hormone by the pituitary gland. Hence a simple feedback-inhibition loop regulates the function of the thyroid gland.



NERVE-CELL COMMUNICATION takes place at synaptic junctions, one of which is depicted schematically here. The nerve cell ends in varicosities, or swellings, that contain packets of a transmitter substance, in this case acetylcholine (*color*). On the arrival of a nerve impulse the acetylcholine is released from the vesicles into the gap between the nerve cell and another cell. Receptors on the membrane of the latter cell bind only the acetylcholine and not any of the other chemical substances (*black squares*) nearby, and the signal is thereby transferred.

The base-line activity of the system is governed by thyroid-releasing hormone (TRH), which is manufactured in cells of the hypothalamus.

The blood plasma of patients with Graves' disease contains a thyroid-stimulating antibody. S. Qasim Mehdi and Joseph P. Kriss of the Stanford University School of Medicine have shown that this immunoglobulin interacts with receptors of thyroid-stimulating hormone in the cells of the thyroid gland, competes with the pituitary hormone and continuously activates the receptors. What triggers the production of the antibody remains unknown. Prior damage to thyroid tissue appears to be important in some instances; a genetic predisposition may also play a role.

In any event the thyroid gland is now driven by a stimulating antibody rather than by the normal regulatory hormone. Moreover, the feedback-inhibition loop has been broken. Overproduction and oversecretion of thyroid hormone ensue, and the patient develops all the serious clinical abnormalities associated with hyperthyroidism. The entire disease process appears to be the consequence of the functional similarity between a part of the antibody molecule and a part of the TSH molecule.

A somewhat similar mechanism is responsible for myasthenia gravis, an often serious disorder in which the patient develops a profound muscle weakness. The repetitive use of a muscle intensifies the symptoms. Jaw muscles become tired after prolonged chewing; the upper eyelids droop after they have been kept open for a sustained period; the voice falters in long conversations.

It is found that most of these patients have a circulating antibody that not only combines with receptors of acetylcholine in the end plates of the motor nerves but also destroys the receptors. Some patients show clear evidence of abnormal function of the thymus gland, which is responsible for the production of one class of immune cells. A passive transfer of the antibody across the placenta to the fetal circulation accounts for the occurrence of the disease in the offspring of affected mothers. Within weeks after birth the antibodies are degraded in the infant's tissues and the infant recovers spontaneously.

A series of ground-breaking experiments by Michael S. Brown and Joseph L. Goldstein of the University of Texas Health Science Center at Dallas has established that a dangerous form of elevated blood cholesterol is another disease of receptors. This disorder, which is inherited and transmitted to half of the offspring, results in a marked elevation of the level of cholesterol in the blood, premature coronary disease and deposits of cholesterol in the skin and certain tendons.

Cells require cholesterol to replenish cholesterol molecules in the cell mem-

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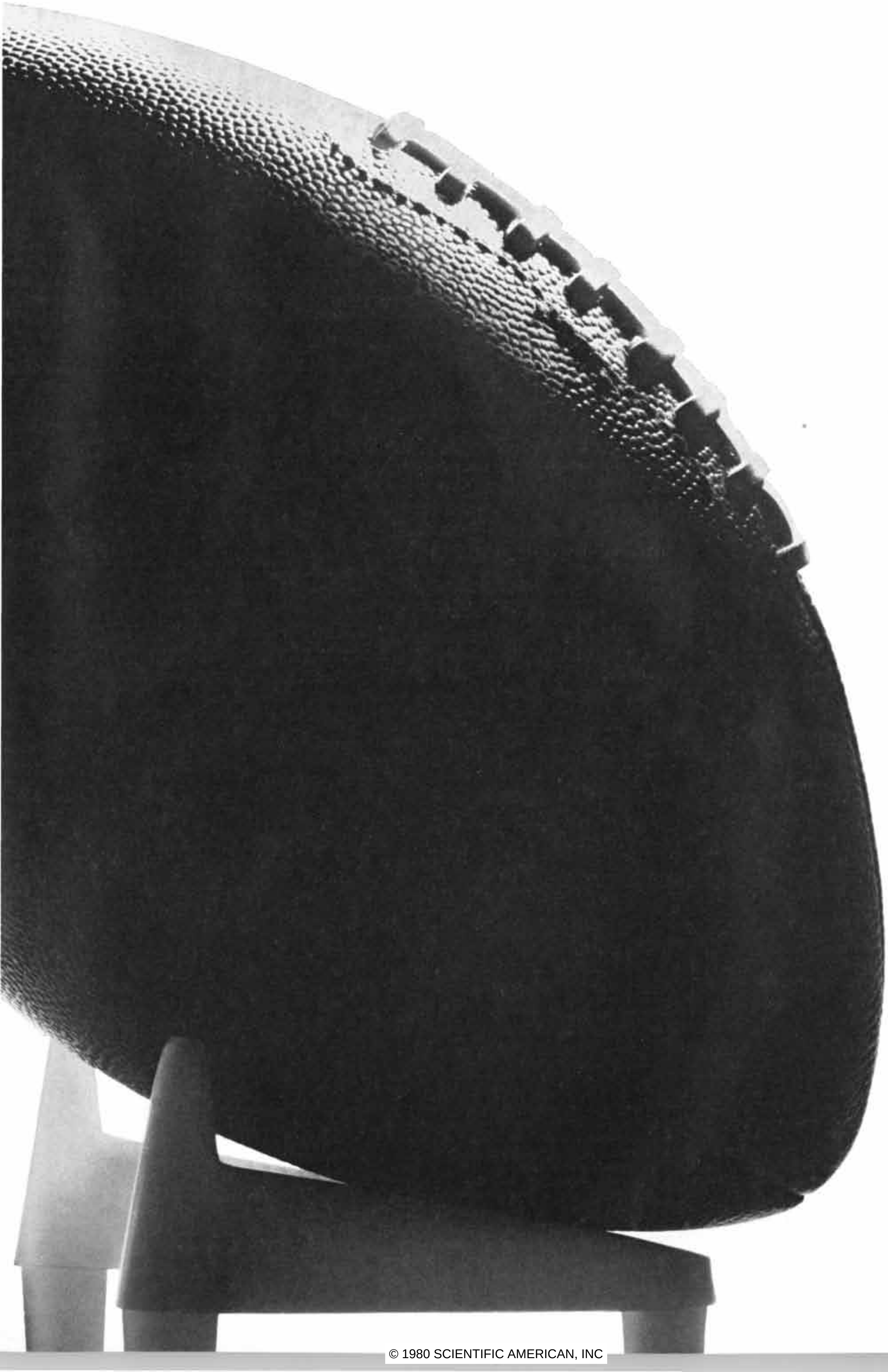
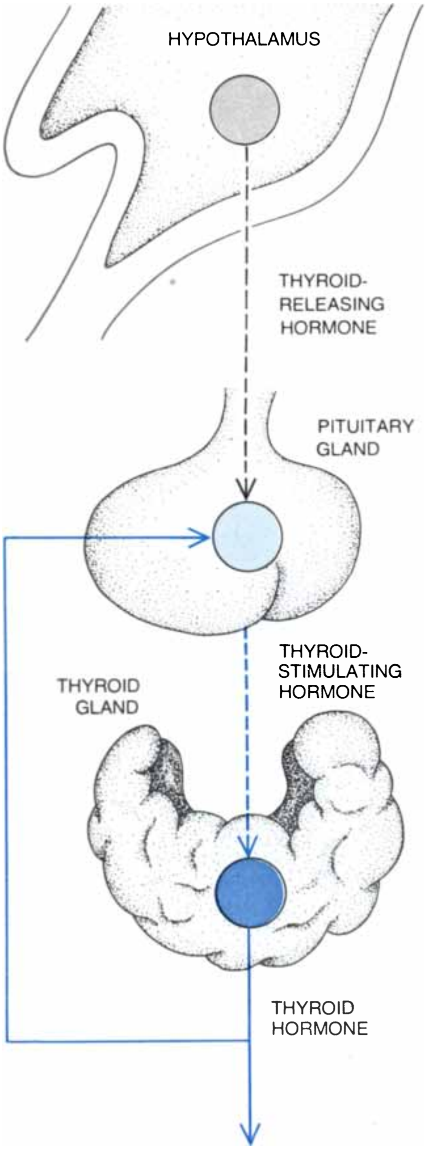


brane that have been lost through wear and tear. The liver synthesizes cholesterol from precursors and releases it into the blood as part of a low-density lipoprotein (LDL) molecule, which is removed from the blood by specific receptors on the cell membrane. When a cell is in need of supplemental supplies of cholesterol, there is an increase in the number of LDL receptors, which then intercept molecules of LDL that are flowing past the cell in the interstitial fluid. When the needs of the cell have been met, there is a decrease in the number of LDL receptors, allowing the LDL cholesterol to float past and reach other cells.



FEEDBACK-INHIBITION LOOP normally controls the hormonal activity of the hypothalamus, the pituitary gland and the thyroid gland. Thyroid-stimulating hormone, manufactured in the pituitary gland, governs the output of thyroid hormone from the thyroid gland. The rise in the level of thyroid hormone subsequently inhibits the release of thyroid-stimulating hormone. The entire system is controlled by thyroid-releasing hormone from the hypothalamus. In Graves' disease, a form of hyperthyroidism, a false signal is given by a thyroid-stimulating antibody in the blood. The thyroid gland overproduces thyroid hormone and feedback-control loop is broken.

Patients with familial hypercholesterolemia, the name of the inherited disorder, are unable to produce adequate numbers of LDL receptors on cell membranes. The blood level of LDL (and therefore of cholesterol) increases, and the damaging effects of excessive cholesterol in the blood ensue. People who are homozygous for this disorder (have inherited the defective gene from both parents) have virtually no LDL receptors. They develop exceedingly high levels of LDL cholesterol in the plasma and often suffer fatal coronary disease in childhood or adolescence. The disorder can be detected early in fetal life by analyzing amniotic fluid. The parents can then be counseled about the difficulties that lie ahead. Another form of the disease has been recognized in which the number of LDL receptors is normal but the process by which cholesterol-laden receptors are moved from the cell's surface to its interior is impaired.

Diabetes and Insulin

A number of types of diabetes mellitus, some of which are common, are now thought to be associated with the defective function of receptors. The tale begins with the interaction of blood glucose and insulin. Blood glucose, which is derived either from the digestive breakdown and absorption of dietary carbohydrates or from stores or manufacture in the liver, is an important source of energy and of building-block molecules for cells. It is essential for the minute-to-minute survival of neurons in the central nervous system. Glucose cannot gain entrance through the membranes of muscle and fat cells without the mediation of insulin. As the concentration of glucose in the blood rises after a meal, the level of insulin in the blood (manufactured and released by the beta cells of the pancreas) increases similarly. The insulin activates specific receptors in cell membranes. The receptors probably provide a passageway through which glucose and other substances can enter.

It has recently been shown that soon after insulin combines with receptors the receptors move from the membrane to target structures within the cell. The movement is highly directed. Eventually many of the insulin-receptor complexes take up positions on the surface of the membrane of the cell nucleus, where they presumably cause some of the long-term biosynthetic effects associated with the action of insulin.

Insulin also plays a key role in regulating the metabolism of carbohydrate. When the level of insulin in the blood plasma is high, the liver stores glucose in the form of glycogen. When the level of insulin in the plasma is low, glycogen is broken down and glucose is released into the bloodstream.

How does impaired communication among cells cause diabetes? One form of the disease, called juvenile, brittle or insulin-dependent diabetes, is probably the result of a viral infection of the beta cells of the pancreas. Either the viral invasion itself or the antibodies produced against the virus destroy the beta cells and permanently halt the manufacture of insulin. In people with such a severe deficiency of insulin the liver releases large amounts of glucose that cannot be taken up by muscle and fat cells. The concentration of glucose in the blood rises sharply. The administration of insulin by injection stops the overproduction of glucose by the liver and activates the receptors, so that the sugar can gain entry to the cells, and thereby reverses many of the metabolic derangements associated with this type of diabetes.

Gerald M. Reaven and Jerrold M. Olefsky of the Stanford School of Medicine have shown that there are reduced numbers of insulin receptors on the cells of several types of tissue in a common form of diabetes that appears primarily in middle-aged people. In some of these people the output of insulin seems to be excessive. When the disease occurs in association with obesity, an improvement can be brought about by a reduction of weight. The concentration of insulin receptors on cell membranes appears to increase as the excess intake of calories is corrected. Whether or not the improvement in the diabetes is attributable to the increased number of insulin receptors, however, has not yet been established. Another form of diabetes has been attributed to a structural abnormality of insulin.

Jesse Roth and his co-workers at the National Institute of Arthritis, Metabolism, and Digestive Diseases have shown that obesity in general is associated with a decrease in the number of insulin receptors and that the number returns to normal when the calorie intake is made negative, that is, less than the person needs to maintain a given weight level. The same workers have demonstrated a decreased affinity of receptors for insulin in the rare disease known as ataxia telangiectasia. (The victims of this genetic disease suffer from uncoordinated muscle contractions and recurring infections owing to an impaired immune response.) Such studies have provided strong evidence that insulin receptors play a role in certain disorders of glucose metabolism.

In a related study at the National Institutes of Health, Jana B. Havrankova, Michael J. Brownstein and Roth found insulin receptors widely distributed throughout the brain of the rat. Although it is not clear whether the recep-

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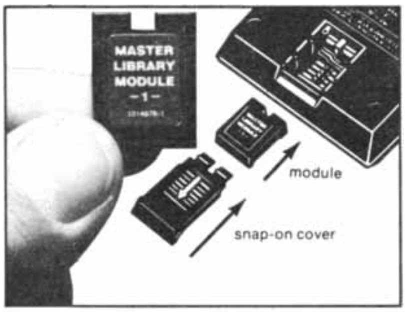

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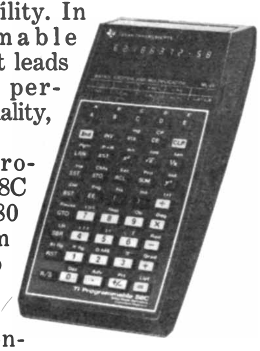

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tors are on nerve cells or on the cells of supporting connective tissue and blood vessels, their high concentration in the pathways controlling feeding activity is an intriguing discovery. It has long been known that insulin is not required for the entry of glucose into the neurons of the central nervous system. Does insulin then play some other role there, such as influencing the appetite? Does this finding provide a clue to the link between overeating and diabetes?

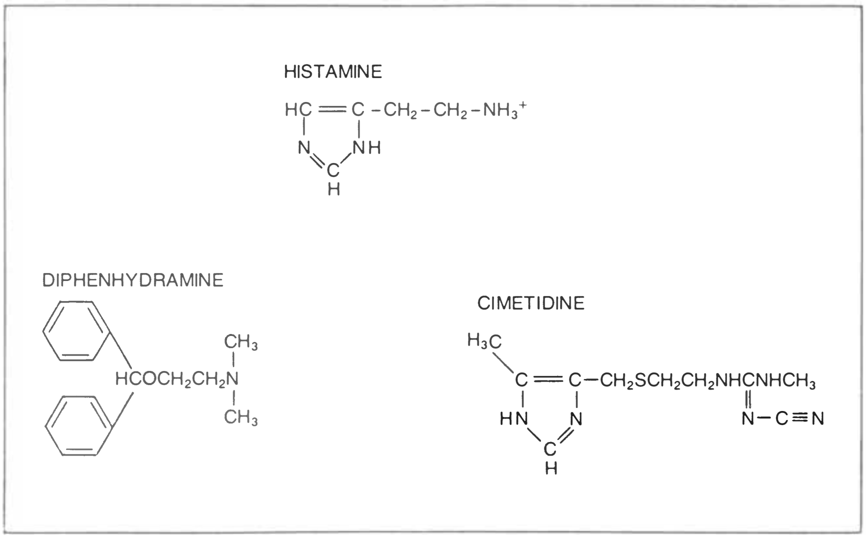
Substances in the Brain

A large number of other chemical substances are concentrated in brain cells but do not serve as neurotransmitters. Many of them appear to be modulators of the activity of nerve cells, scaling up or down the response at a synapse to the arrival of various electrical inputs. The compounds include sex hormones, prostaglandins, adrenal glucocorticoids and endogenous opioids. (A remarkable endogenous opioid, a brain peptide with a high specificity for its receptor, was recently discovered by Avram Goldstein of the Stanford School of Medicine and the Addiction Research Foundation and named dynorphin by him. It is 200 times more potent than morphine and 50 times more potent than the previously identified beta endorphin. Its function may be related to how the brain regulates the tolerance of pain.) Some of the compounds appear to interact with biochemical processes directly, whereas others function through specific receptors.

Studies in rodents have shown that gonadal hormones not only influence urges and drives but also play an important role during critical periods of early development in determining the sexual differentiation of the brain. It is likely that in such animals sex steroids influence the development of neuronal pathways and the function of neurons.

The relative importance of hormonal and environmental influences on gender development in human beings is the subject of controversy. Studies by Julianne Imperato-McGinley and her co-workers at the Cornell University Medical College and at the National University Pedro Henríquez Ureña in the Dominican Republic of a rare genetic form of pseudohermaphroditism found among villagers in the Dominican Republic appear to indicate that androgens play an important role in the formation of male gender identity. During or shortly after puberty almost all the affected children, who have male chromosomes and levels of testosterone in the blood that are typical of boys but who have been raised as girls because their external genitalia appear to be female, change their gender identity and gender roles. Clearly more information is needed about the contributions of chromosomes, gonads, hormones and receptors (including sex-hormone receptors in the brain) to resolve some of the complex issues surrounding gender dysfunction.

Indirect evidence of impaired chemical communication among cells has been found in a number of abnormal behavioral states. For example, functional deficiencies of the neurotransmitters serotonin and norepinephrine appear to be involved in some forms of depression, which can be precipitated or exacerbated by the administration of drugs that deplete the neuronal supply of those compounds. Recently it has been found that some antidepressant drugs act by blocking certain histamine receptors in the brain. Many of the manifestations of schizophrenic states appear to be the expression of excessive activity of dopamine in certain nerve pathways. The symptoms are intensified by the dopaminelike effects of amphetamines and relieved by a large number of antipsychotic agents, all of which are known to block neurotransmission involving dopamine.



HISTAMINE AS MESSENGER evokes responses from two different kinds of receptors. The H_1 receptors are in the respiratory tract and mediate the events of hay fever and asthma; the H_2 receptors are in the stomach and mediate the secretion of hydrochloric acid. Curiously, the molecular structure of the conventional antihistamine drug, diphenhydramine, which acts by blocking H_1 receptors, bears no resemblance to that of histamine, whereas the structure of cimetidine and related compounds, which block H_2 receptors, is similar to that of histamine. Ordinarily a substance that mimics the effects of a mediator resembles the mediator itself.

Several neurological diseases are now viewed as probable examples of neurotransmitter dysfunction. Consider Parkinson's disease, which is the result of damage to certain lower centers in the brain caused by encephalitis, arteriosclerosis, poisons or metabolic defects. Its symptoms are disturbances in gait or posture characterized by the failure of the arms to swing during walking and by small, shuffling and slow footsteps, interrupted by sudden, spontaneous, hurried movements that propel the body forward in a bent-over position. Spasticity of the muscles of the eyelids, cheeks and mouth irons out the facial expression of emotions, which are feebly communicated even when they are deeply felt. Rhythmical tremors often appear, particularly when the affected person is at rest.

Chemical analysis of the brain tissues involved in Parkinsonism has revealed a marked depletion of dopamine and its metabolites. Because dopamine cannot penetrate the walls of the capillaries in the brain a precursor, L-DOPA, is employed therapeutically to replenish the supplies of the neurotransmitter. The treatment has been further refined by the addition of a drug that inhibits the breakdown of L-DOPA in the peripheral tissues. In some patients the regimen is of little benefit; in others it is remarkably effective, probably because the underlying defect is limited to functions for which dopamine is the mediator.

Another possible neurotransmitter disease is Huntington's chorea, a devastating hereditary disorder of the central nervous system that causes a progressive dementia and ceaseless jerky and writhing movements. The disease is not clinically evident until the afflicted person is well into adult life, and therefore it is frequently passed to individuals in the next generation, half of whom will be affected. Victims often go through years of dread and depression, and a frequent cause of death is suicide.

Certain areas of the brain of patients dying of this disease show large losses of neurons that contain the neurotransmitter gamma-aminobutyric acid (GABA). Recent studies suggest that abnormalities of phospholipids in the membrane of the neuron prevent GABA from gaining access to its receptor. A search for an analogue drug capable of reaching brain cells and activating GABA receptors is under way. (GABA does not cross the physiological barrier between the blood and the brain.)

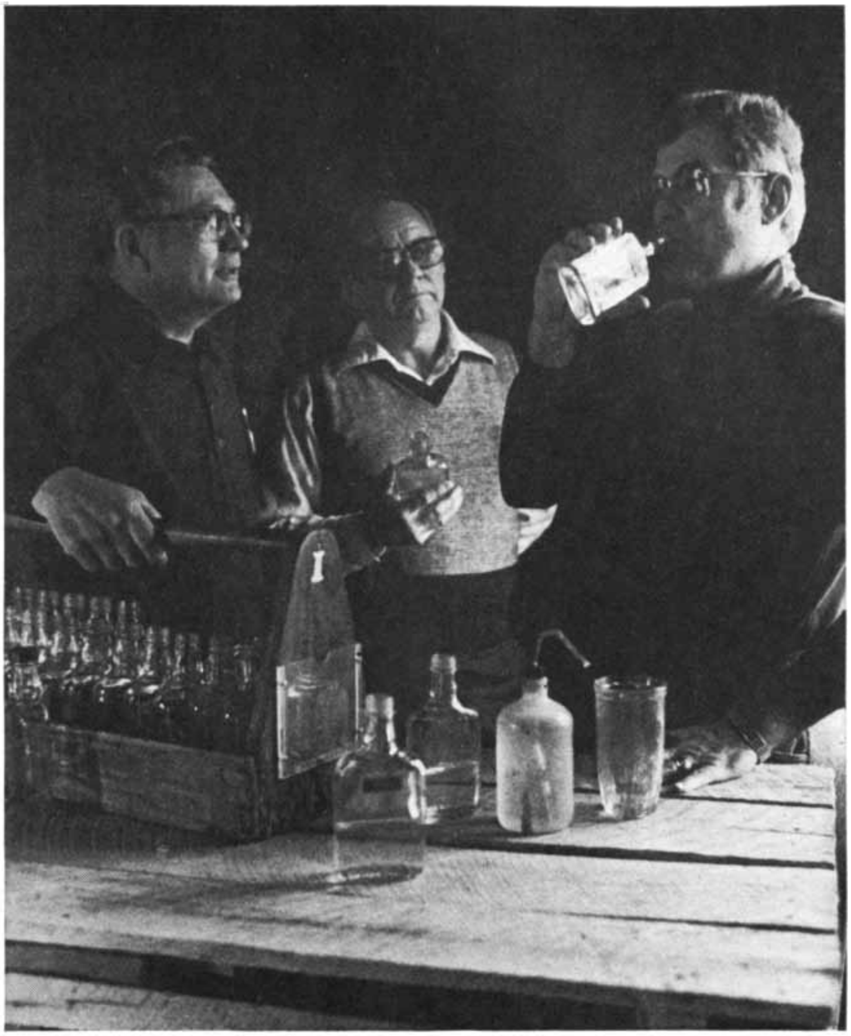
When specimens of primary breast cancer are obtained by biopsy or in the course of surgery, about two-thirds of them show the presence of receptors that bind estrogen. A reliable clinical assay for the detection of such receptors is now widely available. (Tumors from postmenopausal women are more likely to contain estrogen-binding receptors than tumors from premenopausal women, which is strange because the older women are no longer producing estrogen.) The majority of the breast cancers found to contain these receptors respond to hormonal manipulations, and the test is therefore useful in selecting patients for whom the treatment is likely to be effective.

At least two kinds of receptors respond to histamine and both are important in drug therapy. What are collectively called H_1 receptors are found in the respiratory tract; they mediate some of the vascular, smooth-muscle and secretory changes associated with hay fever and asthma. H_2 receptors are found mainly in the stomach; they mediate the gastric secretion of hydrochloric acid.

The conventional antihistamine drugs block H_1 receptors and have long served in the treatment of allergic disorders. Their chemical configuration bears no resemblance to that of histamine. Such agents have no effect on H_2 receptors. Compounds of a new class, related to the drug cimetidine, powerfully block H_2 receptors and are useful in reducing the secretion of acid in certain peptic ulcers. Cimetidine and similar compounds resemble histamine structurally and so serve as substitute mediators.

Another important new class of drugs blocks beta-adrenergic receptors in the heart and blood vessels. These agents, of which propranolol is at present the one most widely administered in the U.S., blunt the effects of adrenergic stimulation. They reduce the work of the heart during physical or psychic stress and so prevent attacks of chest pain in patients whose coronary blood flow is inadequate. The drugs are also effective in preventing certain types of heart-rhythm disorder and in treating some forms of high blood pressure.

The concepts of mediators, receptors and disordered communication among cells are new and are therefore difficult to put in proper perspective. Nevertheless, the ideas I have described (having mentioned only a few of the many investigators who have made important contributions to this field) represent important advances in biology and medicine. It is likely future research will reveal that many diseases are caused by the overproduction or underproduction of a mediator or by the faulty structure of receptors or of the organelles with which the receptors interact.



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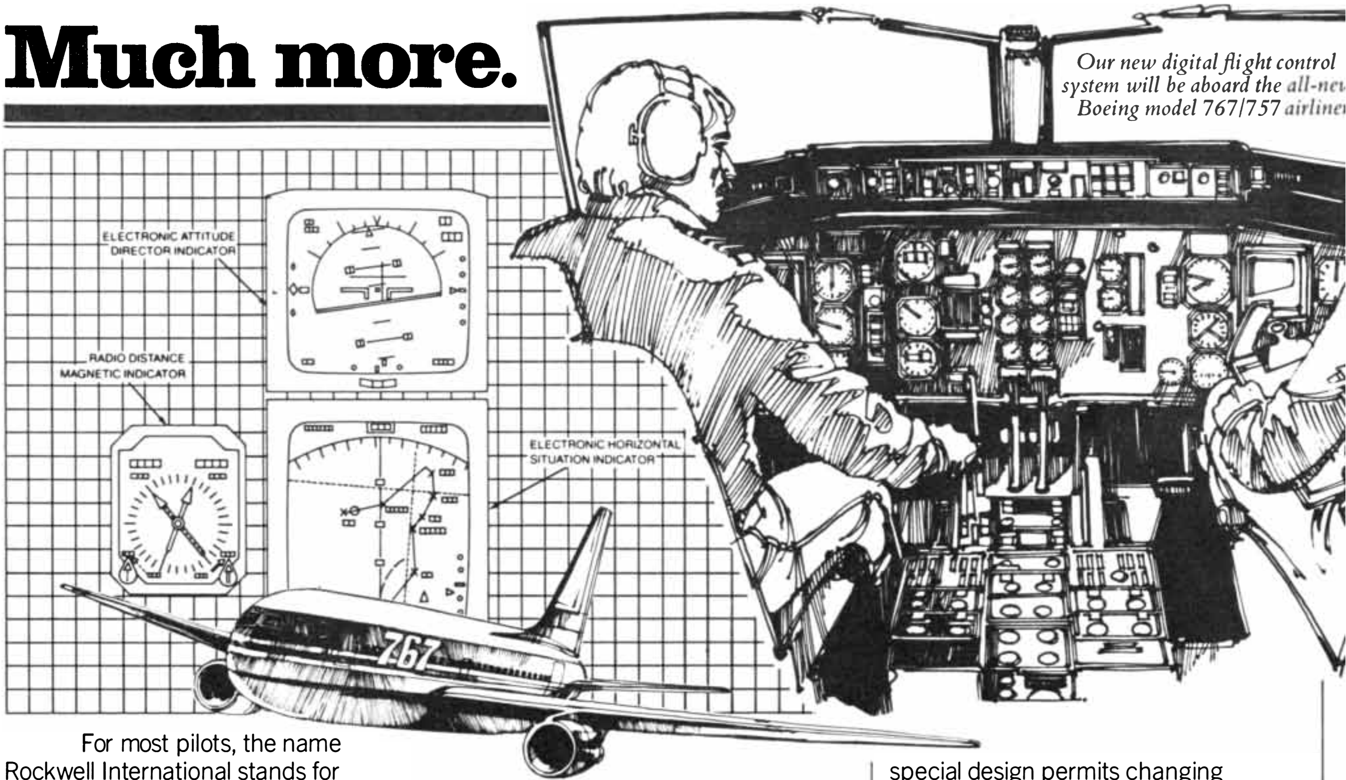

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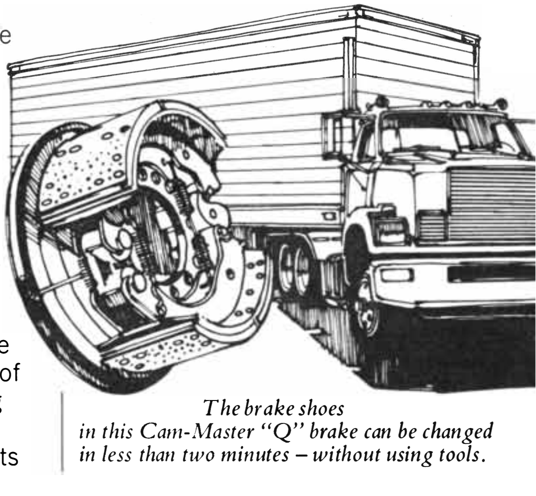

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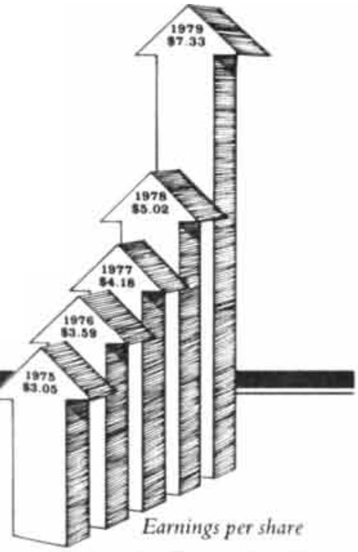

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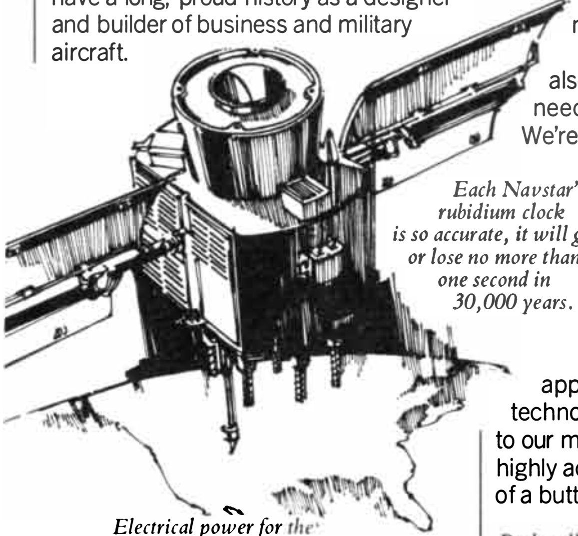

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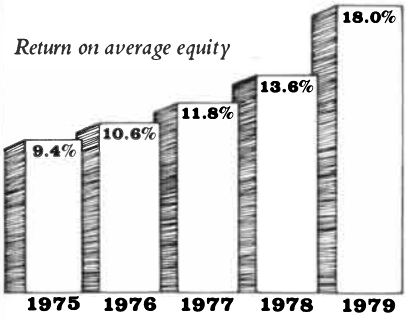

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The Spin of Comets

Puzzling changes in the orbital period of Comet Encke, which circles the sun every 3.3 years, can be attributed to the rotation of its icy nucleus and the thrust of gases evaporated from it

by Fred L. Whipple

A comet, like an atom, has a nucleus. The nuclei of comets, however, have been more elusive than those of atoms. The atomic nucleus was first identified in 1911, some 40 years before I was able to show that comets have a nucleus (which I likened to a dirty snowball). There was a somewhat greater interval between the introduction of the concept that atomic nuclei spin and the first measurements of a few rotation periods for comet nuclei in 1977. The spin axes of atomic nuclei have long been known to gyrate when they are subjected to a magnetic field. Here I shall describe the gyration of the spin axis of a comet nucleus.

In the study of the nuclei of atoms and the nuclei of comets two similarities stand out: invisibility and relative size. No one can see an atomic nucleus, and very rarely, if ever, can anyone see the true solid nucleus of a comet, even with the aid of a large telescope. The nucleus of an atom is about a hundred-thousandth of the diameter of the atom. A similar ratio holds for the nucleus of a comet with respect to the comet's gassy and dusty coma, or head, which is what is seen or photographed.

The physicist has had an advantage over the astronomer in the study of a body so much smaller than the object of which it is a part. Atoms are vastly more abundant than comets. Moreover, their nuclei have an electric charge and a magnetic polarity (because of their spin). Where the physicist can probe an atomic nucleus whenever laboratory apparatus is available, the astronomer must wait patiently for a distant view of one of the few comets that swing by. The astronomer's handicap would be greatly eased, however, if a proposed space mission were viewed favorably by Congress. The National Aeronautics and Space Administration has developed detailed plans for a spacecraft rendezvous with Halley's comet in November, 1985, followed by a prolonged visit three years later to a much less famous comet: Tempel 2. In a period of budgetary austerity funding for the mission is currently uncertain. Meanwhile astronomers do the best they can with the tools they have at hand.

The most valuable comet for the study of the comet nucleus is the one with the shortest orbital period (3.3 years), discovered in 1786 by Pierre Méchain but named for the German mathematician and physicist Johann Franz Encke. In 1819 Encke studied the motion of the comet and concluded that its motion deviated "wildly" from predictions based on Newton's law of gravitation. He found that its period was getting about 2½ hours shorter with every revolution around the sun.

At that time the decrease was ascribed to a resistant medium in space. It was even suggested that the medium might be the "luminiferous aether" supposedly needed to carry light waves through otherwise empty space. As late as 1950 an elementary textbook of astronomy stated that "a comet appears to be a swarm of relatively small and widely separated solid bodies held together loosely by mutual attraction." It is only such a "flying gravel bank" that would meet resistance in space. Larger solid bodies such as asteroids and planets show no such effect, and neither would a solid comet nucleus.

By 1868, however, the rate at which Comet Encke's period was getting shorter had mysteriously decreased and thereafter continued to do so. Today the decrease in period amounts to only a few minutes per revolution. By 1950 several other comets had also been observed to follow a pattern of erratic deviation from pure gravitational motion, some with decreasing periods like the period of Comet Encke but some with increasing ones. Halley's comet, for example, returns about four days late after each of its 76-year revolutions around the sun.

From such observations I developed my theory of the comet nucleus as a ball of dirty ice. Let us imagine that the ice ball is also rotating on its axis so that it has a day and a night. Points on its surface alternately face toward the sun and away from it. Surface ices will evaporate (more correctly, sublime) much faster when they are heated by the sun than they will at night, when they are exposed to the near absolute zero of black outer space. In the "morning" of each comet "day" the frigid ices are gradually warmed by the sun and reach a maximum temperature toward the late afternoon. The outflowing gases arising from the sublimating ices generate a reactive jet force that pushes the nucleus of the comet at an angle equal and opposite to the angle the thrust of maximum sublimation makes with a line drawn to the sun.

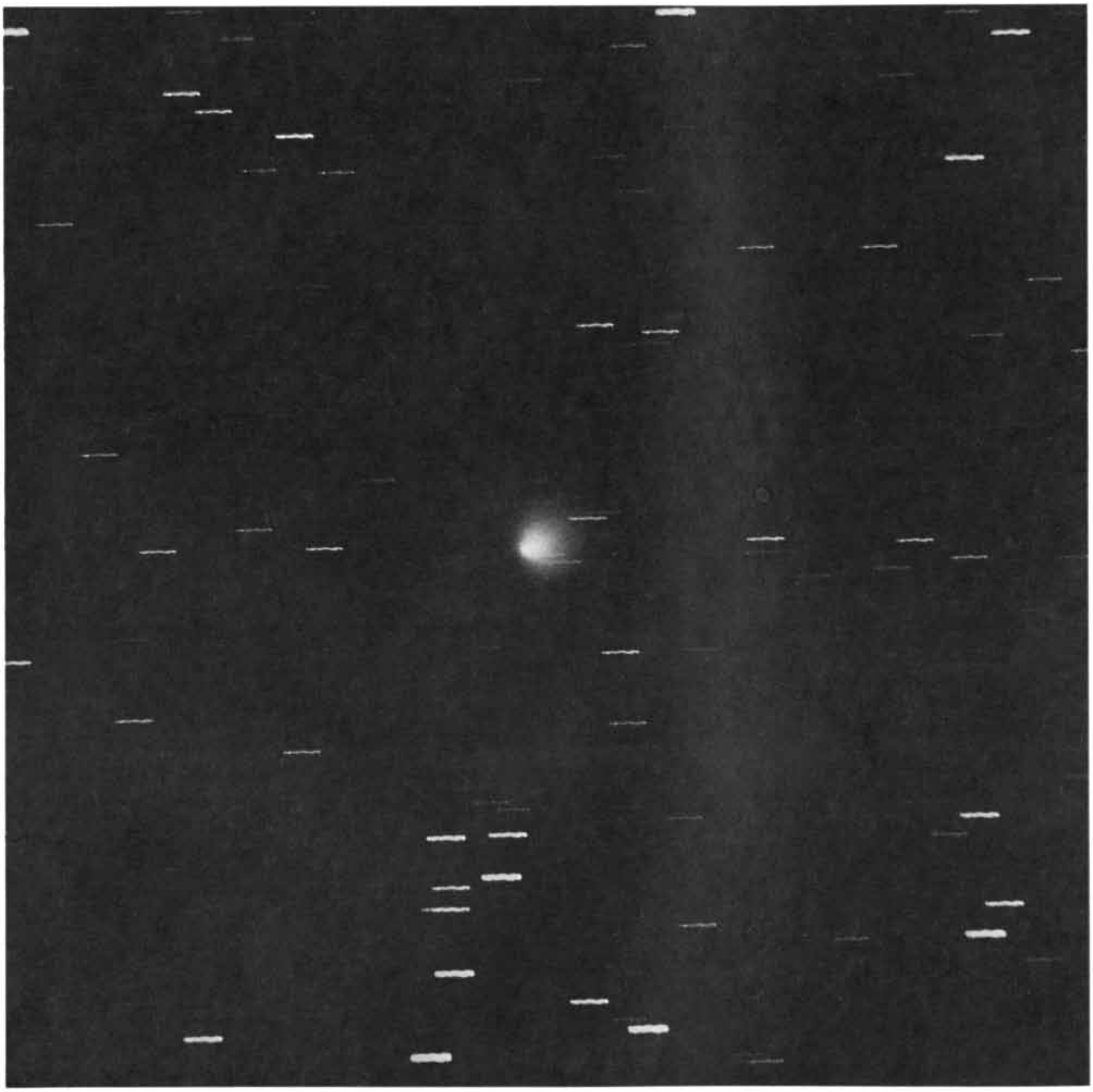
If the nucleus is rotating in a direction opposite to that in which it revolves around the sun, the afternoon jet thrust will oppose the comet's motion, thereby slightly reducing its orbit and hastening its arrival at perihelion: its closest approach to the sun. The reverse direction of rotation will accelerate the comet, thereby expanding its orbit and delaying its arrival at perihelion.

A reverse sense of rotation must therefore hold for Comet Encke and for about half of some three dozen other comets whose orbital-period changes have been determined by Brian G. Marsden and Zdenek Sekanina of the Smithsonian Astrophysical Observatory and Donald K. Yeomans of the Jet Propulsion Laboratory of the California Institute of Technology. A comet need lose only a small fraction of 1 percent of its total mass per revolution to account for the observed changes in period; most comets can therefore survive a great many revolutions around the sun before they exhaust their deep-freeze supply of ices.

Why, however, should the period change for Comet Encke be so drastically reduced in less than 200 years from 2½ hours per revolution to a few minutes? The popular explanation has been that Comet Encke is slowly losing mass and that the jet force has simply decreased over the period of observation. This explanation is somewhat too pat, even though Comet Encke may not be quite as bright as it was 200 years ago. (The brightness observations are open to question.) Still, the surface of an aging comet might accumulate dusty material that would cover up the volatile ices and so reduce the jet effect. On the other hand, why did the nongravitational change in period rise to a maximum in about 1810 and then fall?

Sekanina, my colleague at the Smithsonian Astrophysical Observatory, and I had long suspected that the real cause might lie in the changing spin axis of the nucleus. This could affect the geometry of the jet forces and so account for the phenomenon. But how could one find the spin axis of a tiny comet nucleus buried inside the coma, brilliant with fluorescing gases and dust-scattered sunlight? At about the same time we both came to approximately the same method, although we approached it from entirely different points of view. For the sake of brevity I shall describe only Sekanina's method, which applies directly to Comet Encke.

The delay time in the sublimation of ices on a rotating comet nucleus will cause the escaping gas and dust to form an asymmetrical or fan-shaped jet on the afternoon side of the nucleus. Generally the jet will point in a direction



COMET ENCKE, the comet with the shortest period of revolution around the sun (3.3 years), was photographed on November 22, 1937, 35 days before perihelion (the point at which the comet comes closest to the sun). Comet Encke was then 131 million kilometers from the sun and 43 million kilometers from the earth. Its distance from the sun at perihelion is about 51 million kilometers. Close inspection of such photographs discloses that the invisible solid nucleus of the comet is emitting a jet of volatilized gases at an angle that is not on a line with the sun. Normally the gas and dust surrounding a comet nucleus is formed into a tail pointing directly away from the sun. The asymmetrical jet is evidence that the nucleus of Comet Encke is spinning. Although Comet Encke is never a spectacular object, its frequent apparitions make it probably the most thoroughly studied comet. The photograph was made by George Van Biesbroeck with a 24-inch reflector at the Yerkes Observatory. Bright streaks in the background are stars in apparent motion as telescope tracked the moving comet.

different from that of the tail of the comet, which points directly away from the sun. The coma will be elongated or will be displaced from the bright region centered on the nucleus. Observers frequently note such asymmetries in the head of comets and record the direction of the jets and fans.

To determine the spin axis of a comet nucleus Sekanina wrote an elaborate computer program that provides for each comet observation a printout of a three-dimensional table. The table gives the position on the celestial sphere toward which a jet points for all possible directions of the spin axis and all possible angles of the lag in sublimation. From the table Sekanina can pick out the possible ranges of spin-axis direction and lag angle to fit each observation. The range of solutions narrows as he compares more observations.

Applying this method to four short-period comets, Sekanina discovered that as of 1947 the spin axis of Comet Encke was tilted five degrees with respect to the plane of the comet's orbit around the sun. At perihelion the spin axis made an angle of 25 degrees with respect to a line between the sun and the comet. The lag angle of the jet action was 45 degrees. Clearly the change of period caused by the jet action is complicated to calculate because the jet force varies tremendously both in amount and in direction as the comet travels around its orbit. Only by a numerical integration can one calculate how the orbital period should change. Without the modern electronic computer the task of integration would take a lifetime.

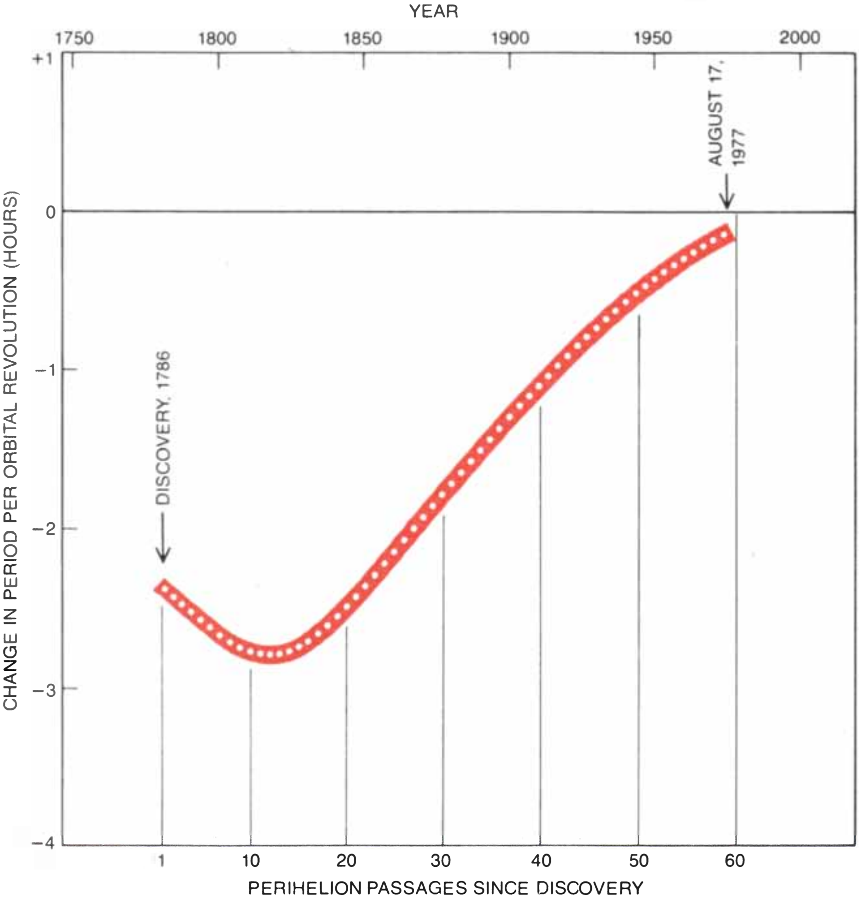
Sekanina and I next assumed that the nucleus of Comet Encke is not a sphere but an oblate spheroid, something like a doorknob. A nearly rigid rotating body in space will quickly adjust its spin axis and mass so that the spheroid rotates stably about its shortest axis. This is recognized in physics as the axis with the maximum moment of inertia. The geometry immediately indicates that the jet force perpendicular to the surface will rarely pass through the center of the nucleus. The result is an overturning force that tends to tip the pole of the nucleus in one direction or the other. It is well known, however, that a spinning top or a gyroscope does not respond to the pull of gravity by falling over. The pole of the top turns in a direction 90 degrees with respect to a plane defined by the force and the axis. Hence the oblate comet nucleus precesses like the earth, which is tipped by the pull of the moon and the sun on its equatorial bulge. For the earth the precession is extremely slow, having a period of about 25,000 years.

With the geometry in order for our computer programs, Sekanina and I devised a theoretical model of the jet force, which for comets increases faster near the sun than the inverse square of the distance to the sun. We were guided by the many observations showing that Comet Encke has a very peculiar light curve. Instead of brightening rather uniformly as it comes closest to the sun at perihelion and then dimming more slowly after perihelion, as most comets do, Comet Encke is brightest very nearly at perihelion and then almost immediately gets much dimmer than it was at the same distances before perihelion.

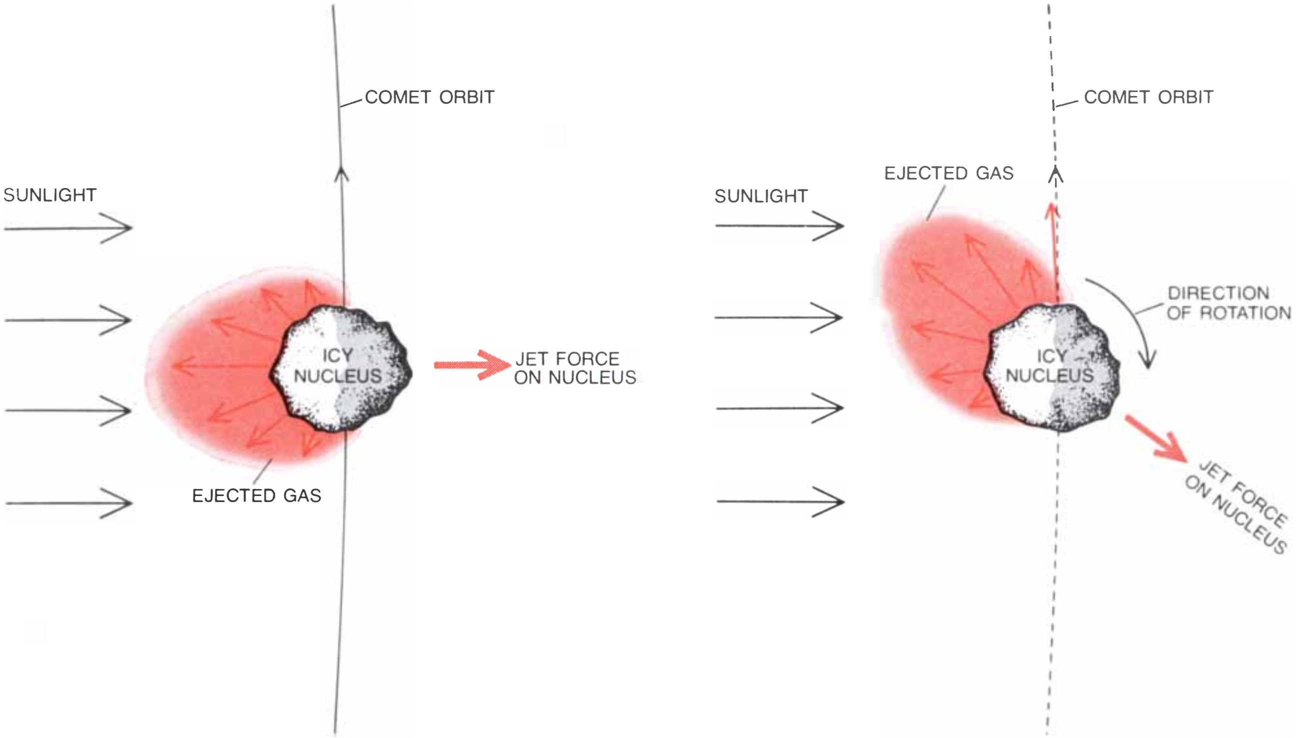
By 50 days after perihelion it is three magnitudes, or 16 times, dimmer than it was 50 days before it. The observations compel one to conclude that one polar hemisphere of the comet is much more active than the other. This conclusion gives an additional numerical relation for the jet force, determined by the latitude on the nucleus at which the sun is overhead at each moment in the comet's orbit. When the sun shines directly on the pole that approximately faces the sun just after perihelion, the comet is nearly three times fainter than it is when the sun shines on the opposite pole, a surprising fact demanded by the observations.

Separately we programmed two different computers, working with two different coordinate systems to calculate both the precession rate of the spin axis and the nongravitational orbital forces. The jet force varied in direction and amount with the actual position of the comet in its orbit from 1786 to 1977, representing 59 perihelion passages. We were gratified with the immediate results. They showed that the pole would sometimes precess as much as one degree a year, which accounts for the strange nongravitational motion of the comet.

After a number of iterations of the computations to fit the nongravitational motion determined by Marsden and Sekanina, we derived only small corrections of about four degrees in the direction of the polar axis and less than one degree in the lag angle of 45 degrees determined earlier by Sekanina. The solution reproduces the curve of observations within the accuracy of the orbital calculations [*see bottom illustration on page 130*]. Slight discrepancies between the observations and the calculated



CHANGES IN ORBITAL PERIOD of Comet Encke were first recognized in 1819 by Johann Franz Encke, for whom the comet was named. Encke found that the comet returned to perihelion some $2\frac{1}{2}$ hours early after each trip around its orbit. Since about 1830, however, the amount by which the orbital period is getting shorter has declined steadily; it is now only a matter of minutes. Colored curve is a highly smoothed representation of actual observations. White dots mark perihelion passages. The next perihelion passage will be on December 6 of this year.



THRUST OF VOLATILIZED GASES can alter the orbit and hence the period of a rotating comet. If the comet nucleus is nonrotating (*left*), surface ices heated by the sun can generate a small but steady jet force that will push the comet radially outward from the sun. Because the outward thrust constantly subtracts a small amount from the acceleration due to the sun's gravity the orbital period will not change from one revolution to the next. In principle it should be possible to tell if the radial jet force exists: a comet subjected to it should occupy an orbit slightly larger than the orbit of a comet in which the force is absent. In actuality the difference in the size of the orbit would probably amount to less than one part in 10^5 and so would be below the limit of detectability. If the comet nucleus happens to be rotating in a direction opposite to the direction of its motion around the sun (*right*), the thrust of volatilized gases will reach a peak in the "afternoon" of the comet's "day." The resulting jet force will subtract slightly from the kinetic energy of the comet, steadily contracting its orbit. As a result the comet's period will be observed to shorten slightly with each perihelion passage. A comet rotating in a direction opposite to the one at the right will experience an expansion of its orbit and therefore a lengthening of its period. Evidently shortening of Comet Encke's period has been basically due to the comet's rotation in a direction opposite to the direction in which it moves around the sun.

points are caused by the gravitational action of Jupiter. The pull of the giant planet changes the orbital plane of the comet by a fraction of a degree and consequently changes the geometry of the jet action.

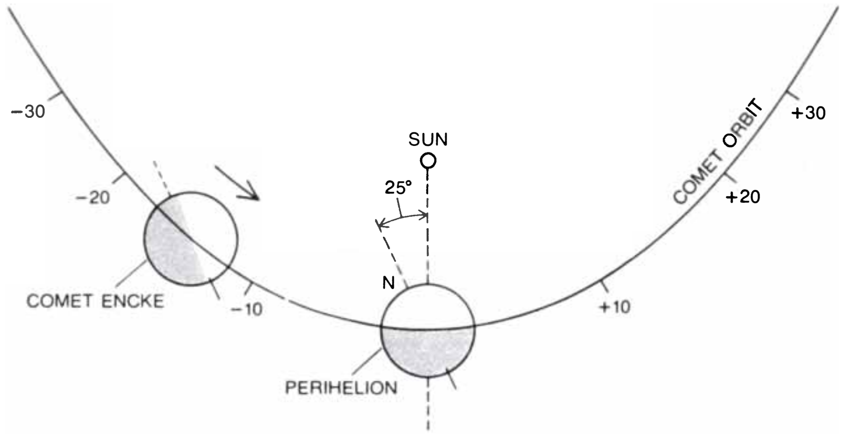
When we plotted the pointing direction of the spin axis of the nucleus of Comet Encke on the celestial sphere, we were astonished: in 191 years the pole of rotation of the nucleus has gyrated through more than 100 degrees across the sky. This large gyration completely accounts for the changes in the orbital period. The century-old mystery was solved.

One independent check on our theory remained. Would the calculated spin axis agree with the observed directions of the fans and asymmetrical comas, data that we had not used in developing our solution? To our delight the fit with more than 30 such observations from 1805 to 1904 was completely satisfactory, and the fit with the later observations used originally by Sekanina was greatly improved. The spin axis of Comet Encke has assuredly moved as is indicated by the calculations.

Where will the spin axis of Comet Encke be pointing in future years? Our calculations show that by 1990 the decrease in the period of the comet's revolution will stop and the period will begin to increase again. If the shape of the nucleus is not changed too much by the loss of ices, the spin axis will be almost perpendicular to the plane of the comet's orbit by the year 2200. Then the comet will be spinning like the earth: in the same sense as it revolves around the sun. Such a rotation axis is quite satisfactory for a planet but is eventually unstable for a comet. Since the sun shines mostly on the equatorial regions the nucleus will become spindle-shaped, elongated along its polar axis because of the loss of mass. The body of the comet will then twist around so that further prediction of the gyration is impossible today.

The past history of the spin axis is more interesting and determinable. According to our calculations, the axis was stuck in almost the same position for perhaps hundreds or even thousands of years before A.D. 1700. One pole was pointed nearly along the long axis of the orbit so that almost all the mass loss occurred on that polar hemisphere when the comet was close to the sun. Indeed, that hemisphere is the one we see today as being the most active. Is Comet Encke rockier or dustier on one side and icier on the other? Apparently it is. Is this property, however, basic to the structure of the comet? Sekanina and I prefer another explanation, one that does not call for such a drastic nonuniformity in the initial composition of the object.

Comets are known to blow quite sizable pieces of rocky material off into free orbit around the sun. When such comet debris happens to enter the atmosphere of the earth, it is seen as a meteor or a meteor shower. For a given comet at a given distance from the sun there is a limit on the size of the pieces the gas escaping from the ices can blow off. A comet nucleus is only one kilometer to a few kilometers in diameter, but it still has some small gravitational pull. The gas pressure, however, is also small. Sekanina and I suggest some of the particles near the size limit that are ejected from the most active areas of the comet go into long orbital trajectories and finally land on the night hemisphere of the nucleus. If one polar hemisphere never faces the sun except at great distances where the comet is inactive, the dusty or rocky debris slowly blankets that hemisphere during hundreds of rev-



ORIENTATION OF THE SPIN AXIS of Comet Encke in 1947 was determined by Zdenek Sekanina of the Smithsonian Astrophysical Observatory. On the basis of observed asymmetries in Comet Encke's appearance Sekanina concluded that the spin axis was rotated about 25 degrees eastward from a line drawn between the comet and the sun at perihelion. Pole nearest the sun (designated north) was tilted five degrees below the plane of the orbit. Ten-day intervals are marked on the orbit. At perihelion in 1947 comet was 51,017,000 kilometers from the sun.

olutions around the sun. By that time, the gyration having turned the inactive hemisphere toward the sun near perihelion, the blanket of debris insulates the underlying ices of the comet from the solar heat and greatly reduces the comet's activity. This sequence of events could account for the peculiar light curve of Comet Encke.

A space mission to Comet Encke could check this suggestion about the character of the comet nucleus. Otherwise astronomers hundreds of years from now might note that the rocky blanket had finally blown off the dark hemisphere, or perhaps determine that the nucleus is indeed lopsided with respect to icy and rocky material. The answer to the question is important in reconstructing the evolution of comets and of the entire solar system. Do larger comets have a rocky core? Do some of them finally lose their icy mantle and contribute small asteroids to the inner solar system?

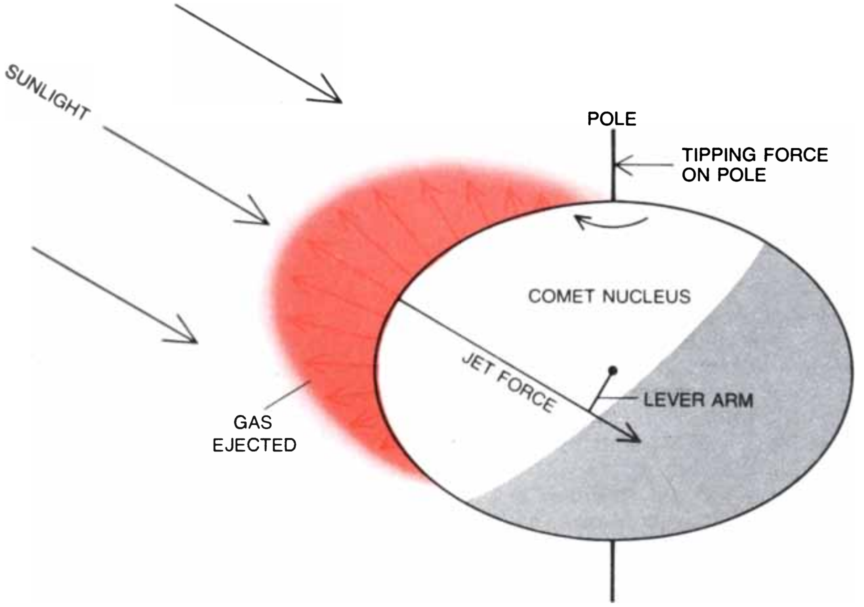
All the evidence of modern astronomy supports the idea that stars like the sun and their planetary systems (if any) originate in collapsing clouds of interstellar gas and dust. The material is extremely cold, only a few degrees above absolute zero, until it is heated by the collapse to the region where the star is forming. If comets have no rocky core, they must have formed at the edge of the primordial nebula where the gas and dust was never heated. If comets do have a rocky core, the temperature must first have risen enough to sublimate the ices so that the dust in the comet could aggregate into a rocky core. Then the temperature would have had to fall in order to enable the core to collect its icy mantle, still containing considerable dust.

Our calculations provide another new fact about the nucleus of Comet Encke: the ratio of the precession rate of the spin axis to the total nongravitational motion in the orbit. Clearly the precession rate should increase with the oblateness of the nucleus. Moreover, the faster the nucleus spins, the slower the precession rate should be. It turns out that the ratio decreases with the diameter of the nucleus but does not involve the density. Therefore our new ratio is closely proportional to the oblateness of the nucleus multiplied by the period of rotation and divided by the diameter of the nucleus. If we can determine any two of three quantities (oblateness, rotation period and diameter), the third is also determined. There is no hope, however, of directly observing the oblateness without a space mission to the comet, so that one must try to measure or estimate the other two quantities. First consider the diameter.

Comet Encke has never come close enough to the earth for astronomers to see its nucleus, and so there is no direct measure of the diameter of the nucleus. If it were known how well the nucleus reflects sunlight, the diameter could easily be calculated by its brightness when it is at great distances from the sun and therefore inactive. Unfortunately it is not known. If the nucleus is a good reflector like clean snow, its diameter is about a kilometer. If it is a poor reflector like the moon, its diameter might be four to six kilometers or even more.

Fortunately one can estimate the diameter through another approach: by placing limits on the rate at which the comet is losing mass. Knowing the velocity of ejection and the accelerations thereby produced one can calculate the total mass. In 1973 two French investigators, J. L. Bertaux and Jacques E. Blamont, estimated the mass being lost by Comet Encke with the aid of instruments in a satellite, which measured the ultraviolet radiation emitted by hydrogen atoms being blown away from the comet. If one assumes that all the hydrogen comes from water molecules dissociated by sunlight, one can arrive at a lower limit for the total mass lost by the comet with each revolution around the sun. It is 6.5×10^8 kilograms, or 650,000 metric tons.

The minimum reasonable value for



TIPPING FORCE ON A COMET NUCLEUS arises if the nucleus is slightly oblate, which is likely, rather than spherical. A rigid or nearly rigid rotating body will rotate stably about its shortest axis. Gases that are being volatilized from the comet's surface by solar heating will exert a reactive force perpendicular to the surface. In this illustration the average force passes below the center of the comet, which tends to push the spin axis to the left. Because the comet is spinning, however, the actual movement of the pole is 90 degrees away from a plane that is defined by the force and the spin axis. In this case the movement is into the plane of the page.

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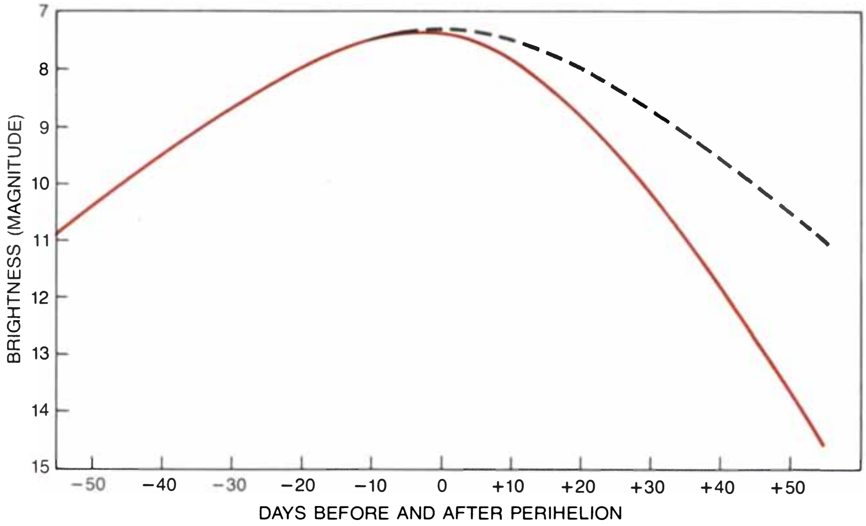
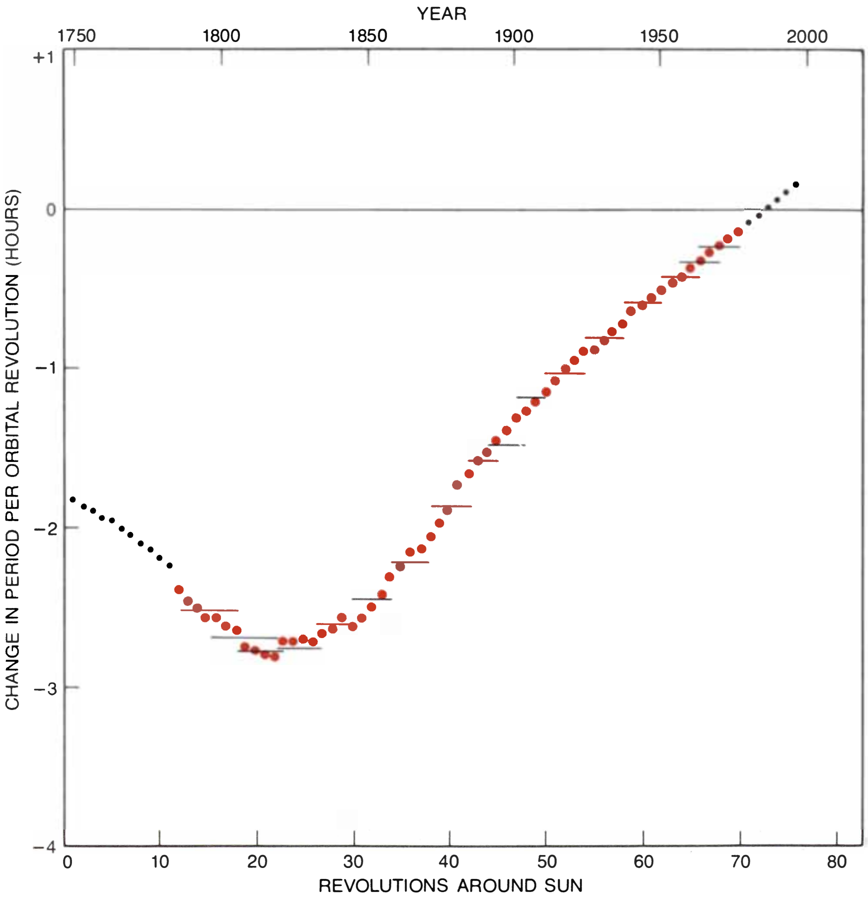


LIGHT CURVE FOR COMET ENCKE (*color*) **exhibits a peculiar asymmetry. After perihelion the comet's brightness fades much faster than it had increased before perihelion. The curve, corrected to a standard earth distance, is based on observations of 11 perihelion passages between 1937 and 1974. The broken black curve is the postperihelion luminosity expected if comet's fading mirrored its brightening. One magnitude equals a factor of 2.51 in brightness.**



CHANGES IN THE PERIOD OF COMET ENCKE can be attributed to small cumulative changes in the comet's kinetic energy produced by the volatilization of gases from its surface. The magnitude and direction of the jet forces acting on the comet vary enormously with the comet's distance from the sun and with the precession of the comet's spin axis. The author and Sekanina devised separate computer programs to integrate the effect of the jet forces acting on Comet Encke from 1786 to 1977. The colored dots are the computed changes in the comet's period for each revolution. Black dots are extrapolations. Black bars are the actual changes in the comet's period averaged over four or five apparitions for each bar. Sekanina was assisted in his calculations by Brian G. Marsden of the Smithsonian Astrophysical Observatory.

the bulk density of a comet nucleus is one gram per cubic centimeter, the density of water. One can then use the known velocity of the jet action to calculate that the diameter of Comet Encke is greater than 1.2 kilometers. Similarly, one can use estimates of the loss of dust made by Sekanina and Hans E. Shuster to calculate that the diameter is probably less than 2.6 kilometers. Hence the best estimate we can make at present for the diameter of the nucleus of Comet Encke is two kilometers. If that figure is approximately correct, the nucleus reflects 25 percent of the incident sunlight and is a dirty gray, about as one might expect.

The loss of, say, two million tons of ice per revolution corresponds to a mass loss of only one part in 2,000, or an average radius loss of only 16 centimeters per revolution, or 13 meters integrated according to Comet Encke's changing brightness over the 59 revolutions since the comet was discovered in 1786. The shape of the nucleus would change very little in that time, although it is perhaps being flattened a bit because of the different rates of mass loss on its two hemispheres. A mass loss of much less than one part in 1,000 per period is all that is needed to maintain Comet Encke's observed activity, its nongravitational motion and its spin-axis gyration.

Sekanina and I have attempted to determine the period of rotation for Comet Encke by a method I devised three years ago. Many comets, including Comet Encke, develop areas on their surface that actively eject gas when the rotation of the comet exposes those areas to the sun. The result of the periodic ejection of gas is a series of concentric or nearly concentric halos, some of which can be measured on photographic images of the coma. Comet Donati, the great comet of 1858, is the most conspicuous example. From measurements of the diameter of such halos and a knowledge of the expansion velocity as a function of distance from the sun, one can calculate "zero dates": times when the areas that eject gas are turned toward the sun and become active. The zero dates should be separated by multiples of the period of rotation. Comet Donati ran like clockwork with a period of 4.6 hours for three weeks. Usually, however, the observations are so scattered and the uncertainties in the zero dates are so great that several solutions for the period will fit the observations. From four apparitions of Comet Encke in the 19th century and five in this century we find a probable mean value of $6\frac{1}{2}$ hours for the rotation period of the comet's nucleus. We consider this result indicative but not definitive. There is also some evidence for a shortening of the rotation period of possibly 20 to 40 minutes per century.

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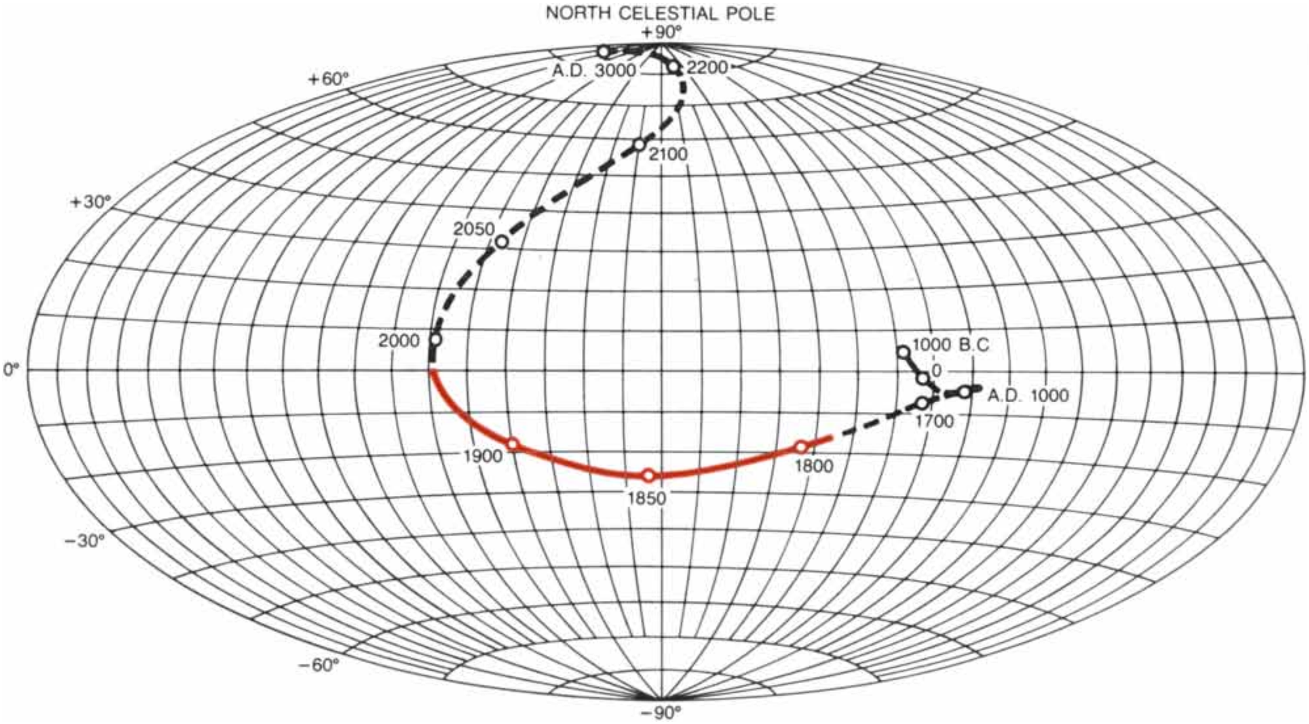
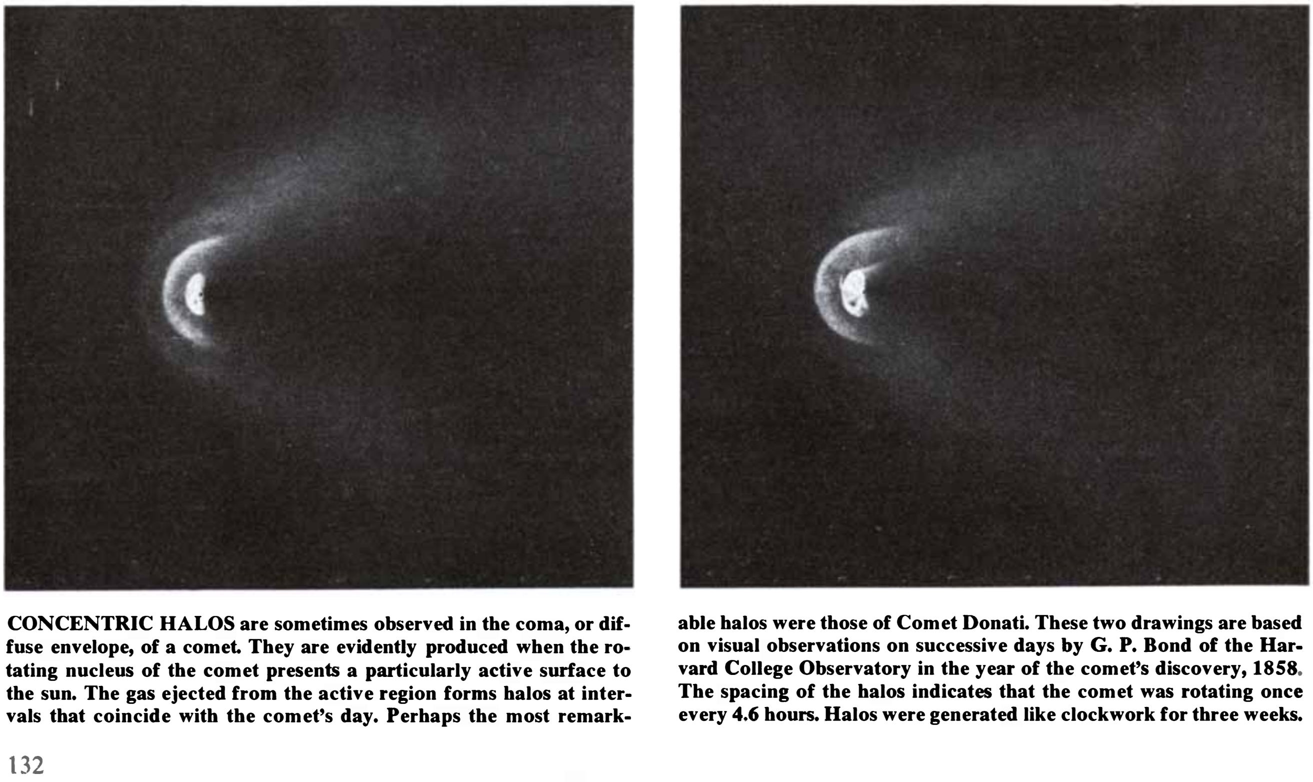


POLAR MOTION OF THE SPIN AXIS of Comet Encke shows wide excursions when it is plotted on the celestial sphere. Solid curve, based on observations and computer studies, shows pointing direction of spin axis from 1786 to 1977. The broken curves are extrapolations.

ameter of two kilometers the required oblateness of the nucleus of Comet Encke is only about .03. The meaning of this figure is that the diameter of the nucleus at the spin axis need be only 60 meters shorter than the diameter at the equator in order to give rise to the observed gyrations of the spin axis. Actually the nucleus is probably covered with pits, craters, mounds and pedestals, so that what is being discussed is only a systematic trend in a very rough-hewn body that averages out to be spherical within 3 percent.

One may ask: If comets are only little dirty snowballs, why is their study of any importance with respect to the study of other astronomical bodies? The answer is straightforward. Comets clearly represent the most primitive bodies left over from the making of the sun and the planets. The interstellar material that formed comets may never have been heated significantly. Comets or bodies like them were the building material of the great outer planets Uranus and Neptune. Hence the study of comets can be expected to solve some of the puzzles about the formation of the earth and the rest of the solar system.

Another reason for studying comets is their possible role in making life on the earth possible. The conjecture is,



CONCENTRIC HALOS are sometimes observed in the coma, or diffuse envelope, of a comet. They are evidently produced when the rotating nucleus of the comet presents a particularly active surface to the sun. The gas ejected from the active region forms halos at intervals that coincide with the comet's day. Perhaps the most remarkable halos were those of Comet Donati. These two drawings are based on visual observations on successive days by G. P. Bond of the Harvard College Observatory in the year of the comet's discovery, 1858. The spacing of the halos indicates that the comet was rotating once every 4.6 hours. Halos were generated like clockwork for three weeks.

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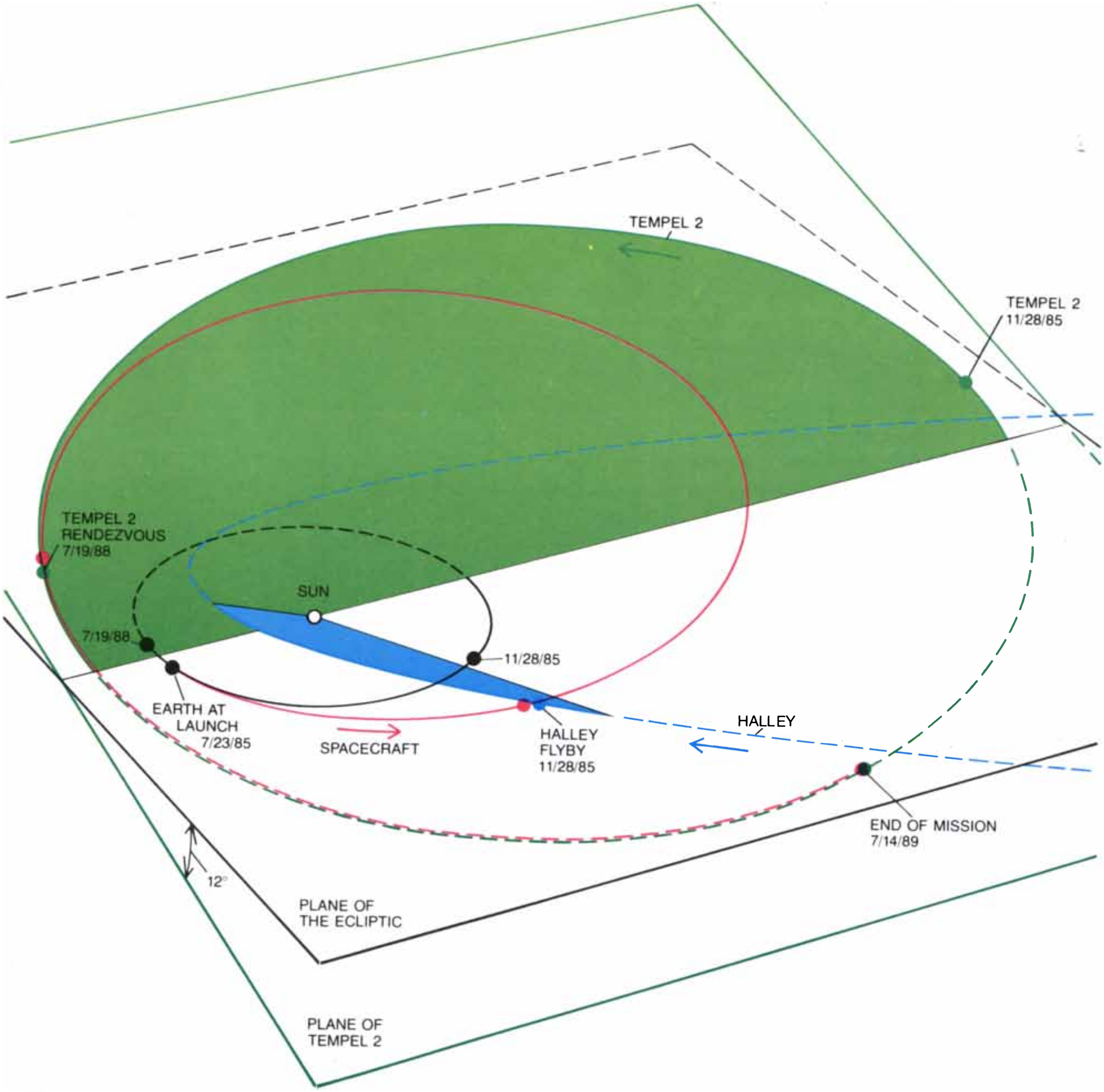
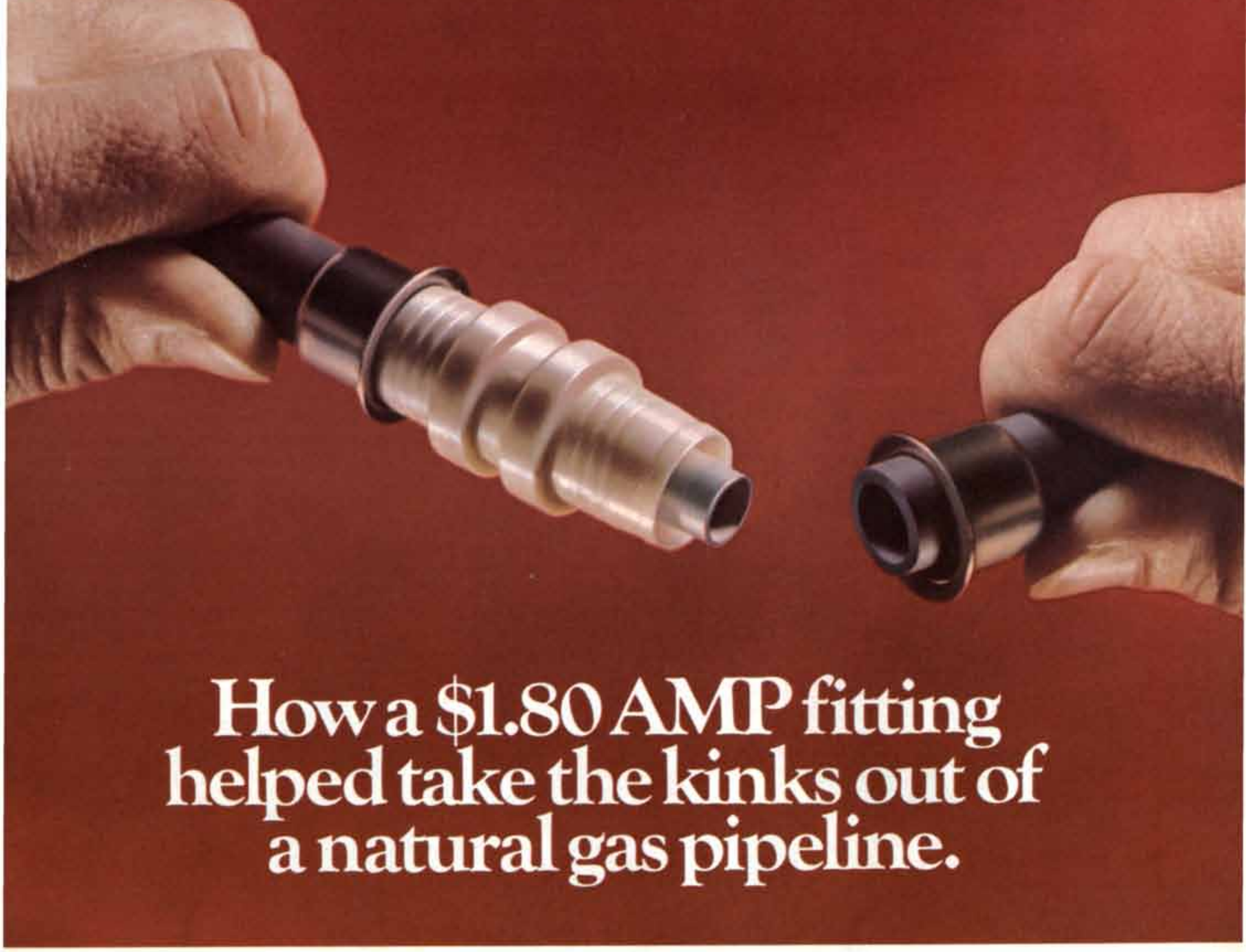
I would grant, controversial. The evidence is nonetheless clear that when the earth was young, it was too hot to hold the primordial atmosphere supplied by the coalescence of the nebula that gave rise to the sun and the planets. Geologists have argued that the outgassing of volatile substances from the earth's interior was sufficient to supply a second atmosphere as the earth cooled. On the other hand, it is known that the earth, like the other inner planets and the earth's moon, was bombarded during the first half-billion years of its existence by a huge number of smaller bodies, including many whose composition must have been cometlike. Comets could therefore have supplied a not inconsiderable fraction of the water, nitrogen, oxygen and carbon from which life on the earth developed. Moreover, interstellar dust and comets are believed to contain a variety of organic compounds that could provide a good start toward the evolution of living organisms. Fred Hoyle has speculated that life itself originated in "little warm pools" in comets. One need not go that far to hope money will be found to support a space mission to examine a comet at close range.



SPACE MISSION TO TWO COMETS will be attempted in the near future if Congress approves a pending proposal of the National Aeronautics and Space Administration. The key to the mission is an advanced propulsion system in which electricity from solar cells will power a cluster of ion-drive rocket engines. After the spacecraft has been lifted into earth orbit by the space shuttle and boosted to escape velocity by a solid-fuel rocket the ion drive will take over and provide continuous thrust for the rest of the three-year mission. If the spacecraft is approved, it will be launched in July, 1985. Four months later, as the craft passes between the sun and Halley's comet, it will drop off a probe aimed directly at the comet's nucleus. The spacecraft will continue on its course and rendezvous with Comet Tempel 2 in July, 1988, observing the comet from a distance of less than 2,000 kilometers as the comet passes through perihelion. When the comet has proceeded farther along its orbit and has settled into a quiescent state, the spacecraft will approach it close enough to be captured by it and will circle its nucleus at a distance of 10 kilometers. After a year a landing on the comet nucleus will be attempted. This illustration of the mission was prepared with the help of Rolf C. Hastrup of the Jet Propulsion Laboratory of the California Institute of Technology.



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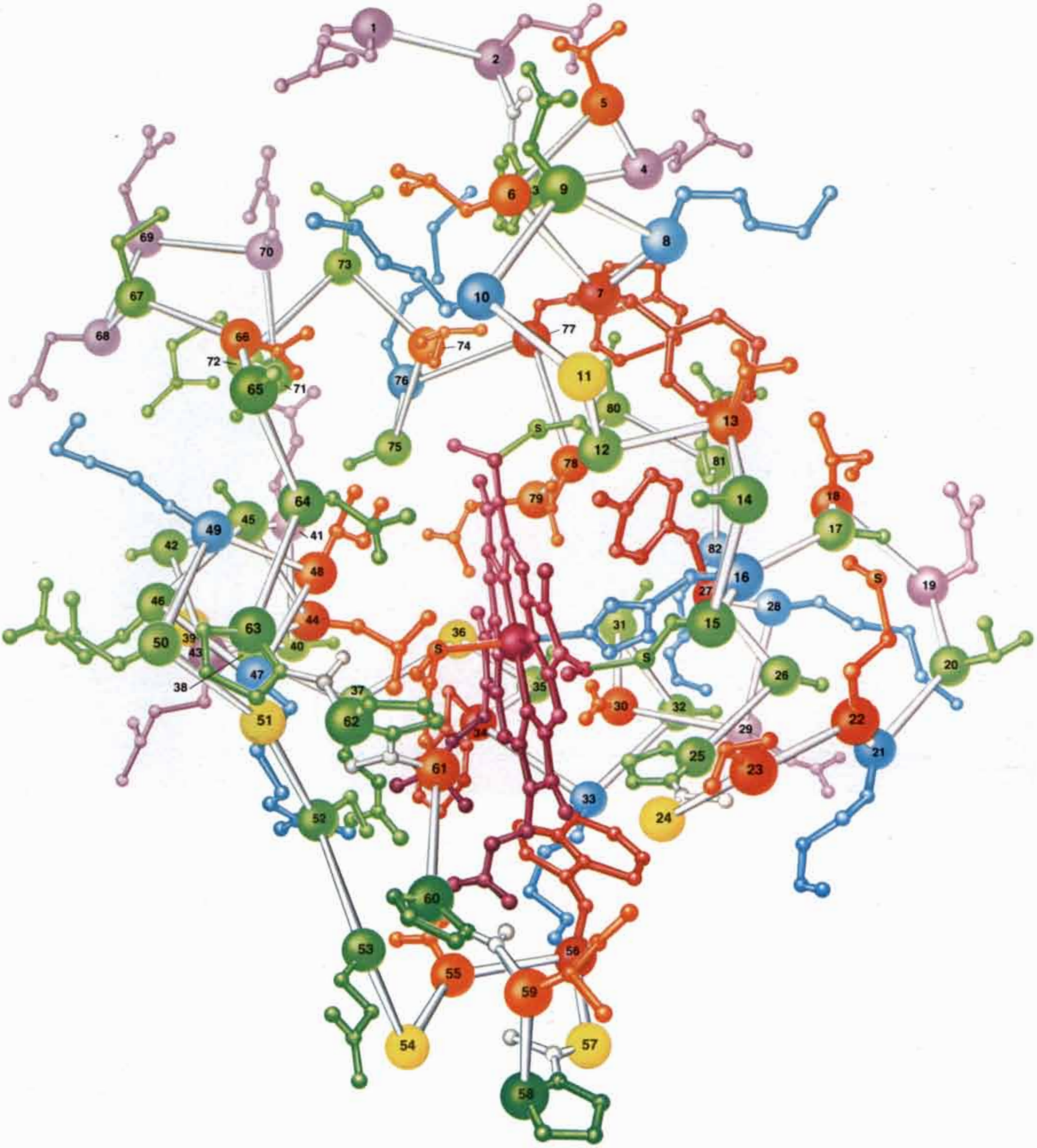

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● HYDROPHILIC, ACIDIC

● HEME

● HYDROPHOBIC, NOT AROMATIC

● AMBIVALENT

● HYDROPHILIC, BASIC

Cytochrome c and the Evolution of Energy Metabolism

The history of this ancient family of electron-transferring proteins suggests that our metabolic ancestors may have been photosynthetic bacteria for which respiration was only a standby energy mechanism

by Richard E. Dickerson

Everybody at one time or another has had fantasies about time travel, perhaps including being able to go back in time to see what early life on the earth was like and how it all started. The urge to seek out beginnings is almost a compulsion in the human species, and it has found outlets in religion, in history and more recently in science. One of the great attractions of Charles Darwin's theory of evolution was that it provided a rational framework for thinking about the available evidence bearing on the history of life on the earth. There are two kinds of classical evolutionary evidence: information concerning living organisms as they are today and more fragmentary information about earlier life that can be read in the fossil record. In this article I shall report recent efforts to enlarge the picture on the basis of molecular evidence: the three-dimensional folding and the amino acid sequences of protein molecules.

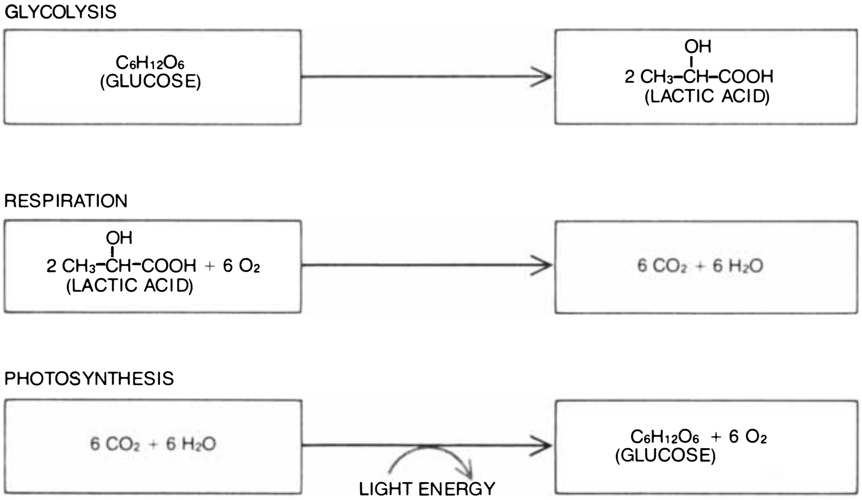
The fossil story itself can be extended back with reasonable confidence to the beginning 600 million years ago of the Cambrian period, an interval marked by the explosive radiation of the metazoans (multicelled organisms), which left easily discernible fossil remains. The Precambrian fossil evidence is harder to get, but it is still informative. There are fossils of a few soft-bodied metazoans that go back to 800 or 1,000 million years ago and of one-celled organisms that may be eukaryotes (cells whose DNA is organized within nuclei) as old as 1.4 billion years. Traces of prokaryotes (bacteria) go back 3.4 billion years.

Fossil vertebrates leave many traits that can be compared and from which evolutionary history can be deduced: not only bone structures but also teeth, imprints of skin or hair, fossilized stomach contents and feces and even footprints. Fossil bacteria, in contrast, often leave nothing more than a shadowy outline of a cell boundary in microscopically thin sections of rock. This makes the task of the evolutionary biologist much harder. If eukaryotic life forms are distinguished by their anatomy, bacteria are distinguished by their metabolism, and metabolic pathways leave few fossils. One can infer from deposits of sulfates, iron or carbonates that life forms once existed for which these compounds were end products, but this does not tell one very much about either the life forms themselves or their relationships.

And yet the situation is less bleak than the foregoing might suggest. Over the past 15 years an entire new body of evolutionary evidence has come from studies at the molecular level: analyses of the three-dimensional structure of proteins and the sequence of amino acids in them (and more recently of the sequence of nucleotides in DNA). Organisms having the same metabolism have the same enzymes, and although in different organisms those enzymes function in the same way and have quite similar three-dimensional structures, they can differ in details of the sequence of the amino acid units along the protein chain, at least in the less critical parts of the molecule. These differences in sequence make it possible to construct a molecular "pedigree" diagram because the further back in the past the ancestors of two present-day organisms became separated, the more changes will have accumulated in the amino acid sequences of their proteins [see "Computer Analysis of Protein Evolution," by Margaret Oakley Dayhoff, SCIENTIFIC AMERICAN, July, 1969, and "The Structure and History of an Ancient Protein," by Richard E. Dickerson, SCIENTIFIC AMERICAN, April, 1972]. The phylogenetic tree derived for animals by comparing the sequences of any protein examined in detail is essentially the same as the tree built up over the past century by more traditional methods. That gives one confidence in the validity of using molecular data to study evolution. Now that the method has been checked and found to be valid in principle it can, with caution, be extended back in time to the age of the bacteria, where the traditional methods fail.

One of the most interesting problems in the development of life on this planet is to understand how organisms have obtained, stored and consumed energy. A living cell, like Lewis Carroll's Red Queen, has to run at top speed to stay in the same place. Without a constant input of energy, either from an outside source or from its own storage reservoirs, it will die. The earliest forms of life presumably were scavengers of compounds with a high content of free energy that had been formed by nonbiological means; the scavengers broke these compounds down into molecules with a lower free-energy content, which they ejected as waste products, and consumed the energy thereby liberated to keep going. This is the process of fermentation, which is still the source of

CYTOCHROME c_{551} MOLECULE from the respiring bacterium *Pseudomonas aeruginosa* has a rosette-shaped, iron-containing heme group wrapped in a protein chain consisting of 82 amino acids. Here the alpha carbon atoms (*numbered*) of the main chain of the protein and the side chains that branch from them are colored (*see key*) to emphasize the way the heme group is largely buried in the molecule's hydrophobic (water-repellent) interior, with only one edge exposed at a crevice facing the viewer; the more hydrophilic side chains are toward the outside of the molecule, exposed to the aqueous environment. Here the main chain has been drawn in simplified form, with amide linkages (–CO–NH–) between alpha carbons represented only by stick bonds (*white*). The hydrogen atoms that are bonded to most carbon atoms are not shown.



THREE FUNDAMENTAL MECHANISMS of energy extraction and storage are glycolysis, respiration and photosynthesis. Glycolysis, a molecular rearrangement with little change of oxidation state, releases some energy. In respiration much energy is emitted as carbon compounds are oxidized. In photosynthesis energy is taken up and stored as carbon dioxide is reduced.

energy for anaerobic bacteria such as *Clostridium;* glycolysis, the fermentation of glucose, is the first step in the human energy-extracting machinery. Photosynthesis probably came next: the trapping of solar energy to make molecules with a high free-energy content and thereby store energy for future use. Respiration followed for some bacteria but not for all; it made possible the extraction of a maximum of energy from molecules by combining them with an oxidant such as sulfate, nitrate or molecular oxygen (O_2) rather than merely breaking them down into smaller pieces.

Glycolysis and respiration are the universal heritage of all eukaryotes today: one-celled protists, plants, animals and fungi. Among eukaryotes photosynthesis is shared only by algae and green plants. In order to look at the trial-and-error process by which these metabolic pathways first evolved one must turn to an earlier era and to prokaryotes: the bacteria. Comparisons of the structure of a single protein, cytochrome *c*, as it is found in a number of bacteria can act as Ariadne's thread, leading the biologist through the labyrinth of bacterial evolution and suggesting a history for the machinery of energy storage and retrieval.

Energy storage during photosynthesis involves the reduction of carbon dioxide through the addition of hydrogen atoms (or of equal numbers of protons and electrons) and the removal of some oxygen. Respiration, on the other hand, is a process in which glucose or another organic molecule is oxidized, with hydrogens (or protons plus electrons) being removed and transferred to an oxidant such as molecular oxygen (O_2). In either case, reduction or oxidation, electrons must flow, and proteins are needed to accept the electrons and pass them along the chain. One of the most conveniently studied of these proteins is cytochrome *c*, which is found almost everywhere electrons are transferred in photosynthesis or respiration.

When I wrote about the evolution of cytochrome *c* in *Scientific American* in 1972, molecular-structure studies of the protein were still confined to the eukaryotes. Now those studies have been extended back in time some two billion years. Investigations carried out in my laboratory at the California Institute of Technology and in two other laboratories have established the three-dimensional structure of four cytochromes *c* in bacteria by means of X-ray crystallography, and a fifth such study is in progress; the amino acid sequences of almost 40 bacterial cytochromes have been determined by Richard P. Ambler of the University of Edinburgh, by Martin D. Kamen of the University of California at San Diego and by others. From these structures and sequences and from what has been learned about comparative bacterial metabolism it is possible to piece together a coherent picture of the evolution first of photosynthesis and then of respiration.

Cytochrome *c* of the type considered in this article is a heme protein in which an iron-containing heme group is almost completely enfolded in a protein chain consisting of from 82 to 134 amino acids. It serves as an electron shuttle near the low-free-energy end of the electron-transport chain of photosynthesis or respiration. In the respiratory chain of eukaryotes cytochrome *c* receives electrons from a cytochrome reductase complex containing several other cytochromes, iron-sulfur proteins and lipids. It passes electrons on to a cytochrome oxidase complex, which ultimately uses the electrons (along with protons from solution) to reduce oxygen to water. The original source of reducing power that is fed into the eukaryotic respiratory chain is reduced nicotinamide adenine dinucleotide (NADH), which is produced by glycolysis and by the citric acid cycle, the final common pathway for the oxidation of fuel molecules. The overall reaction of the respiratory chain is $NADH + H^+ + \frac{1}{2}O_2 \rightarrow NAD^+ + H_2O$. Part of the 53 kilocalories of energy per mole of NADH released by this reaction is stored at three steps in the chain by the synthesis of adenosine triphosphate (ATP) molecules from adenosine diphosphate and inorganic phosphate. This storage of free energy in ATP is really the rationale behind the entire respiratory chain: the energy released as food molecules are broken down is passed first to NADH and then to ATP, and NAD^+ is cycled back to pick up more free energy.

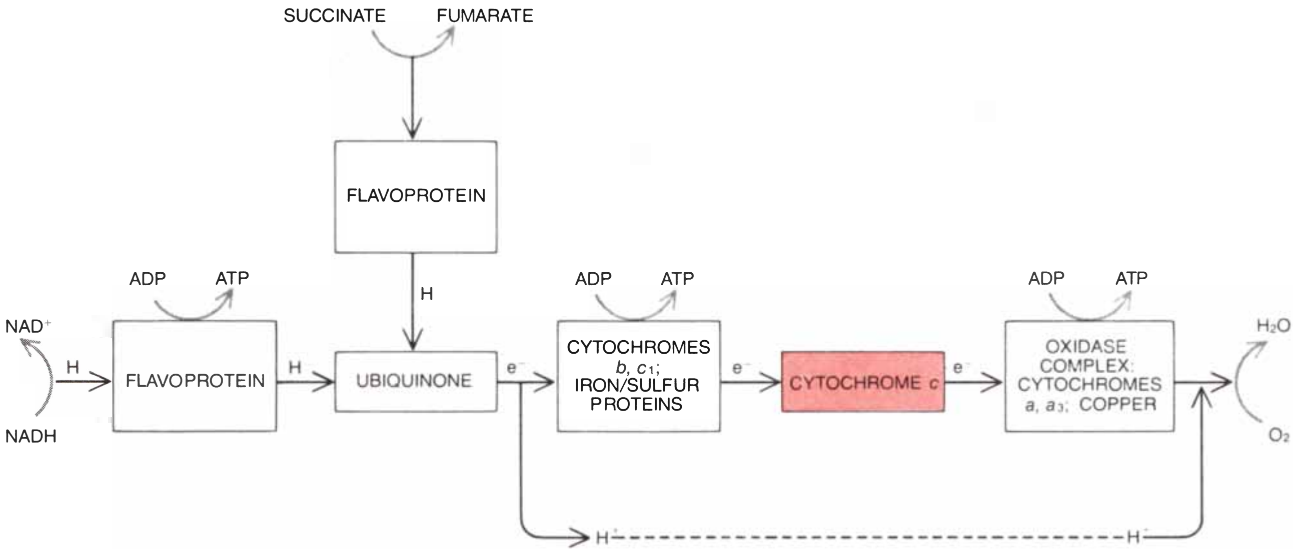
Similar respiratory chains are found in many bacteria. Some bacteria that prefer oxygen can make do with nitrate if they must; the change lies only in the final cytochrome oxidase complex. Still others, such as *Desulfovibrio,* carry out an anaerobic respiration in which the oxidant is sulfate and the waste product is hydrogen sulfide (H_2S) instead of water. Cytochromes *c* are present in all these respirers.

Cytochromes *c* are also found in similar positions in the electron-transport chains of photosynthesis. The two-photocenter, water-splitting photosynthesis that is familiar in green plants and eukaryotic algae occurs among prokaryotes only in the cyanobacteria. All other photosynthetic bacteria have only a single photocenter; they are incapable of using water as a source of hydrogen for reducing carbon dioxide and must depend on reduced sulfur compounds, hydrogen gas or organic molecules. They all have electron-transport chains, however, and all those chains contain a cytochrome *c*.

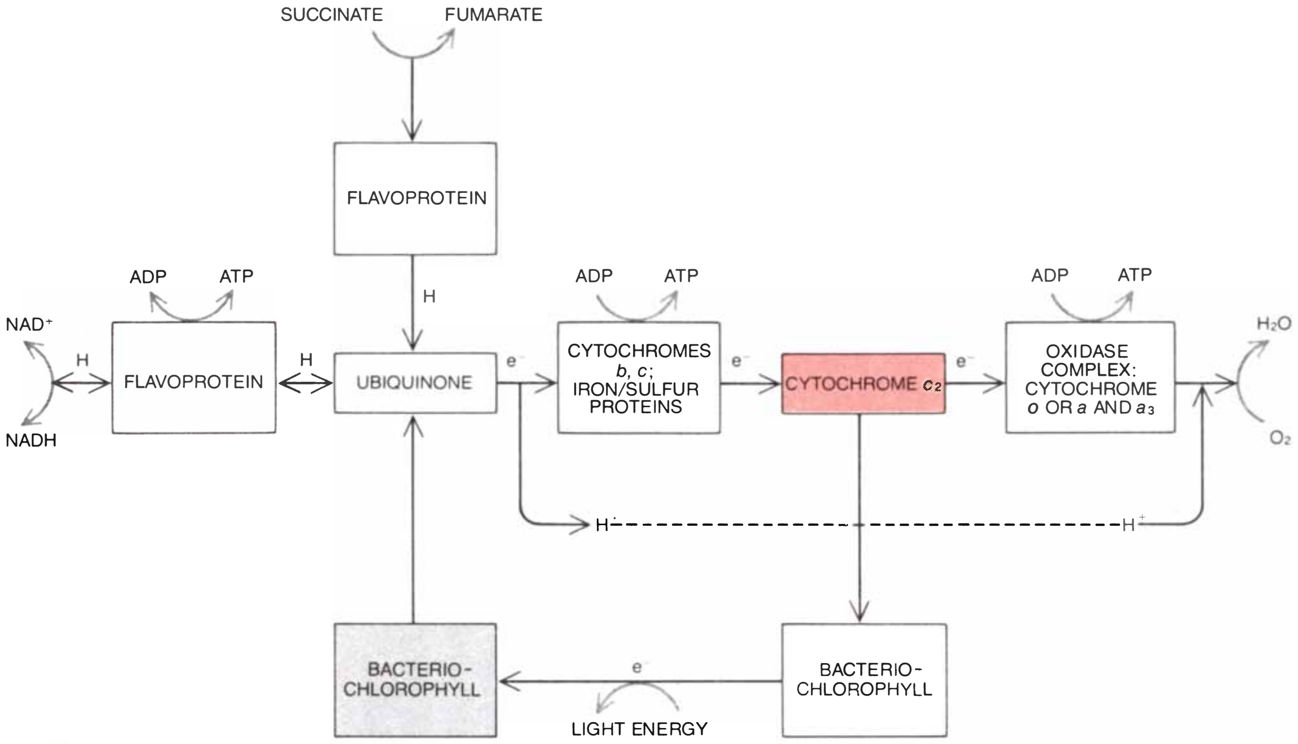
The contribution of X-ray structure analysis in the past five years has been to show that certain of these cytochrome *c* molecules from each class of bacteria are folded in an identical way, with only the addition or deletion of loops of chain at the surface of the molecule. These identically folded cytochrome *c* molecules make up a strikingly coherent family of related proteins, whether the electron-transport chains from which they come are involved in photosynthesis or respiration or both.

The heart of all these cytochrome *c* molecules is the heme group: a porphyrin ring surrounding a central iron atom. The outer electrons in the atoms of the porphyrin skeleton are delocalized, that is, they are free to wander from one atomic center to another, rather as they do in benzene or graphite; the iron atom itself is a part of this delocalized-electron system. An electron flowing into the heme from one edge can move freely to the central iron atom. Conversely, if an electron is lost at one edge, the vacancy can migrate (like a bubble in a liquid) inward until it reaches the iron, making it into a ferric iron atom (Fe^{+3}) rather than a ferrous atom (Fe^{+2}) as in the reduced heme iron. This is now thought to be the way electrons migrate into and out of cytochrome *c:* through one exposed edge of the heme.

The heme is held rigidly within the protein framework by four covalent bonds. Two bonds connect edges of the heme to sulfur atoms in the side chains of two amino acids (cysteines) in the protein; two more connect the iron itself to a sulfur atom (in a methionine side chain) and to a nitrogen atom (in a histidine side chain) on each side of the planar heme. The two cysteines are separated by two other amino acids along the



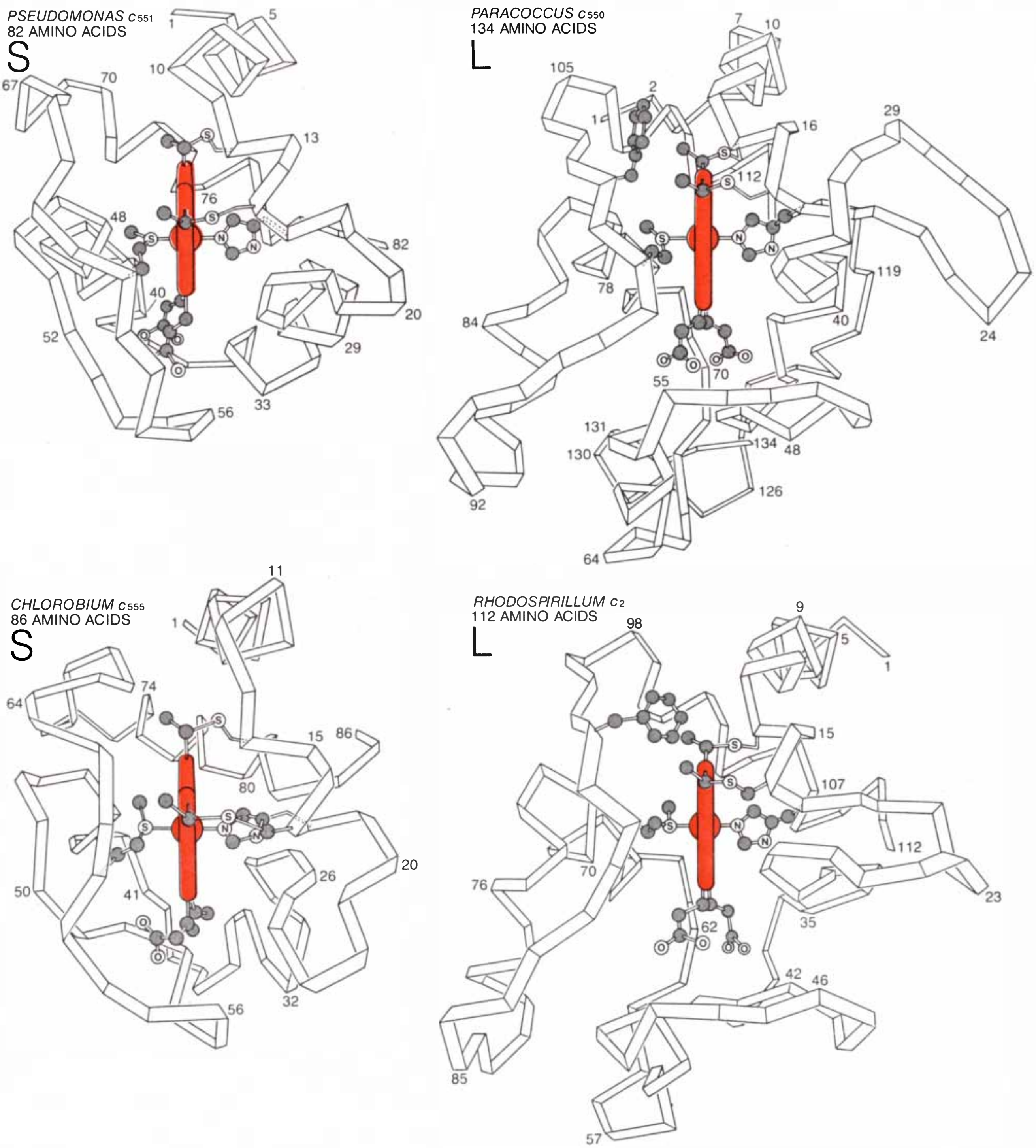
RESPIRATORY electron-transport chain in mitochondria, the energy-transducing organelles of eukaryotic cells (which is to say of all life above the level of bacteria), delivers electrons (e^-) to a cytochrome oxidase complex that combines the electrons with hydrogen ions (H^+) and oxygen to form water; energy extracted at three steps along the respiratory chain phosphorylates adenosine diphosphate (ADP) to form the cellular energy carrier adenosine triphosphate (ATP). Cytochrome *c* (*color*) plays a central role in the electron-transfer process.



PHOTOSYNTHESIS AND RESPIRATION are both carried out by such purple nonsulfur bacteria as *Rhodopseudomonas capsulata,* the electron-transport chain of which is shown here as it has been proposed by Barry L. Marrs of the Saint Louis University School of Medicine and Howard Gest of Indiana University. Here cytochrome c_2 can pass electrons not only to bacteriochlorophyll (to be energized by light) but also to cytochrome oxidase (to reduce oxygen). Without bacteriochlorophyll loop, chain is similar to that of mitochondria.

protein chain, and the histidine immediately follows the second cysteine. This sequence, cysteine–*X*–*Y*–cysteine–histidine, is one of the distinguishing characteristics of a cytochrome of the *c* type. (The methionine ligand is much farther along the chain, where it curls around to the other side of the heme.)

The same heme is also present in hemoglobin, but there it is held within the protein framework in a different way. The covalent attachments to cysteines are missing, and only the histidine ligand is present. A heme has two polar (water-attracting) propionic acid side chains ($-CH_2-CH_2-COOH$) attached to one edge. In hemoglobin these side chains stick out into the aqueous surroundings, whereas the rest of the heme is buried in a pocket formed by hydrophobic (strongly water-repellent) amino acid side chains. This arrangement is the stablest one from an energy standpoint, and yet it is not what is found in cytochrome *c*. Instead the heme is rotated 90 degrees, so that one propionic acid group is just under the surface of the


PSEUDOMONAS c551
82 AMINO ACIDS
S

PARACOCCUS c550
134 AMINO ACIDS
L

CHLOROBIUM c555
86 AMINO ACIDS
S

RHODOSPIRILLUM c2
112 AMINO ACIDS
L

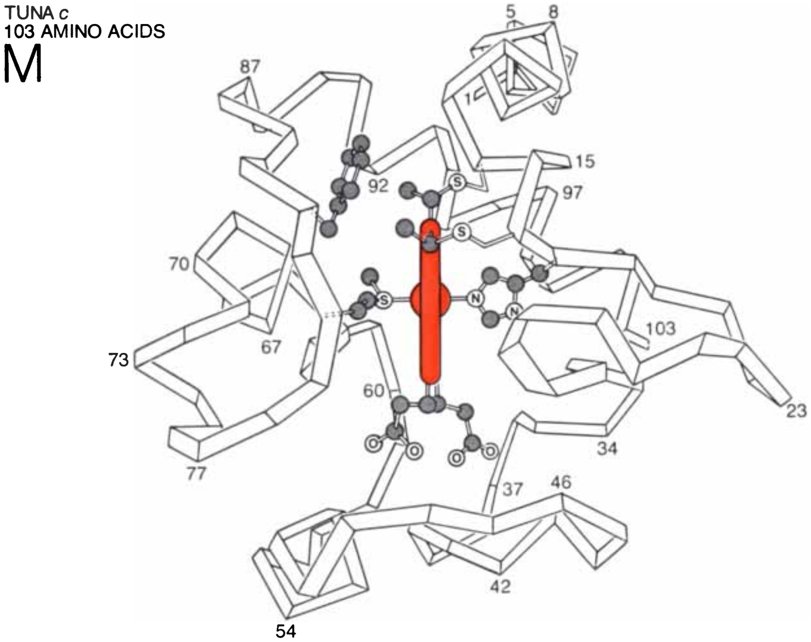
PORTRAIT GALLERY OF CYTOCHROME C FAMILY on these two pages displays the structure of the four bacterial cytochromes *c* for which X-ray analyses have been completed, along with that of tuna as a representative of the mitochondrial protein. *Pseudomonas* and *Paracoccus* are respiring bacteria; *Chlorobium* is a photosynthetic green sulfur bacterium, *Rhodospirillum* a purple nonsulfur bacteri-

molecule and the other group is deeply buried.

A price in energy must be paid for burying such a polar, water-attracting group in the hydrophobic interior, and the cytochrome molecule compensates by forming hydrogen bonds between the buried propionic acid and two large amino acid side chains, those of tyrosine and tryptophan (amino acids No. 48 and No. 59 in the sequence determined for the cytochrome *c* of tuna). These two hydrogen-bonded side chains are absolutely constant among all eukaryotes—animals, plants, fungi and protists—and functionally equivalent groups are always found in bacteria as well. Why should the heme in cytochrome *c* be positioned in this awkward and energy-expensive way? The answer seems to be that the position is required for the proper flow of electrons in and out through the exposed heme edge. If the propionic acid groups stuck out from the surface as they do in hemoglobin, they would block the approach of other large molecules that exchange electrons with cytochrome *c*. Hence the heme is reoriented by means of covalent and hydrogen bonds so that an edge with only small, nonpolar groups is exposed. This is a nice example of specialized molecular engineering: an inherently less-than-optimum structure is built into the molecule to carry out a specific function.

The first cytochrome *c* for which the three-dimensional structure and the amino acid sequence were determined was the respiratory cytochrome *c* of horse, followed by those of two fishes: the tuna and the bonito. X-ray structural analyses have now been completed for four cytochromes *c* from photosynthetic and respiring bacteria, and their structures are shown, along with that of the cytochrome *c* of tuna, on these two pages. The various bacterial cytochromes *c* have subscripts assigned either for historical reasons (c_2, for example) or to indicate the particular molecule's peak absorption frequency in nanometers for visible light (c_{551}, for example). *Pseudomonas* and *Paracoccus* are respiring bacteria that can exploit either oxygen or nitrate for oxidation, *Chlorobium* is a green sulfur photosynthetic bacterium and *Rhodospirillum* is a purple nonsulfur photosynthetic bacterium. In *Pseudomonas, Paracoccus* and tuna the role of the cytochrome *c* as an electron carrier is strictly respiratory, in *Chlorobium* it is strictly photosynthetic and in purple nonsulfur bacteria the same electron chain and cytochrome c_2 function in both photosynthesis and respiration.

The folded ribbons in these diagrams represent the path of the protein chain, each fold indicating an alpha-carbon atom with its amino acid side chain. Side chains are numbered sequentially (and independently in each molecule) from the amino terminus of each protein. The flat, colored slab is the heme group seen edge on, with its histidine and methionine ligands to the right and left and its propionic acid side chains extending downward. All these molecules have similar chain folding and side-group packing around the heme, but the extended loops of chain at their surfaces differ in detail. The molecules fall naturally into three structural subfamilies. The short (S) cytochromes *c* (*Pseudomonas* and *Chlorobium*) lack the loop of chain that builds the bottom of the molecule in the others (roughly from amino acids No. 37 through No. 59 in the tuna numbering system). The medium (M) cytochromes *c*, represented here by the cytochrome *c* of tuna, are the type found in mitochondria, the respiratory organelles of all eukaryotic cells. The long (L) cytochromes *c* have additional loops of chain inserted in the vicinity of amino acids (in the tuna system) No. 54 and No. 77, and sometimes near amino acid No. 23.



um able to photosynthesize and respire. The protein chain is represented here as a folded ribbon, with an amino acid side chain at each fold. The heme group (*color*) is seen edge on. The molecules fall naturally into three structural classes: short (S), medium (M) and long (L).

The *Rhodospirillum* structure was determined by F. Raymond Salemme and Joseph Kraut at the University of California at San Diego, and that of *Chlorobium* by Zbigniew R. Korszun and Salemme at the University of Arizona. The structures of the tuna, *Pseudomonas* and *Paracoccus* molecules were determined respectively by Tsunehiro Takano and his co-workers, by Robert J. Almassy and by Russell Timkovich in the author's laboratory at Cal Tech. An analysis of photosynthetic cytochrome c_{554} from the cyanobacterium *Anacystis nidulans* by Martha L. Ludwig at the University of Michigan is far enough along to show that it clearly belongs to the S class.

The similarities among the five molecules illustrated are even greater than can be shown on simplified folding diagrams. The same kinds of hydrophobic amino acids, either aliphatic (straight-chain) or aromatic (ring), tend to be packed around the heme at corresponding positions, both in three-dimensional space and in amino acid sequence, in each of the five molecules. These amino acids are shown in orange and red in the detailed drawing of *Pseudomonas* c_{551} on page 136. For example, the M and L cytochromes *c*, c_2 and c_{550} all have a cluster of three aromatic amino acids at the bottom of the molecule (Nos. 46, 48 and 59 in the tuna numbering system), three more to the left of the heme (Nos. 67, 74 and 82) and two more to the upper right (Nos. 10 and 97). Some of these amino acids are invariant; others vary between tyrosine and phenylalanine, with tryptophan occasionally substituting. With one or two exceptions in bacteria, they all come at exactly the same positions along the protein chain.

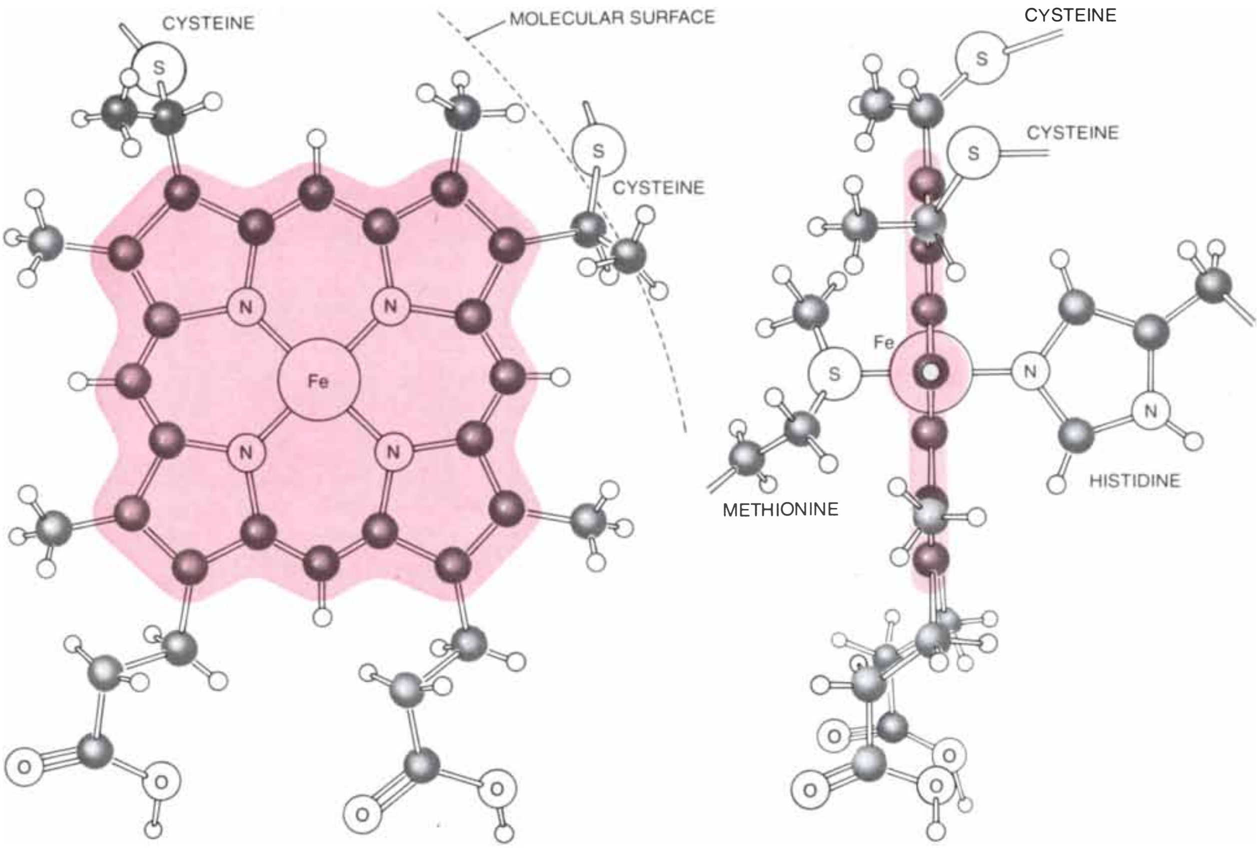
The pattern of aromatic amino acids is more varied in the S class, but the two at the upper right seem to be quite important (tyrosine Nos. 10 and 80 in c_{555}, or phenylalanine No. 7 and tryptophan No. 77 in c_{551}), as is the presence of something at the bottom of the molecule that can form a hydrogen bond with the heme's buried propionic acid. Cytochromes c_{555} and c_{551} solve this bottom-bond problem in different ways. In *Chlo-*

robium c_{555} tryptophan No. 34 occupies the same position along the amino acid chain as tryptophan No. 59 does in tuna, if allowances are made for chain deletions at the bottom of c_{555}. In c_{551} from various pseudomonads this tryptophan is gone, having been replaced by tyrosine, phenylalanine or asparagine. Instead an entirely unrelated tryptophan No. 56 (corresponding in sequence to the amino acids in the middle 70's in tuna) reaches back from the bottom front of the molecule to make a compensating hydrogen bond with the buried propionic acid. The cytochrome *c* family as a whole is an example of divergent evolution: divergence from a common ancestral gene. Tryptophan No. 56 in c_{551} and tryptophan No. 34 in c_{555} provide a minor example of convergent evolution: arrival at the same structural solution by way of different evolutionary paths.

On pages 146 and 147 are tabulated the amino acid sequences of prokaryotic cytochromes *c* that belong to this particular evolutionary family. The name cytochrome *c* is given to any heme protein that shows a particular spectrum in the reduced state, and this spectrum arises from the particular side groups on the heme and from the heme's covalent cysteine–*X*–*Y*–cysteine–histidine attachment to the protein chain. Not all such cytochromes *c* are necessarily related, however, by the sharing of a common ancestral gene. In the cytochromes *c'* found in some photosynthetic bacteria the heme is attached near the carboxyl end of the protein chain rather than at the beginning and there is no sixth bond to a methionine. The cytochromes c_3 in sulfate-respiring bacteria have four heme groups attached to the same chain. Still other cytochromes *c* are also flavoproteins. None of these has been shown to be evolutionarily related to the cytochromes *c* of this article, which can be classified as an interrelated evolutionary family on three lines of evidence: their great similarity in amino acid sequence and three-dimensional folding and their common role near the low-free-energy end of photosynthetic and respiratory electron-transport chains.

In the sequence table *Paracoccus, Pseudomonas, Azotobacter* and *Micrococcus* are respiring bacteria. *Rhodospirillum, Rhodopseudomonas* and *Rhodomicrobium* are the three genera of the family Rhodospirillaceae. *Spirulina* and *Anacystis* are cyanobacteria and the other entries classified with them are eukaryotic algae. *Chlorobium* and *Prosthecochloris* are green sulfur bacteria. The cytochromes *c* from different Rhodospirillaceae are quite diverse, with examples in all three size categories, L, M and S. Those from respiring organisms are thoroughly mixed in with them. *Paracoccus* c_{550} is distinguished from the c_2 only by being the longest of the L class, tuna *c* is among the M sequences, and *Pseudomonas* c_{551} sequences make up most of the S group. The cytochromes from cyanobacteria and eukaryotic algae have been segregated into a separate S^* class because their sequences are very different from those of S even though their chains are of similar length.

In the table the sequences have been arranged so that regions of corresponding structure (and therefore presumably regions that were transcribed from corresponding portions of the gene encoding the protein) are aligned vertically above one another. The alignment could not have been done correctly until the three-dimensional structures of the five cytochromes were known. Biochemists are not yet clever enough to predict folding successfully from sequence data



STRUCTURE OF HEME and its attachments to the protein chain of cytochrome *c* are shown. The face view (*left*) shows how the central iron atom is attached to four nitrogen atoms within the planar heme ring; as is shown in the edge view (*right*), the iron also has bonds to the sulfur atom of a methionine side chain on the protein and to the nitrogen atom of a histidine. The heme is also attached to the protein chain covalently through the sulfur atoms of two cysteines. Electrons are "delocalized" within the porphyrin skeleton (*colored region at left*).

SCIENCE/SCOPE

A new weapon guidance system uses satellite radio signals to accurately guide medium-range tactical missiles to targets on land or at sea. The on-board system determines a missile's precise position and velocity anywhere on earth by calculating the time it takes signals from four NAVSTAR Global Positioning System satellites to reach the weapon. The information is used to correct the missile's inertial navigation computation. The technique offers several advantages over conventional guidance methods, including simplicity, stealth, and the flexibility to fly over any terrain. A missile launched beyond enemy defenses would be hard to detect on enemy radar because the missile would emit no telltale radar signal. Hughes is developing the system for use by the U.S. Air Force in the late 1980s.

Lasers, though generally considered to be exotic devices, are finding greater uses in everyday manufacturing. One such application using a Hughes helium-neon laser is looking for defects in bottles. The laser scans the bottles while sensors on the opposite side detect the amount of light that passes through. Too much light indicates the glass has a hole, is too thin, or lacks proper color. Too little light means the glass is cracked, too thick, or colored too dark. Hughes, which achieved the world's first laser action in 1960, today is one of the world's largest suppliers of helium-neon lasers for industry.

A new liquid-crystal reticle for a gunner's telescopic sight is significantly smaller and less expensive than the mechanical devices now used in fire control systems on military vehicles. The computer-generated crosshairs move on two axes to provide an accurate aim point for the gunner. The all-digital device has no moving parts and has a flexible format for numerical displays. Hughes is developing the reticle under contract to the U.S. Army.

"High technology" best describes the products, environment, and production processes of the manufacturing division of Hughes Electro-Optical and Data Systems Group. Our major programs include laser rangefinders and designators, thermal imaging systems, and missile launching systems. We have immediate openings for experienced or graduating engineers who seek the challenge and satisfaction of advanced production methods, including computer-aided manufacturing. Send your resume to Dan O'Daly, EDSMD Professional Employment, P.O. Box 92746, Dept. SE, Los Angeles, CA 90009. Or call (213) 641-5510 collect. Equal opportunity M/F/HC.

Sensitive missile electronics can now be protected from searing heat by a device with no moving parts or electrical connections. The device, a thermal diode heat pump, is a closed metal tube containing metal mesh that circulates fluid via capillary action. During subsonic flight, the heat pipe cools missile electronics by pumping heat to the skin of the missile. Air flow carries the heat away. During supersonic flight, the heat pipe protects the internal electronics by absorbing heat from the hot surface of the missile. The thermal diode, built by Hughes, is being installed in the U.S. Air Force's High-speed Anti-Radar Missiles (HARM).

Creating a new world with electronics

HUGHES

HUGHES AIRCRAFT COMPANY
CULVER CITY, CALIFORNIA 90230

alone, even though all the information is in principle present there (since the sequence determines the way a protein chain folds). Before the X-ray analyses were done four groups of investigators tried independently to find the correct alignment for the sequences of c_{551} on the one hand and of c and c_2 on the other. The groups arrived at different results, all of which were shown by the structural analysis of c_{551} to have been wrong.

Without the three-dimensional structures the problem of where to place the massive deletions in the c_{551} sequence was insurmountable, but with the structures in hand it became trivial: it was the location of the folds, as revealed by the X-ray map, that made it clear which part of the tuna molecule had to be "removed" to make it fit the c_{551} map. This illustrates a basic principle: At the present level of understanding of protein folding, the three-dimensional structures of molecules are better guides to similarities between distantly related proteins than the amino acid sequences are.

Two points in the sequence table are interesting for the light they shed on the history of gene duplication. *Rhodospirillum molischianum* and *R. fulvum* each have two slightly different cytochromes c_2, the products of different genes; they are designated isozymes 1 and 2. Each isozyme is more like the corresponding one from the other species than the two isozymes in the same species are like each other. This suggests that the duplication leading to the isozyme-1 and isozyme-2 genes took place before the separation of the two species. *Pseudomonas aeruginosa* has, in addition to its c_{551}, a cytochrome c_4 that is a double-length molecule with two heme attachments and two liganding methionines. Each half of the c_4 sequence fits well with the other cytochromes in the table, suggesting that this protein is a result first of gene duplication and then of a mutation that deleted the "stop" signal between the two genes, so that the two sequences are now transcribed as one continuous message. The duplication must be ancient, since the first half of the *Pseudomonas* c_4 is more like the sequence of *Micrococcus* c_{554} than it is like its own second half.

PHOTOSYNTHESIZERS

A. GREEN PHOTOSYNTHETIC BACTERIA
  1. GREEN SULFUR BACTERIA (CHLOROBIACEAE).
    One photocenter.
    Source or reducing hydrogens: hydrogen sulfide, sulfur, thiosulfate or molecular hydrogen.
    Emit as by-product: sulfate.
    Strictly anaerobic; cannot respire.
  2. GREEN FILAMENTOUS BACTERIA (CHLOROFLEXACEAE).
    One photocenter.
    Source of hydrogens: hydrogen sulfide and organic molecules.
    Aerobic; oxygen respiration.

B. PURPLE PHOTOSYNTHETIC BACTERIA
  1. PURPLE SULFUR BACTERIA (CHROMATIACEAE).
    One photocenter.
    Source of hydrogens: hydrogen sulfide, sulfur, thiosulfate or molecular hydrogen;
    in some cases also organic molecules.
    Anaerobic; cannot respire.
  2. PURPLE NONSULFUR BACTERIA (RHODOSPIRILLACEAE).
    One photocenter.
    Source of hydrogens: mainly organic molecules, in some cases also hydrogen sulfide, but not sulfur.
    Aerobic; oxygen respiration.

C. BLUE-GREEN ALGAE (CYANOBACTERIA).
  Two photocenters.
  Source of hydrogens: water.
  Emit oxygen as by-product.
  Aerobic; oxygen respiration.

NONPHOTOSYNTHETIC RESPIRERS

A. SULFATE RESPIRERS (*DESULFOVIBRIO* AND OTHERS).
  Reduce sulfate to hydrogen sulfide.
  May be only distantly related to photosynthetic bacteria.

B. OXYGEN RESPIRERS (MANY BACTERIA).
  Reduce oxygen to water.
  Several lineages probably evolved from one or another of the photosynthetic bacteria. Some
  can also use nitrate as oxidant.

PHOTOSYNTHESIS IS FOUND in three groups of bacteria: the green, the purple and the blue-green photosynthesizers. Some members of each group can also respire, and respiration is a key energy-producing mechanism for other groups of bacteria that are not photosynthetic.

For closely related protein sequences a "difference matrix" showing the number of amino acid differences in all pairwise comparisons of sequences is effective for evaluating the degree of relatedness and as a starting point in constructing phylogenetic trees of the host organisms. This approach has been pursued with success by Walter M. Fitch, Emanuel Margoliash, Morris Goodman, Margaret Dayhoff and others. For more distantly related sequences an "identities matrix" is better. It avoids the difficult question of whether to treat a long deletion as one evolutionary event or many events, and it provides a measure of how nearly identical two sequences are in the regions of chain they have in common.

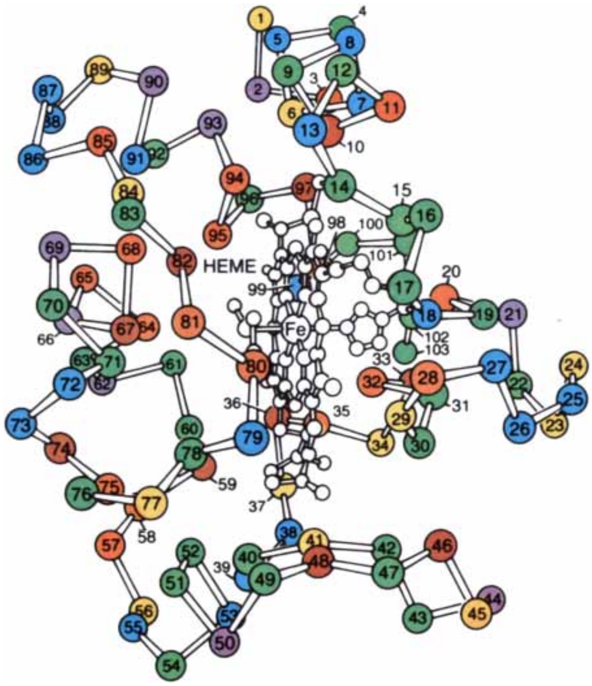
A condensed version of an identities matrix is shown on page 153. Instead of giving the number of amino acids that are identical in individual sequences the table shows the averaged values for all six cytochromes in the L class, all nine in M, all eight in S and all seven in S*; the scatter of numbers within each category is small compared with the differences between categories. The table shows each of the structural classes L, M, S and S* also to be a legitimate class in terms of sequence, because the sequences within any one class are identical (on the average) at more than 43 positions, whereas the number of identities between chains in different classes is considerably smaller. Only the L and M classes are so similar that one might be tempted to group them into one category with 38 or more identities, but this is ruled out by the presence of extra loops of chain at specific positions in the long cytochromes.

The large difference between the S and the S* sequences in spite of the two groups' similarity in size is not surprising when one considers their origin. The S cytochromes are found in pseudomonads and purple photosynthetic bacteria, whereas the S* ones are in cyanobacteria and eukaryotic algae. The small cytochromes c_{555} from green photosynthetic bacteria are quite distinct from all of these. Least similar of all, in sequence as well as source, is the cytochrome c_{553} from the sulfate-respiring *Desulfovibrio.* Yet the sequence alignment suggests that even this cytochrome may have the same chain folding as the others. An X-ray analysis is needed to settle the point.

All these cytochromes, regardless of their origin or their metabolic function, appear to belong to one evolutionarily related family of protein molecules. Furthermore, they occupy similar positions in their respective electron-transport chains: they are preceded by flavoproteins, quinones, iron-sulfur proteins


OH
WHAT
A
FEELING!
TOYOTA


EFI
CELICA



HYDROPHOBIC, AROMATIC RINGS

F	PHENYLALANINE
■	TRYPTOPHAN
Y	TYROSINE

HYDROPHOBIC, NOT AROMATIC

I	ISOLEUCINE
L	LEUCINE
M	METHIONINE
V	VALINE

AMBIVALENT (HYDROPHOBIC BUT SMALL, OR POLAR BUT UNCHARGED)

A	ALANINE
B	ASPARAGINE OR ASPARTIC ACID
C	CYSTEINE
N	ASPARAGINE
P	PROLINE
Q	GLUTAMINE
S	SERINE
T	THREONINE
Z	GLUTAMINE OR GLUTAMIC ACID

AMBIVALENT (NO SIDE CHAIN)

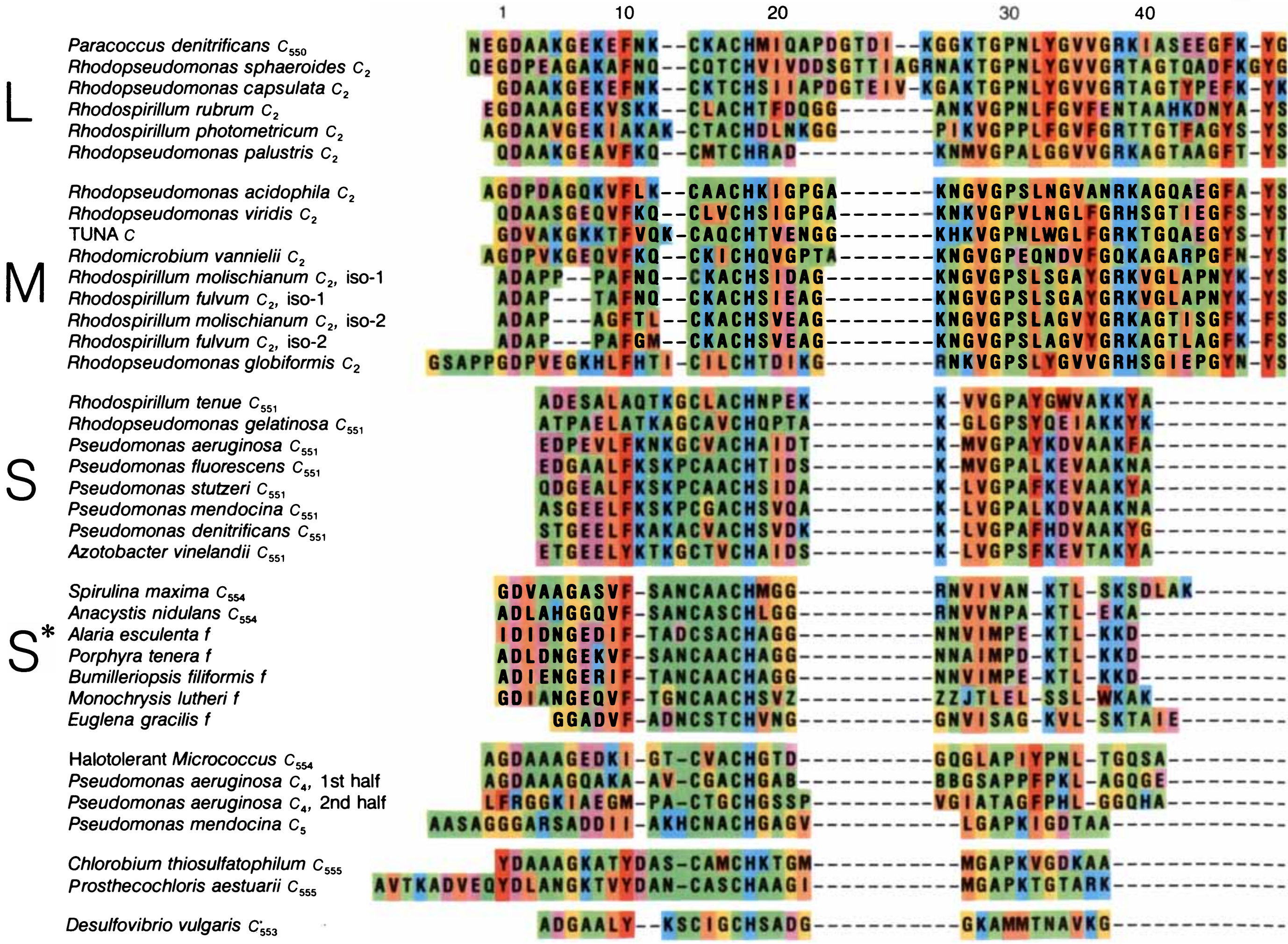
G	GLYCINE

HYDROPHILIC, BASIC

H	HISTIDINE
J	MONOMETHYL LYSINE
K	LYSINE
R	ARGININE

HYDROPHILIC, ACIDIC

D	ASPARTIC ACID
E	GLUTAMIC ACID



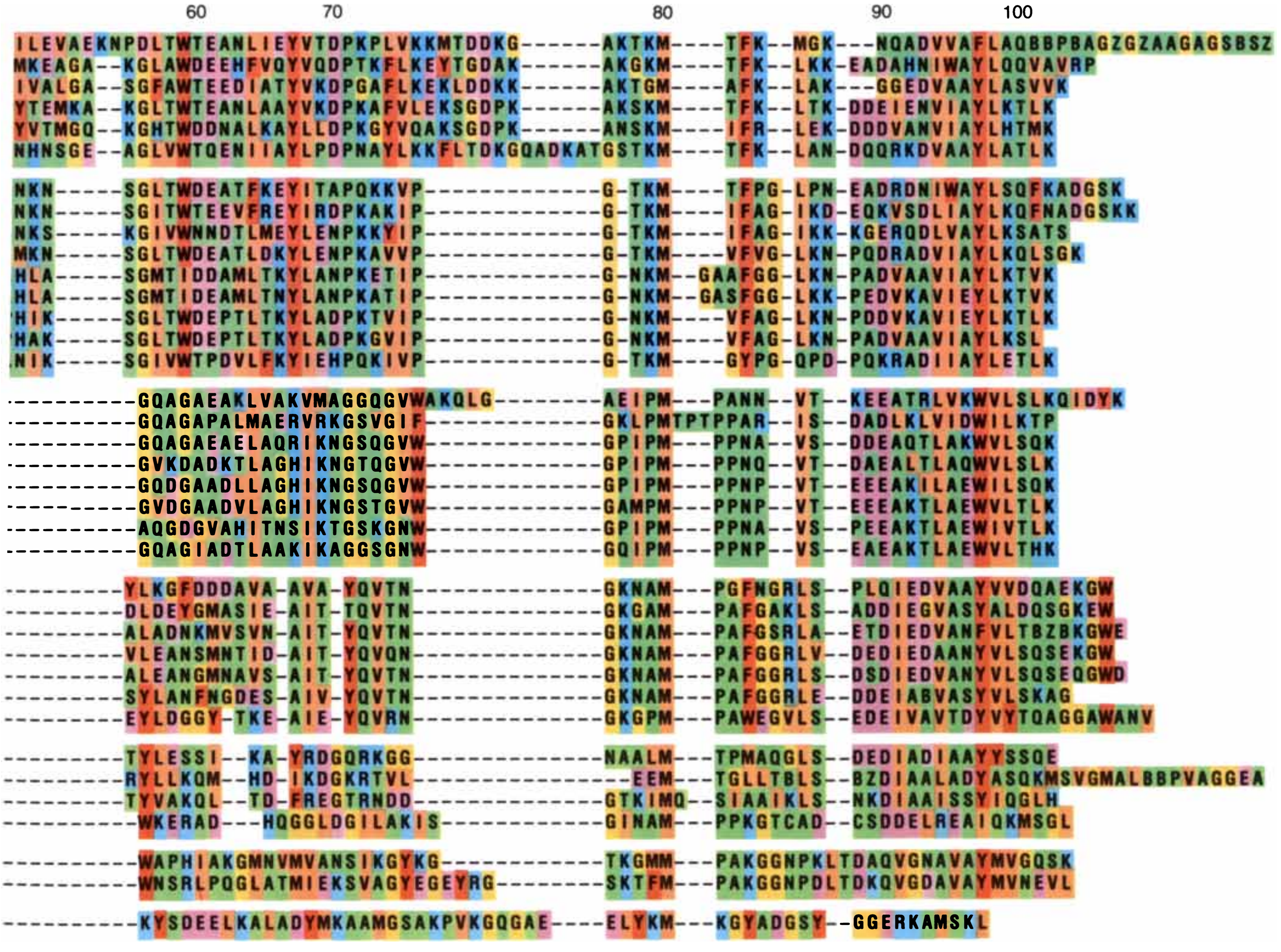
		1 10 20 30 40
L	*Paracoccus denitrificans* c_{550}	NEGDAAKGEKEFNK--CKACHMIQAPDGTDI--KGGKTGPNLYGVVGRKIASEEGFK-YG
	Rhodopseudomonas sphaeroides c_2	QEGDPEAGAKAFNQ--CQTCHVIVDDSGTTIAGRNAKTGPNLYGVVGRTAGTQADFKGYG
	Rhodopseudomonas capsulata c_2	GDAAKGEKEFNK--CKTCHSIIAPDGTEIV-KGAKTGPNLYGVVGRTAGTYPEFK-YK
	Rhodospirillum rubrum c_2	EGDAAAGEKVSKK--CLACHTFDQGG-------ANKVGPNLFGVFENTAAHKDNYA-YS
	Rhodospirillum photometricum c_2	AGDAAVGEKIAKAK-CTACHDLNKGG-------PIKVGPPLFGVFGRTTGTFAGYS-YS
	Rhodopseudomonas palustris c_2	QDAAKGEAVFKQ--CMTCHRAD----------KNMVGPALGGVVGRKAGTAAGFT-YS
M	*Rhodopseudomonas acidophila* c_2	AGDPDAGQKVFLK--CAACHKIGPGA-------KNGVGPSLNGVANRKAGQAEGFA-YS
	Rhodopseudomonas viridis c_2	QDAASGEQVFKQ--CLVCHSIGPGA-------KNKVGPVLNGLFGRHSGTIEGFS-YS
	TUNA *c*	GDVAKGKKTFVQK-CAQCHTVENGG-------KHKVGPNLWGLFGRKTGQAEGYS-YT
	Rhodomicrobium vannielii c_2	AGDPVKGEQVFKQ--CKICHQVGPTA-------KNGVGPEQNDVFGQKAGARPGFN-YS
	Rhodospirillum molischianum c_2, iso-1	ADAPP--PAFNQ--CKACHSIDAG--------KNGVGPSLSGAYGRKVGLAPNYK-YS
	Rhodospirillum fulvum c_2, iso-1	ADAP---TAFNQ--CKACHSIEAG--------KNGVGPSLSGAYGRKVGLAPNYK-YS
	Rhodospirillum molischianum c_2, iso-2	ADAP---AGFTL--CKACHSVEAG--------KNGVGPSLAGVYGRKAGTISGFK-FS
	Rhodospirillum fulvum c_2, iso-2	ADAP---PAFGM--CKACHSVEAG--------KNGVGPSLAGVYGRKAGTLAGFK-FS
	Rhodopseudomonas globiformis c_2	GSAPPGDPVEGKHLFHTI-CILCHTDIKG--------RNKVGPSLYGVVGRHSGIEPGYN-YS
S	*Rhodospirillum tenue* c_{551}	ADESALAQTKGCLACHNPEK---------K-VVGPAYGWVAKKYA----------
	Rhodopseudomonas gelatinosa c_{551}	ATPAELATKAGCAVCHQPTA---------K-GLGPSYQEIAKKYK----------
	Pseudomonas aeruginosa c_{551}	EDPEVLFKNKGCVACHAIDT---------K-MVGPAYKDVAAKFA----------
	Pseudomonas fluorescens c_{551}	EDGAALFKSKPCAACHTIDS---------K-MVGPALKEVAAKNA----------
	Pseudomonas stutzeri c_{551}	QDGEALFKSKPCAACHSIDA---------K-LVGPAFKEVAAKYA----------
	Pseudomonas mendocina c_{551}	ASGEELFKSKPCGACHSVQA---------K-LVGPALKDVAAKNA----------
	Pseudomonas denitrificans c_{551}	STGEELFKAKACVACHSVDK---------K-LVGPAFHDVAAKYG----------
	Azotobacter vinelandii c_{551}	ETGEELYKTKGCTVCHAIDS---------K-LVGPSFKEVTAKYA----------
S*	*Spirulina maxima* c_{554}	GDVAAGASVF-SANCAACHMGG----------RNVIVAN-KTL-SKSDLAK--------
	Anacystis nidulans c_{554}	ADLAHGGQVF-SANCASCHLGG----------RNVVNPA-KTL-EKA----------
	Alaria esculenta f	IDIDNGEDIF-TADCSACHAGG----------NNVIMPE-KTL-KKD----------
	Porphyra tenera f	ADLDNGEKVF-SANCAACHAGG----------NNAIMPD-KTL-KKD----------
	Bumilleriopsis filiformis f	ADIENGERIF-TANCAACHAGG----------NNVIMPE-KTL-KKD----------
	Monochrysis lutheri f	GDIANGEQVF-TGNCAACHSVZ----------ZZJTLEL-SSL-WKAK----------
	Euglena gracilis f	GGADVF-ADNCSTCHVNG----------GNVISAG-KVL-SKTAIE--------
	Halotolerant *Micrococcus* c_{554}	AGDAAAGEDKI-GT-CVACHGTD----------GQGLAPIYPNL-TGQSA----------
	Pseudomonas aeruginosa c_4, 1st half	AGDAAAGQAKA-AV-CGACHGAB----------BBGSAPPFPKL-AGQGE----------
	Pseudomonas aeruginosa c_4, 2nd half	LFRGGKIAEGM-PA-CTGCHGSSP---------VGIATAGFPHL-GGQHA----------
	Pseudomonas mendocina c_5	AASAGGGARSADDII-AKHCNACHGAGV----------LGAPKIGDTAA------------
	Chlorobium thiosulfatophilum c_{555}	YDAAAGKATYDAS-CAMCHKTGM----------MGAPKVGDKAA------------
	Prosthecochloris aestuarii c_{555}	AVTKADVEQYDLANGKTVYDAN-CASCHAAGI----------MGAPKTGTARK------------
	Desulfovibrio vulgaris c_{553}	ADGAALY--KSCIGCHSADG----------GKAMMTNAVKG------------

AMINO ACID SEQUENCES are given on these two pages for 36 related bacterial and algal cytochromes *c* and for the mitochondrial cytochrome *c* of tuna. The sequences have been arranged, on evidence from X-ray structural analyses, so that structurally equivalent regions of the chain are aligned vertically. The numbering along the top of the table is that of the tuna sequence, and a skeletal model of and cytochromes *b* and are followed by cytochrome oxidase or bacteriochlorophyll. It seems probable that the cytochromes are related because the electron-transport chains of which they are a part are also related, which implies that the electron chains of photosynthesis and of respiration have a common origin.

To learn more about this point one should obviously go to the bacteria that can both photosynthesize and respire, and of these most is known about the Rhodospirillaceae, or purple nonsulfur bacteria. Parts of the electron-transport chain of *Rhodopseudomonas capsulata,* including cytochrome c_2, are shared by both metabolic processes [*see lower illustration on page 139*]. Light-excited bacteriochlorophyll feeds electrons into a ubiquinone pool from which they pass to cytochromes *b* and c_2 and back to the chlorophyll again, with the absorbed light energy utilized to synthesize ATP. Organic molecules such as succinate can feed reducing equivalents into the pool, and these can serve to reduce NAD$^+$ to NADH with the help of driving energy provided by ATP; this reduction of NAD$^+$ with electrons from the ubiquinone pool is called reversed electron flow. This combination of cyclic photophosphorylation and reversed electron flow, however, is not the whole story. NADH from glycolysis or from the citric acid cycle can also (as it does in the mitochondrial respiration of eukaryotic cells) feed reducing equivalents into the ubiquinone pool. At the low-free-energy end of the chain cytochrome c_2 can pass electrons to a cytochrome oxidase complex as well as to bacteriochlorophyll, and this oxidase can reduce oxygen to water, just as in mitochondrial respiration. In fact, if the bacteriochlorophyll electron loop is deleted, the electron-transport chain is virtually identical with the chain of mitochondrial respiration.

It seems likely that some of the purple sulfur bacteria (Chromatiaceae) first developed the ability to obtain reducing equivalents from organic matter. That freed them from dependence on sulfides and turned them into the ancestors of the purple nonsulfur bacteria (Rhodospirillaceae). Some of the latter then "invented" respiration by adapting a heme protein as a bridge to carry electrons from the photosynthetic loop to oxygen. This invention would have come about in response to the gradually increasing availability of free oxygen in the atmosphere, itself a product of water-splitting photosynthesis by cyanobacteria.

The cytochromes of bacterial oxidases are more diverse than the other components of electron transport. They include cytochromes *a* (as in mitochondria), *b, o* and *cd;* many bacteria have both cytochromes *a* and *o* and others have both *a* and *cd*. Moreover, as Kamen has pointed out, bacterial cytochromes c_2 generally exhibit good reactivity with mitochondrial reductase but poor reactivity with mitochondrial oxidase. That is just what would be expected if the reductase was a common evolutionary heritage whereas the oxidases were more diverse. Perhaps this



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ILEVAEKNPDLTWTEANLIEYVTDPKPLVKKMTDDKG------AKTKM----TFK--MGK---NQADVVAFLAQBBPBAGZGZAAGAGSBSZ
MKEAGA--KGLAWDEEHFVQYVQDPTKFLKEYTGDAK------AKGKM----TFK--LKK-EADAHNIWAYLQQVAVRP
IVALGA--SGFAWTEEDIATYVKDPGAFLKEKLDDKK------AKTGM----AFK--LAK---GGEDVAAYLASVVK
YTEMKA--KGLTWTEANLAAYVKDPKAFVLEKSGDPK------AKSKM----TFK--LTK-DDEIENVIAYLKTLK
YVTMGQ--KGHTWDDNALKAYLLDPKGYVQAKSGDPK------ANSKM----IFR--LEK-DDDVANVIAYLHTMK
NHNSGE--AGLVWTQENIIAYLPDPNAYLKKFLTDKGQADKATGSTKM----TFK--LAN-DQQRKDVAAYLATLK

NKN-----SGLTWDEATFKEYITAPQKKVP-------------G-TKM----TFPG-LPN-EADRDNIWAYLSQFKADGSK
NKN-----SGITWTEEVFREYIRDPKAKIP-------------G-TKM----IFAG-IKD-EQKVSDLIAYLKQFNADGSKK
NKS-----KGIVWNNDTLMEYLENPKKYIP-------------G-TKM----IFAG-IKK-KGERQDLVAYLKSATS
MKN-----SGLTWDEATLDKYLENPKAVVP-------------G-TKM----VFVG-LKN-PQDRADVIAYLKQLSGK
HLA-----SGMTIDDAMLTKYLANPKETIP-------------G-NKM--GAAFGG-LKN-PADVAAVIAYLKTVK
HLA-----SGMTIDEAMLTNYLANPKATIP-------------G-NKM--GASFGG-LKK-PEDVKAVIEYLKTVK
HIK-----SGLTWDEPTLTKYLADPKTVIP-------------G-NKM----VFAG-LKN-PDDVKAVIEYLKTLK
HAK-----SGLTWDEPTLTKYLADPKGVIP-------------G-NKM----VFAG-LKN-PADVAAVIAYLKSL
NIK-----SGIVWTPDVLFKYIEHPQKIVP-------------G-TKM----GYPG-QPD-PQKRADIIAYLETLK

----------GQAGAEAKLVAKVMAGGQGVWAKQLG--------AEIPM---PANN--VT--KEEATRLVKWVLSLKQIDYK
----------GQAGAPALMAERVRKGSVGIF-------------GKLPMTPTPPAR--IS--DADLKLVIDWILKTP
----------GQAGAEAELAQRIKNGSQGVW-------------GPIPM---PPNA--VS--DDEAQTLAKWVLSQK
----------GVKDADKTLAGHIKNGTQGVW-------------GPIPM---PPNQ--VT--DAEALTLAQWVLSLK
----------GQDGAADLLAGHIKNGSQGVW-------------GPIPM---PPNP--VT--EEEAKILAEWILSQK
----------GVDGAADVLAGHIKNGSTGVW-------------GAMPM---PPNP--VT--EEEAKTLAEWVLTLK
----------AQGDGVAHITNSIKTGSKGNW-------------GPIPM---PPNA--VS--PEEAKTLAEWIVTLK
----------GQAGIADTLAAKIKAGGSGNW-------------GQIPM---PPNP--VS--EAEAKTLAEWVLTHK

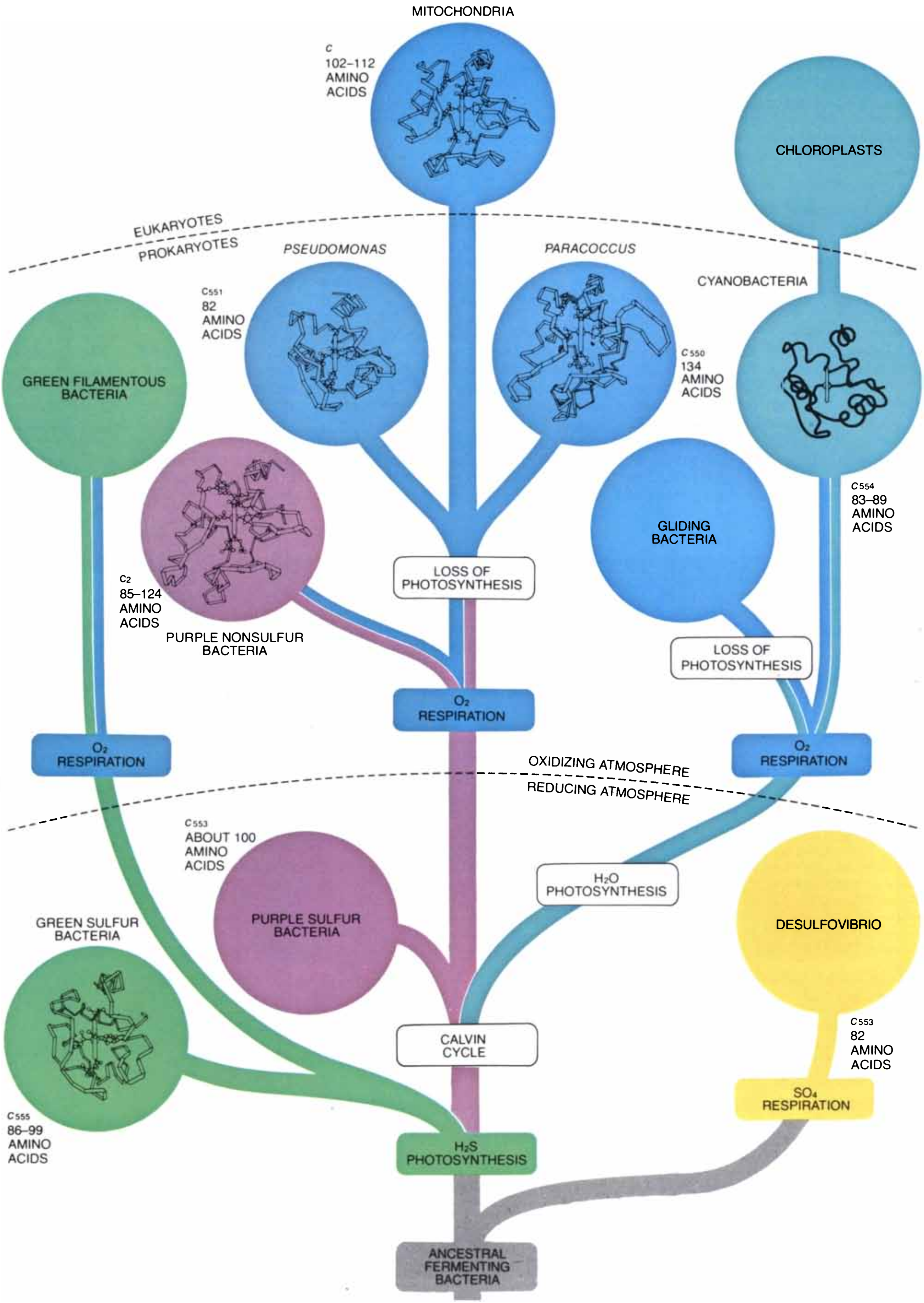
---------YLKGFDDDAVA-AVA-YQVTN--------------GKNAM---PGFNGRLS--PLQIEDVAAYVVDQAEKGW
---------DLDEYGMASIE-AIT-TQVTN--------------GKGAM---PAFGAKLS--ADDIEGVASYALDQSGKEW
---------ALADNKMVSVN-AIT-YQVTN--------------GKNAM---PAFGSRLA--ETDIEDVANFVLTBZBKGWE
---------VLEANSMNTID-AIT-YQVQN--------------GKNAM---PAFGGRLV--DEDIEDAANYVLSQSEKGW
---------ALEANGMNAVS-AIT-YQVTN--------------GKNAM---PAFGGRLS--DSDIEDVANYVLSQSEQGWD
---------SYLANFNGDES-AIV-YQVTN--------------GKNAM---PAFGGRLE--DDEIABVASYVLSKAG
---------EYLDGGY-TKE-AIE-YQVRN--------------GKGPM---PAWEGVLS--EDEIVAVTDYVYTQAGGAWANV

---------TYLESSI--KA-YRDGQRKGG---------------NAALM---TPMAQGLS--DEDIADIAAYYSSQE
---------RYLLKQM--HD-IKDGKRTVL------------------EEM---TGLLTBLS--BZDIAALADYASQKMSVGMALBBPVAGGEA
---------TYVAKQL--TD-FREGTRNDD---------------GTKIMQ--SIAAIKLS--NKDIAAISSYIQGLH
----------WKERAD---HQGGLDGILAKIS-------------GINAM---PPKGTCAD--CSDDELREAIQKMSGL

----------WAPHIAKGMNVMVANSIKGYKG-------------TKGMM---PAKGGNPKLTDAQVGNAVAYMVGQSK
----------WNSRLPQGLATMIEKSVAGYEGEYRG---------SKTFM---PAKGGNPDLTDKQVGDAVAYMVNEVL

----------KYSDEELKALADYMKAAMGSAKPVKGQGAE----ELYKM---KGYADGSY--GGERKAMSKL
```

the tuna molecule is shown (*top left*) to relate the sequences to the shape of the molecule. The key gives both the one-letter designation for each of the 20 amino acids (and for a variant, monomethyl lysine) and the color code, which groups the amino acids according to their chemical type. The retention of chemical character at corresponding sites in the molecules is revealed by the vertical bands of color.


MITOCHONDRIA
c
102–112
AMINO
ACIDS
CHLOROPLASTS
EUKARYOTES
PROKARYOTES
PSEUDOMONAS
PARACOCCUS
CYANOBACTERIA
c_{551}
82
AMINO
ACIDS
GREEN FILAMENTOUS
BACTERIA
c_{550}
134
AMINO
ACIDS
c_{554}
83–89
AMINO
ACIDS
GLIDING
BACTERIA
c_2
85–124
AMINO
ACIDS
PURPLE NONSULFUR
BACTERIA
LOSS OF
PHOTOSYNTHESIS
LOSS OF
PHOTOSYNTHESIS
O_2
RESPIRATION
O_2
RESPIRATION
O_2
RESPIRATION
OXIDIZING ATMOSPHERE
REDUCING ATMOSPHERE
c_{553}
ABOUT 100
AMINO
ACIDS
PURPLE SULFUR
BACTERIA
H_2O
PHOTOSYNTHESIS
DESULFOVIBRIO
GREEN SULFUR
BACTERIA
CALVIN
CYCLE
c_{553}
82
AMINO
ACIDS
SO_4
RESPIRATION
c_{555}
86–99
AMINO
ACIDS
H_2S
PHOTOSYNTHESIS
ANCESTRAL
FERMENTING
BACTERIA

diversity reflects the late, add-on character of the oxidase shunt, a short circuit from cytochrome *c* to oxygen. All that would be needed to turn one of the versatile Rhodospirillaceae such as *R. capsulata* into the ancestor of some of the present-day respiring bacteria would be a mutational deletion of the photosynthetic side of the machinery at a time when the oxygen concentration in the earth's atmosphere had increased to the point where the bacterium could survive on respiration alone.

These relations between photosynthetic and respiratory bacteria can be summarized in a metabolic phylogenetic tree [*see illustration on opposite page*]. It is based on everything we can learn about comparative bacterial metabolism, not just on cytochrome sequence and structure data. It helps to make what we can observe about these cytochromes understandable; indeed, the tree diagram tells us more about cytochrome structures than those structures tell us about how to construct the tree.

The earliest photosynthetic bacteria to leave modern descendants probably were the green sulfur bacteria, photoreducing NAD^+ directly to NADH with the aid of hydrogens from hydrogen sulfide (H_2S) and releasing sulfate into the surroundings as a by-product. They apparently did not have the familiar Calvin-Benson cycle for fixing (reducing) carbon dioxide and may have relied instead on something like the mitochondrial citric acid cycle run in reverse: the reductive tricarboxylic acid cycle. Some opportunistic neighbors, not necessarily closely related, then found ways to profit by exploiting this sulfate as an oxidant, leading to today's *Desulfovibrio.*

The Calvin-Benson cycle developed in the line that led to the purple and blue-green photosynthetic bacteria. Once supplied with the energy from two photocenters, the ancestors of the blue-greens (cyanobacteria) were able to replace hydrogen sulfide with a weaker

PHYLOGENETIC TREE traces the evolution of bacterial photosynthesis and respiration. According to this proposal by the author, sulfate respiration (*yellow*) evolved in response to sulfate-releasing photosynthesis (*green and purple*) early on the primitive earth, just as oxygen respiration (*blue*) evolved later after oxygen-releasing photosynthesis (*blue-green*) had created an oxygen environment. Oxygen respiration arose independently in several lines of photosynthetic bacteria that adapted a heme protein to shunt electrons from the photosynthetic electron-transport chain to oxygen instead of to bacteriochlorophyll. Five clearly established cytochrome *c* structures are shown, as is a sixth structure (for a cytochrome c_{554} from a cyanobacterium) that has been determined only at low resolution.

Perkin-Elmer minicomputers "shuttle" astronauts into space

When the NASA Space Shuttle goes into orbit for the first time, the pilot and crew will feel that they've been through it all many times before.

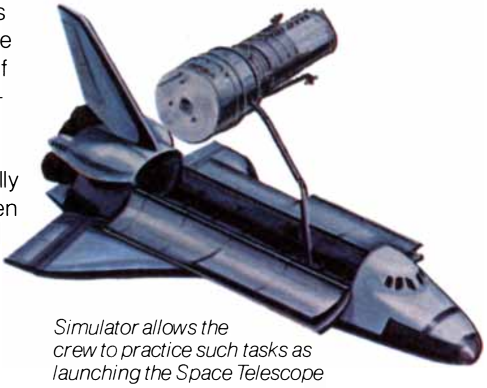
In a sense, they have—at the Johnson Space Center, where they are training in one of the most advanced flight simulators ever built. At the heart of the simulator are 23 Perkin-Elmer 32-bit minicomputers which deliver the real-time response needed to create a true sensation of flight. They also control and coordinate the simulation from takeoff to landing.

Minicomputers give crew the "feel" of real flight.

The simulator windows are actually high-resolution video screens. When the pilot moves the stick, feedback control coordinates video imagery with the motion of the simulator. Crew members see, hear and feel the changes their actions cause—the jerks and bumps, for example, as thrusters are fired or air brakes let out.

The minicomputers also create appropriate instrument readings and simulate ground communication links. They can even tie the "flight" into NASA's worldwide communications network.

The high-speed data acquisition capability of Perkin-Elmer's 32-bit computers makes them ideal for the heavy input/output load of real-time, event-driven simulations. The unique Perkin-Elmer shared memory permits up to 14 computers to share a common memory; if one or more units become overloaded, others can pick up the workload

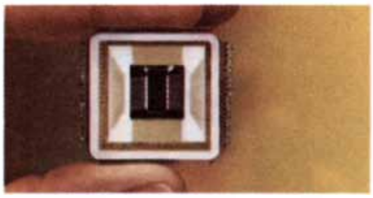


Simulator allows the crew to practice such tasks as launching the Space Telescope

More than 25 commercial and military training simulators are now equipped with Perkin-Elmer 32-bit computers. Several computers have been ordered by the European Space Agency to simulate experiments to be carried into space by NASA's Shuttle.

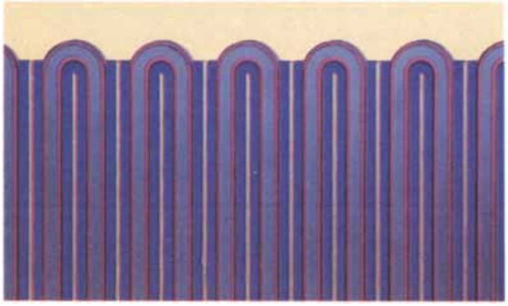
Sharp new eyes warn against laser-guided weapons

Highly accurate laser-guided weapons pose a new kind of threat to military aircraft, tanks and ships. Effective countermeasures depend on fast detection and identification of the laser beams such weapons use to "zero in" on their targets.



Etalon, the "eye" that identifies the laser beam, is the small rectangle in the center of the detector array.

A compact laser warning receiver developed by Perkin-Elmer provides this kind of information swiftly and accurately. The receiver measures a laser beam's direction, wavelength, intensity and modulation characteristics. Its basic optical component is



a small interferometer called an etalon. The etalon refracts and reflects incoming laser light to form an interference pattern that is actually a unique identifying signature for each laser beam. It rejects false signatures such as light from the sun, lightning, searchlights, flares or explosives.

The laser warning receiver is not only efficient but, because of its modular construction, economical to manufacture. It is built with low-cost optical elements and reprogrammable microprocessor logic.

Magnified section of detector array in laser warning receiver.

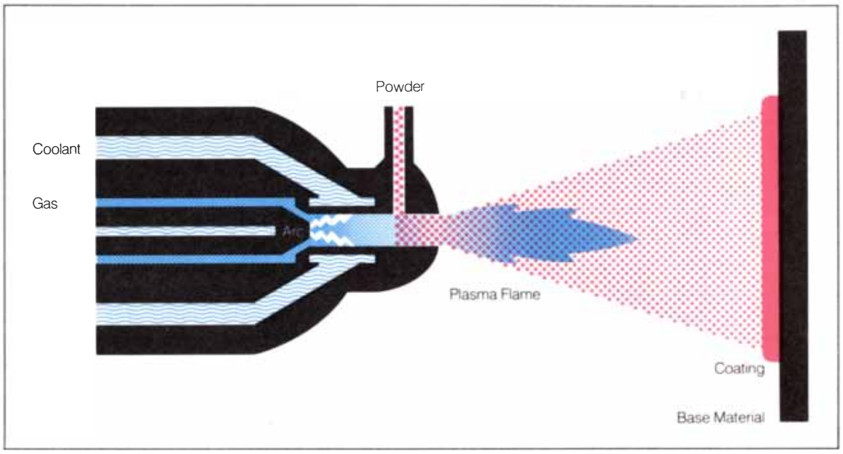
Plasma spray is a life saver for thousands of jet engine parts

When jet engines run, their finely machined parts encounter a variety of wear conditions. A process called plasma spraying—pioneered by METCO, a Perkin-Elmer subsidiary—prolongs the life of original parts and quickly restores worn parts to original dimensions

In plasma spraying, a gas ionized by an electric arc creates a high-velocity plasma stream whose temperature can exceed 30,000°F. A powdered material is melted in the hot plasma and propelled onto a surface where it bonds and rapidly builds up to the required thickness.

The dense coating has superior resistance to wear and, in some cases, to corrosion and high temperature. For example, parts made of titanium, which has an excellent strength-to-weight ratio but virtually no wear resistance, can be protected with a material such as tungsten carbide. In higher temperature areas, chrome carbides are used.

Major jet engine manufacturers use this process to coat a number of components. And airline maintenance shops around the world rebuild more than 2,000 worn parts with plasma spraying to reduce downtime.



Plasma spray coatings are produced by injecting a powder into a plasma gas stream. The powder particles are melted and projected onto the surface being coated.

METCO's latest development is a vacuum-chamber plasma spray system, which opens up the potential for applying protective coatings in areas of high-temperature corrosion, such as turbine seals, blade tips and turbine airfoils.

Other industries with similar problems can follow the airlines' example.

Plasma coatings are finding increasing use in the automotive, chemical, mining, paper, power generating and textile industries. With plasma spraying, these users can stretch service life and reduce maintenance for parts subjected to heat, wear and corrosion.

For More Information

If you would like to learn more about these products, please write:
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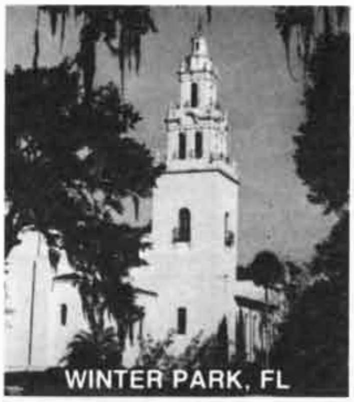
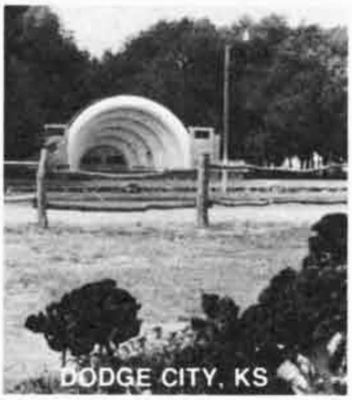
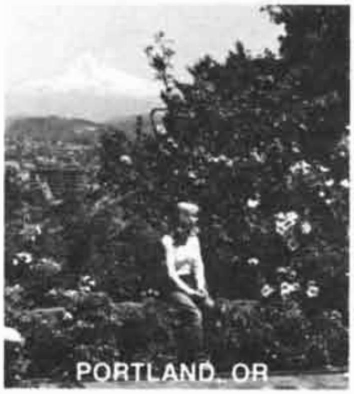

WINTER PARK, FL


NEW ORLEANS, LA


DODGE CITY, KS


PHILADELPHIA, PA


PORTLAND, OR


SHEYBOYGAN, WI


LINCOLN, NE

but much more plentiful reductant: water. Over perhaps a billion-year time span the blue-greens slowly converted the planetary atmosphere from a reducing medium into an oxidizing one, forcing all the anaerobic bacteria to either adapt to the presence of oxygen or retreat to corners of the environment that were still without oxygen. The oxidation of organic molecules with free oxygen is such an efficient source of energy that the general response was to find ways of adapting preexisting photosynthetic electron-transport chains to feed electrons to oxygen.

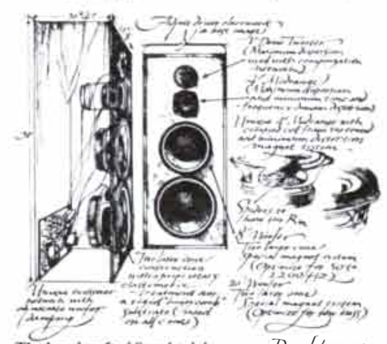
Respiration was born not once but repeatedly in different lines of bacteria. The Chloroflexaceae, the Rhodospirillaceae and gliding bacteria such as *Beggiatoa* and *Leucothrix* are probably respiring adaptations of the green, the purple and the blue-green photosynthetic bacteria respectively. Just as these gliding bacteria appear to be cyanobacteria that have lost photosynthesis, so did many of the respiring bacteria arise from the ancestors of the Rhodospirillaceae through the loss of photosynthesis. Included among these are the pseudomonads, *Paracoccus denitrificans* and the bacterial ancestors of mitochondria in eukaryotes. Philip John of the University of Reading and Frederick R. Whatley of the University of Oxford have suggested that on many lines of evidence *Paracoccus* is most like the probable ancestor of mitochondria; the sequence table shows that *Paracoccus* c_{550} most closely resembles the c_2 of *Rhodopseudomonas sphaeroides* and *R. capsulata*, both of which have respiratory machinery much like that of mitochondria. Perhaps in these two species we are seeing our own metabolic ancestors. If that is the case, it leads to a sobering thought: Human beings are the metabolic offspring of defective purple photosynthetic bacteria.

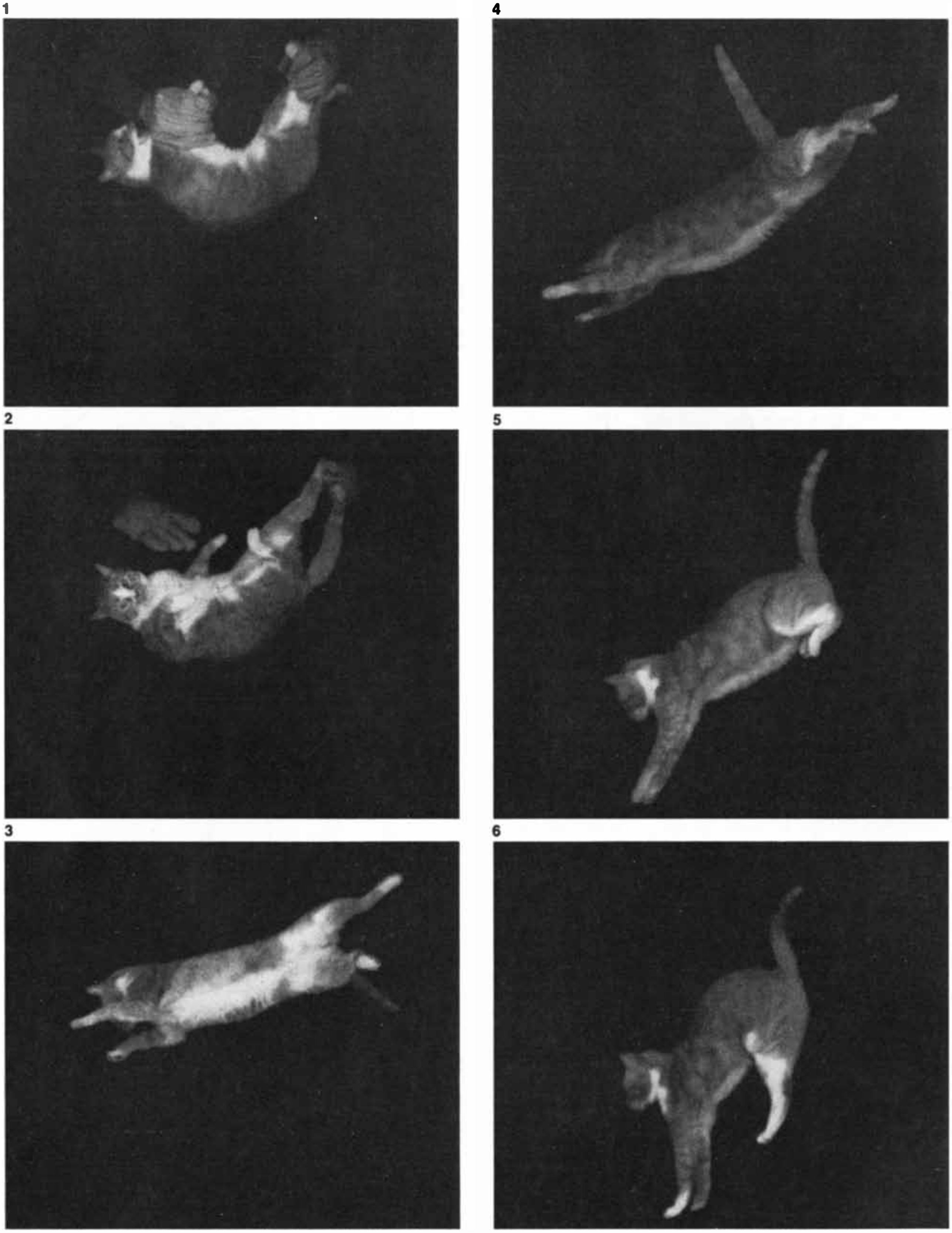
Which of the three size classes of cytochromes *c* is the oldest: S and S*, M or L? That is, has the evolution of cytochrome *c* involved the trimming down of a larger ancestral molecule or the building up of a smaller one? Chains as short as the S group are widely distributed in the evolutionary tree: in *Desulfovibrio, Chlorobium*, cyanobacteria, Rhodospirillaceae and nonphotosynthetic respirers. In contrast, the larger molecules are found only in the purple bacteria and in the respirers that developed from them. Hence one probably must regard the S and S* cytochromes as being more like the common ancestor; the insertions at various places on the surface of the molecule would then have been later developments that came in only one branch of bacteria.

This is just one example of what can be learned about the early history of life through the examination of molecular data. The story could be repeated, in principle, for any other protein all these organisms had in common. It may be that for some proteins the evolutionary record in bacteria has been scrambled by the lateral transmission of genes between otherwise unrelated species (although one is not driven to such a conclusion by the data so far available); if so, these cases should show up as anomalies in the record and should be recognized when enough proteins have been examined. It may also be that the transfer of linked genes has served to bring respiration to lines of bacteria that never had any photosynthetic ancestors. Such details are still to be proved or disproved. The fact remains that the quantity of information potentially available from molecular data is at least an order of magnitude greater than what has been available to the classical taxonomist, and this new source of data has only begun to be mined.

	L (6)	M (9)	S (8)	S* (7)	c_{555}(2)	c_{553}(1)
L (6: c_2, c_{550})	49.7	38.5	17.8	17.5	15.6	12.0
M (9: c_2, c)	38.5	51.6	18.9	19.1	15.1	11.9
S (8: c_2, c_{551})	17.8	18.9	43.8	17.6	13.8	14.4
S* (7: c_{554}, f)	17.5	19.1	17.6	43.6	18.4	6.4
c_{555} (2)	15.6	15.1	13.8	18.4	47.0	12.0
c_{553} (1)	12.0	11.9	14.4	6.4	12.0	—

IDENTITIES MATRIX shows the number of sites occupied by identical amino acids in pairwise comparisons of the sequences of cytochromes *c*, averaged for each structural class (L, M, S and S*) and for two other variants. The digits in parentheses give the number of cytochromes in each group. The sequences are identical at significantly more sites within each class (*color*) than between classes. Only the L and M classes are similar enough to suggest combining them in one category (*broken lines*), but that is ruled out by the extra loops of chain in L molecules.





CAT TURNING OVER IN MIDAIR is shown in this composite sequence of photographs. The cat turns over in an eighth of a second for a half-second free fall of four feet. An experimenter held the cat upside down and released it with zero angular momentum. Since air resistance is negligible, no torques are applied to the cat in the course of its descent. In the absence of torques the angular momentum of a body is conserved, and so the cat's angular momentum remains zero throughout its fall. The cat is nonetheless able to turn over in midair because a body need not be moving linearly in order to have zero angular momentum as is explained by bottom illustration on page 162.

The Physics of Somersaulting and Twisting

Divers, gymnasts, astronauts and cats can do rotational maneuvers in midair that may seem to violate the law of the conservation of angular momentum but in fact do not

by Cliff Frohlich

In the absence of external forces the linear momentum of a body (its mass times its velocity) is conserved. Similarly, in the absence of torques, or rotational forces, the angular momentum of a body (the rotational analogue of linear momentum) is conserved. The concept of angular momentum is deceptively simple, and its misapplication has led to paradox. If a cat is dropped upside down, it turns over in free fall in a fraction of a second and lands on its feet. By the same token, when an expert diver jumps off a springboard, he can start to somersault and twist in midair long after he has left the board. Since the cat and the diver have zero angular momentum, how can they rotate in midair without violating the law of the conservation of angular momentum? Here I want to discuss in detail the physics of somersaulting and twisting in order to flesh out the concept of angular momentum.

Springboard divers routinely execute maneuvers in which their body rotates in space. The basic maneuvers are the somersault and the twist. In the somersault the body rotates head over heels as if the athlete were rotating about an axis extending from his left side to his right side through his waist. In the twist the body spins or pirouettes in midair as if the athlete were rotating about an axis extending from his head to his toes.

Nearly all the most complicated diving maneuvers are either multiple somersaults or combinations of somersaults and twists. A good diver can execute a forward three-and-a-half somersault, which calls for 1,260 degrees of rotation. Another common dive is the forward one-and-a-half somersault with three twists, in which the diver somersaults 540 degrees and twists 1,080 degrees. The best divers have recently begun to perform even more complex feats, such as the forward two-and-a-half somersault with two twists.

The conservation of angular momentum is the fundamental physical principle that governs all maneuvers incorporating somersaults and twists. In such maneuvers air resistance is negligible, so that no torques are applied to the diver once he leaves the board. (The same is of course true of the gymnast once he leaves the mat.) For example, in the forward two-and-a-half somersault with two twists the diver's angular momentum remains fixed at some large nonzero value. This creates a paradox: How can he initiate the twisting rotations in midair without changing his angular momentum?

It is time to precisely define angular momentum, which can be expressed in terms of two other parameters of rotation: angular velocity and moment of inertia. Angular velocity is a vector, represented by a line with an arrowhead, that describes a body's rotational speed and direction. The vector has a length that represents the speed of rotation and an orientation parallel to the axis of rotation. Which end of the vector has the arrowhead attached to it corresponds by convention to whether the rotation about the axis is clockwise or counterclockwise.

For example, when a diver executes a forward double somersault in one second, the magnitude of his average angular velocity is two revolutions per second. The direction of his angular-velocity vector is parallel to the somersaulting axis (and the arrowhead is at the diver's left side). Similarly, when the diver twists, the direction of his angular velocity is along the twisting axis (with the arrowhead at his head if he is twisting to the left). When a diver simultaneously twists and somersaults, his total angular-velocity vector is the vector sum of the angular velocity of twisting and the angular velocity of somersaulting. (The sum of two vectors A and B is found by putting the base of B at the arrowhead of A. The sum is the vector formed by connecting the base of A to

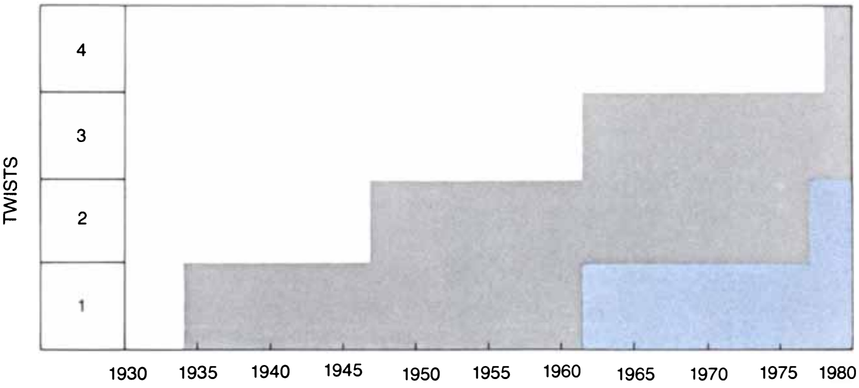
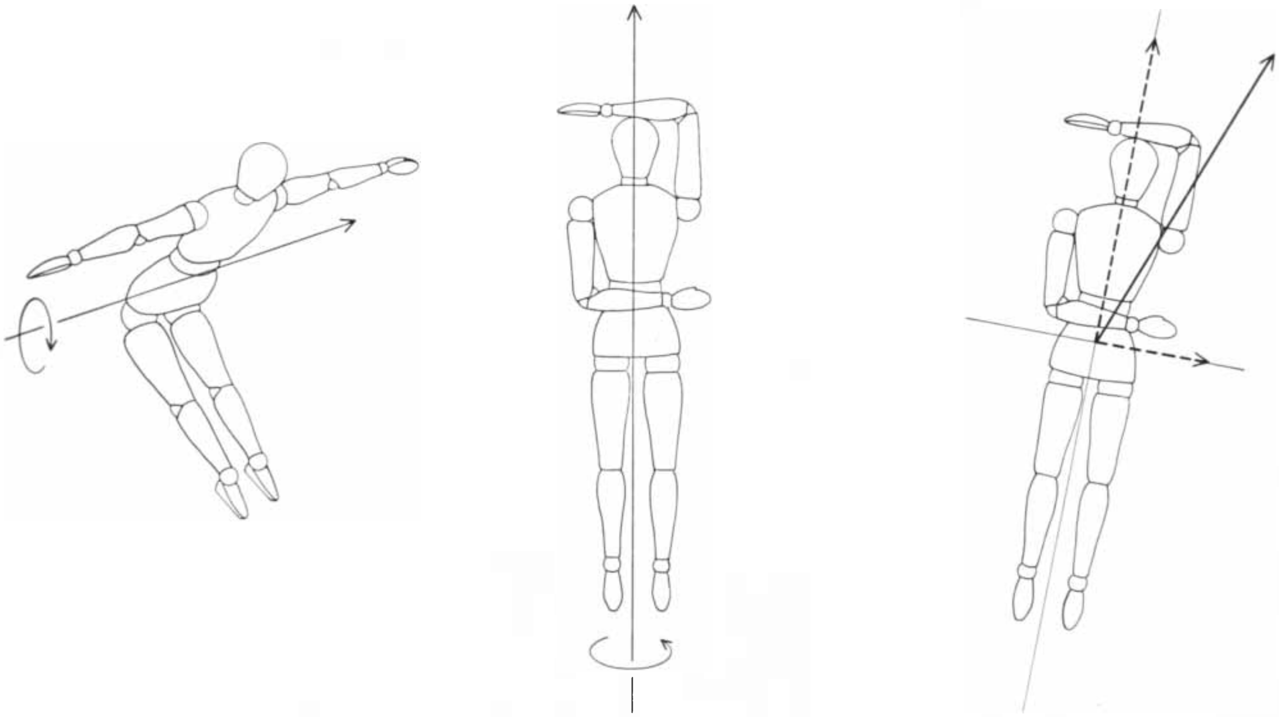
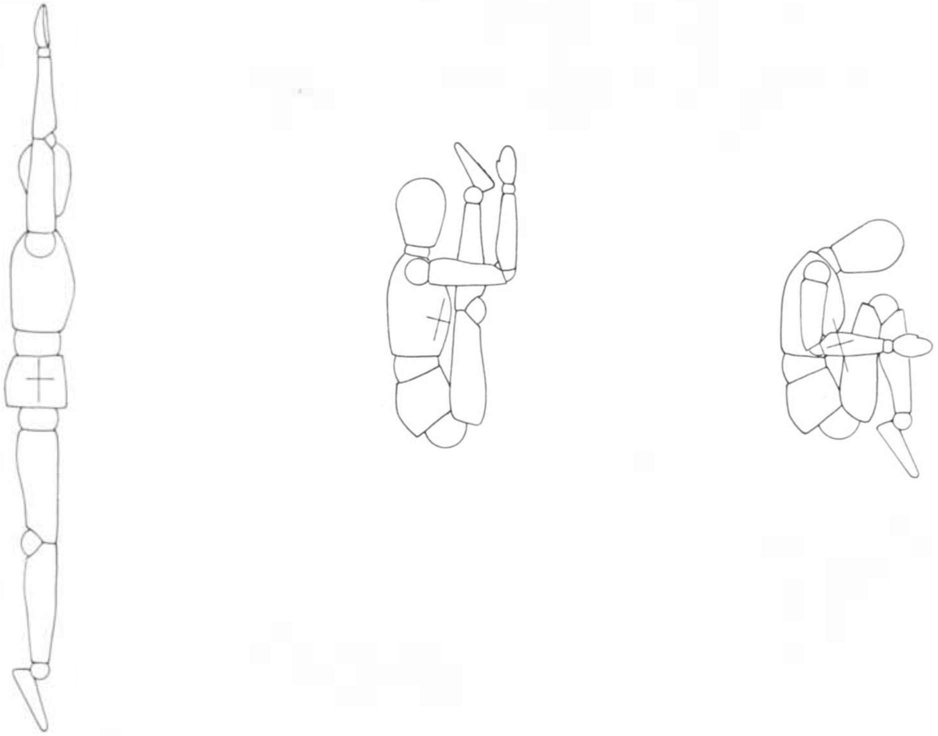


CHART OF THE FORWARD TWISTING SOMERSAULTS that are allowed in intercollegiate three-meter springboard diving competition indicates that maneuvers combining somersaulting and twisting are relatively new. The gray region represents forward one-and-a-half somersault and the colored region forward two-and-a-half somersault. Twists are at the left.



SOMERSAULTS AND TWISTS are the basic maneuvers that make up most of the complicated dives executed in competition. In the somersault (*left*) the body rotates head over heels as if the diver were rotating about an axis extending from his left side to his right side through his waist. In the twist (*middle*) the body spins in midair as if the diver were rotating about an axis from his head to his toes. When a diver simultaneously twists and somersaults (*right*), his total angular-velocity vector (*solid arrow*) is the vector sum of the angular velocity of somersaulting (*short broken arrow*) and the angular velocity of twisting (*long broken arrow*). Twisting angular-velocity vector is three times longer than the somersaulting angular-velocity vector because the diver is twisting three times faster than he is somersaulting.



MOMENT OF INERTIA of a body about an axis, which by definition is the body's tendency to resist changes in angular velocity about that axis, is larger the more the mass of the body is concentrated away from the axis. The moment of inertia of a man rotating about his somersaulting axis (*left*) is largest when his body is straight. The moment of inertia is smaller when his body is piked, or bent at the waist (*middle*). The moment of inertia is smallest when his body is tucked, or bent at both the waist and the knees (*right*). The somersaulting moment of inertia is 19.8 kilograms times meters squared (kg.m.^{2}) when the man's body is straight, 5.9 when his body is piked and 3.8 when his body is tucked. The moment of inertia about his twisting axis when he is straight is smaller: 1.1 kilograms times meters squared.

the arrowhead of *B*. Vector addition is commutative: *A* plus *B* equals *B* plus *A*.)

The moment of inertia of a rigid body about an axis is the body's tendency to resist changes in angular velocity about that axis, just as the mass of a body is its tendency to resist changes in linear velocity. It is obvious that massive and extended bodies have a larger moment of inertia than lighter and smaller ones. In fact, the contribution of each particle in a body to the total moment of inertia about an axis equals the mass of the particle times the square of its distance from the axis of rotation.

For example, a typical male diver with his body straight and his arms at his sides has a moment of inertia of 14 kilograms times meters squared (kg.m.^{2}) about his somersaulting axis but a moment of inertia of only one kilogram times meter squared about his twisting axis. Although the mass of each particle of the diver remains the same for both somersaulting and twisting, the moment of inertia is larger about the somersaulting axis because on the average each particle is farther from that axis than it is from the twisting one.

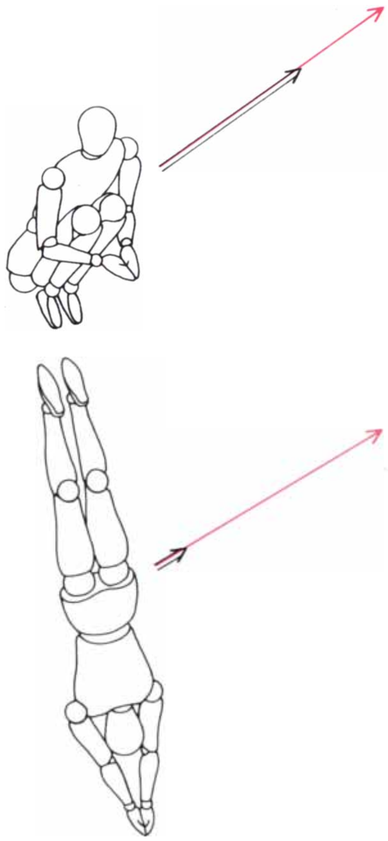
Like angular velocity, angular momentum is a vector. The total angular momentum of an athlete executing a twisting somersault is the vector sum of the angular momentum about his somersaulting axis and the angular momentum about his twisting axis. His somersaulting angular momentum is simply the product of his somersaulting angular velocity and his moment of inertia about his somersaulting axis. In addition his twisting angular momentum is simply the product of his twisting angular velocity and his moment of inertia about his twisting axis. The total angular-momentum vector of an athlete remains constant in direction and magnitude in the absence of torques, just as the linear momentum of a body remains constant in the absence of external forces. This constancy is the essence of the law of the conservation of angular momentum. When the diver is still on the springboard, he can acquire angular momentum if it exerts torques on his body, but once he is in the air his angular momentum remains constant.

The analogy between angular momentum (moment of inertia times angular velocity) and linear momentum (mass times linear velocity) is not perfect. Because the mass of a body is invariant a constant linear momentum means a constant linear velocity. Because the moment of inertia is not invariant but subject to change, however, a constant angular momentum does not mean a constant angular velocity. The angular velocity and the moment of inertia can vary inversely as long as their product remains constant.

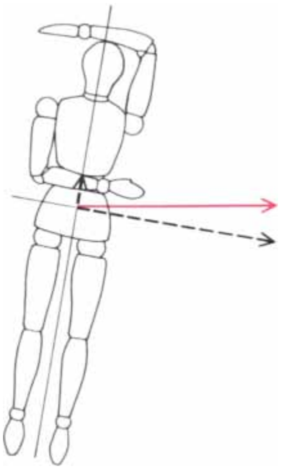
A diver is not a rigid object, so that it is possible for him to vary the moment of inertia about his somersaulting axis by tucking up or straightening out his body and to vary the moment of inertia about his twisting axis by pulling in or extending his arms. For example, in the backward somersault the diver leaves the springboard with his body straight as he begins to somersault backward. If he keeps his body straight, he will somersault about one and a half times before entering the water. If he tucks himself up into a ball by pulling in his arms and legs, he will spin much faster and somersault at least two and a half times. As he tucks up, his angular momentum remains constant in magnitude and direction, but his angular velocity increases by a factor of about four because the moment of inertia about his somersaulting axis decreases by a factor of about four. In the backward somersault the angular-velocity vector changes not in direction but in magnitude. The vector remains parallel to the angular-momentum vector throughout the dive.

The angular-velocity vector does not, however, remain parallel to the angular-momentum vector in all cases. If the rotation is about an axis that is not one of the symmetry axes of the body (such as the somersaulting axis or the twisting axis), then the angular-velocity vector and the angular-momentum vector will point in different directions. Suppose a diver is twisting and somersaulting simultaneously. His total angular-momentum vector is the vector sum of his somersaulting angular velocity times his somersaulting moment of inertia and his twisting angular momentum times his twisting moment of inertia. Since the moments of inertia are not equal, the angular-momentum vector and the angular-velocity vector point in different directions. Of course, the direction and the magnitude of the angular-momentum vector remain constant throughout the dive regardless of how the diver twists, squirms or flails. The lack of parallelism of angular velocity and angular momentum brings out another difference between rotational motion and linear motion. In the linear case the velocity vector and the momentum vector are always parallel.

It is possible for a diver to change in midair both his somersaulting angular momentum and his twisting angular momentum as long as their sum, the total angular momentum, remains constant in magnitude and direction. In a twisting somersault the diver starts to execute an ordinary somersault, in which his angular-velocity and angular-momentum vectors lie along the somersaulting axis. To twist his body he simultaneously "throws" his right arm down and his left arm up in the plane of his body. That causes his body to rotate clockwise a few degrees (as seen from the front) so that his somersaulting axis



STRAIGHTENING OUT OF A TUCK will cause the angular velocity (*black arrow*) of a diver to decrease fivefold because his moment of inertia is five times larger in the straight position than in the tucked one. The angular velocity and moment of inertia can vary inversely as long as their product, the angular momentum (*colored arrow*), remains constant.



ANGULAR-MOMENTUM VECTOR (*colored arrow*) of a diver executing a twisting somersault is the vector sum of the somersaulting angular momentum (*long broken arrow*) and the twisting angular momentum (*short broken arrow*). Because the moments of inertia are not the same about the somersaulting and twisting axes angular-momentum vector need not be parallel to angular-velocity vector.

is no longer parallel to his total angular-momentum vector. In other words, his somersaulting angular momentum is in a direction different from that of his initial angular momentum. As a result the diver's body starts to twist, creating exactly enough twisting angular momentum so that the vector sum of his twisting angular momentum and his somersaulting angular momentum is equal to his initial angular momentum.

Any movement of the body, not just the arms, will bring on twisting if it causes the diver's somersaulting axis to move away from the direction of the total angular-momentum vector. To stop the twisting the diver must move his arms or some other part of his body so that the somersaulting axis is once again parallel to the total angular-momentum vector. Such twists are called angular-momentum twists because they can be executed only if the diver has a nonzero angular momentum.

This last point has been a source of considerable confusion. To initiate continuous twisting in midair the diver need only have some initial angular momentum in any direction; he need not start twisting while he is still in contact with the board. Because some investigators did not realize that the angular-momentum and the angular-velocity vectors can be nonparallel they maintained erroneously that it is impossible for a diver to twist unless he starts to do so on the board. Another incorrect explanation was proposed in 1969 by George Eaves of the University of Leeds in his comprehensive book on the physics of diving. Eaves stated that a diver can initiate twisting in midair but can maintain that twisting motion only if he moves his legs continuously with respect to his torso. High-speed films of divers as well as the theoretical considerations I have discussed so far establish that divers do not have to move their legs to keep twisting and that they can start twisting long after they have left the board. In the 1979 U.S. Outdoor Diving Championships nine divers executed dives in which they somersaulted two and a half times and twisted once, initiating the twist only after completing one and a half somersaults.

Much of the confusion about the physics of diving stems from the fact that the twisting somersault is a relatively new maneuver. The forward one-and-a-half somersault with one twist was allowed in competition for the first time in 1934. Investigations of the mechanics of the twisting somersault were scarcely undertaken until the 1950's, when dives with multiple twists became common. Erroneous old hypotheses about the mechanics of twisting have survived in the diving literature of today.

Another source of misunderstanding about the physics of diving is the fact that although twisting somersaults are often initiated in midair, they are sometimes begun when the diver is still in contact with the springboard. A twist resulting entirely from torques applied to the diver by the board is called a torque twist. In backward twisting somersaults the diver is particularly likely to begin his twisting on the board because his "throw" to initiate twisting in midair is less efficient in the backward somersaulting position than in the forward position.

The rate of twisting depends on the angle θ between the somersaulting axis and the angular-momentum vector during the twist. In the backward somersault the diver's body is nearly straight. Throwing his arms to initiate a twist makes the angle θ about 11 degrees, which causes his body to twist at a rate of about three twists per somersault. In the forward somersault the diver's body is not straight but piked, or bent at the waist. When he throws his arms, the angle θ will be larger than 11 degrees because his moment of inertia in the piked position is smaller than that in the straight position. For an angle θ of 20 degrees the diver will twist at a rate of about five and a half twists per somersault when he comes out of the piked position. In the backward somersault he can twist at a comparable rate if he gets some torque from the board with which to start the twisting motion.

At the beginning of this discussion I posed the question of how with zero angular momentum a cat or a diver can twist in midair. The mechanisms I have outlined so far apply only to bodies with nonzero angular momentum, which is constant but can flow back and forth between different kinds of rotational motion (such as somersaulting and twisting) in the course of a single maneuver. Even with zero angular momentum a cat or a man can accomplish a certain amount of twisting and somersaulting motion because a body need not be motionless to have zero angular momentum.

For example, a man could have zero angular momentum if his arms and upper torso twisted to the right as his legs and lower body twisted to the left. To conserve angular momentum the portion of his body with the smallest moment of inertia would need to twist faster, since angular momentum is equal not to the twisting velocity but to the twisting velocity times the moment of inertia. Since the body of a man is not rigid, he can twist by judiciously varying the relative moments of inertia of his upper body and lower body. Unlike the angular-momentum twists of most twisting somersaults, zero-angular-momentum twists persist only as long as the upper body is in motion in relation to the lower body. If the diver holds his body com-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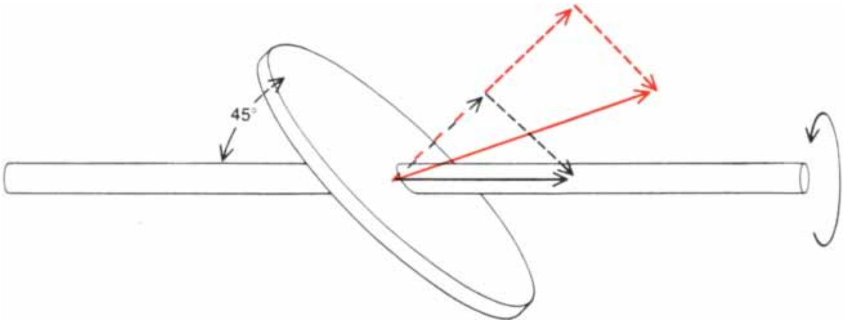
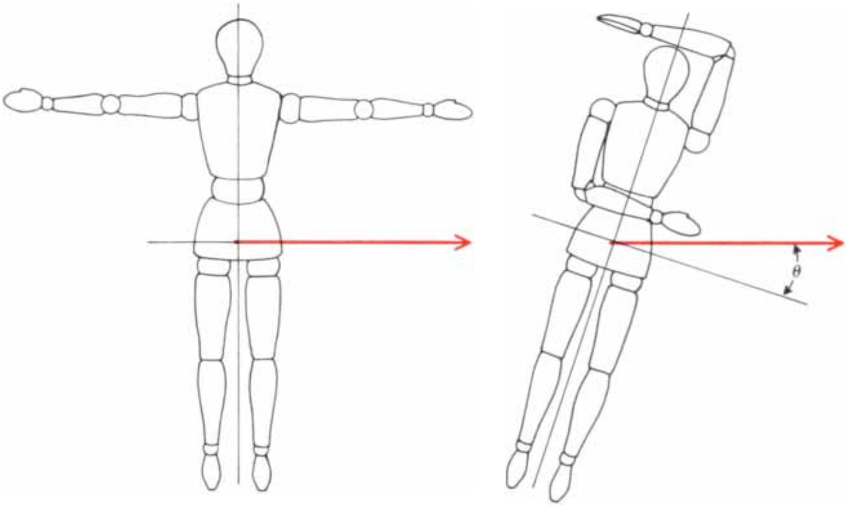
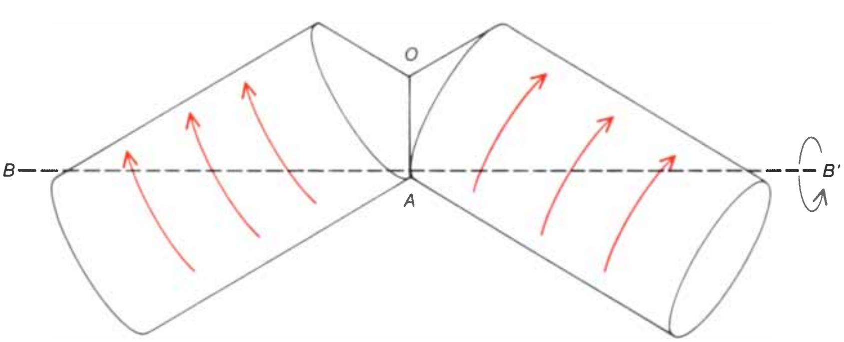


DISK ON A ROTATING SHAFT AT AN ANGLE shows that the angular-velocity vector (*solid black*) and the angular-momentum vector (*solid color*) need not be parallel. The angular-velocity vector can be broken down into a component along the symmetry axis of the disk (*broken black*) and a component parallel to the face of the disk (*broken black*). Because the moment of inertia of the disk about its symmetry axis is twice the moment of inertia about an axis parallel to the disk's face, the magnitude of the component of the angular momentum about the symmetry axis (*broken color*) is twice the magnitude of the component parallel to the disk's face (*broken color*). As the shaft and the disk rotate, the total angular-momentum vector (*solid color*) sweeps out a cone. That the vector is changing direction continuously means that the disk is always experiencing a torque, which is provided by the bearings of the rotating shaft.



IN ANGULAR-MOMENTUM TWISTS, in which the diver leaves the springboard with a nonzero angular momentum, the rate of twisting (ω_T) equals the rate of somersaulting (ω_S) times the ratio of the somersaulting moment of inertia (I_S) to the twisting moment of inertia (I_T) times the sine of the angle θ between the somersaulting axis (*black line*) and the angular-momentum vector (*red arrow*). In other words, ω_T equals $\omega_S(I_S/I_T)\sin\theta$. This means that to maximize the twisting rate the diver must "throw" his arms and head to maximize θ.



"CAT TWISTS," in which a cat or a man with zero angular momentum flips over in free fall, can be accomplished in principle even if the relative moments of inertia of the upper body and the lower body do not vary in the course of the flip. This kind of twist is best understood if the body is viewed as consisting of two rigid cylinders with cone-shaped ends. The cones are attached to each other so that the cylinders can roll without slipping along their line of contact (*OA*). Each cylinder has angular momentum because it is rotating about its own axis. To conserve total nonzero angular momentum the entire body must rotate in the opposite direction about axis *BB′*. The arrows represent not the angular velocity but the direction of rotation.

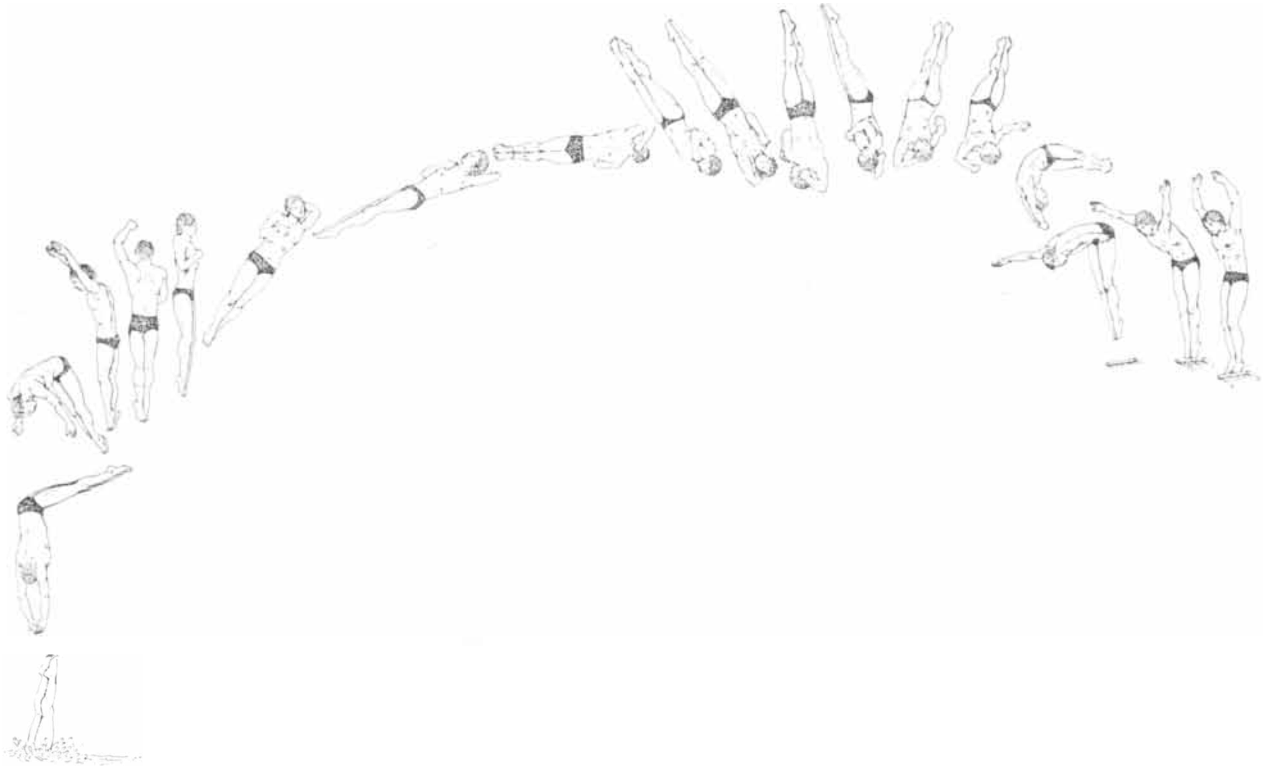
pletely rigid, the twisting motion immediately stops.

In principle it is also possible for a man or a cat to execute zero-angular-momentum twists ("cat twists") without varying the relative moments of inertia of the upper body and the lower body. This kind of twist is best understood if the body is viewed as consisting of two rigid cylinders attached to each other at the ends [*see bottom illustration at left*]. If the body is not straight but bent so that the two cylinders form an angle of, say, 90 degrees, then twisting is possible. If the upper cylinder twists to the right about its axis, the lower cylinder must swing to the left to conserve the zero angular momentum. Similarly, if the lower cylinder twists to the right, the upper cylinder must swing to the left. When both cylinders twist to the right about their respective axes, the entire body must swing to the left to conserve the zero angular momentum. If the dimensions of the cylinders and the angle between the cylinder axes are correctly chosen, the body will do a half twist to the left as its upper and lower parts twist once to the right. Again the twisting stops if the body is held rigid.

It is an open question whether in practice cats and men need to vary the relative moments of their body to execute zero-angular-momentum twists. Thomas R. Kane and M. P. Scher of Stanford University have studied photographs of a twisting cat and have concluded that the relative moments indeed remain the same. Donald McDonald of St. Bartholomew's Hospital in London was unable to reach a conclusion in his studies of cats and divers. Most investigators, including me, think that in practice cats and men usually do vary the relative moments of their upper and lower bodies by adjusting the position of their arms and legs.

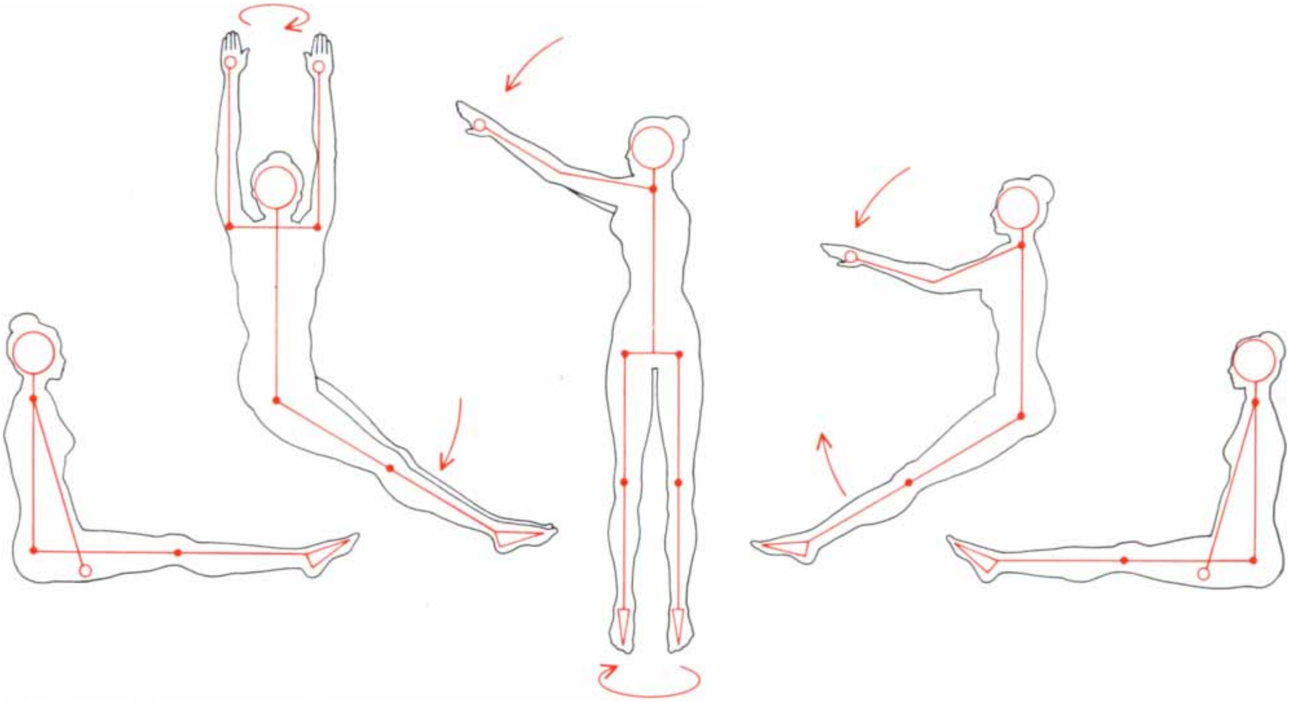
A man with zero angular momentum can not only execute "cat twists" to rotate about his twisting axis but also execute rotations about his somersaulting axis. If he moves his legs in a way that gives his lower body angular momentum, his upper body must also move in order to conserve his total zero angular momentum. As in a cat twist, he can perform a series of motions ("tuck drops") with his arms and legs that will reorient his body about his somersaulting axis, although the somersaulting motion will stop if he holds his body rigid.

Most work on man's ability to control his orientation in midair has centered not on springboard divers or gymnasts but on astronauts. A man working in space in a weightless environment must be able to control his body orientation, but can he start in a motionless position and with a few simple movements reorient himself in any direction



A FORWARD ONE-AND-A-HALF SOMERSAULT with three twists is a maneuver in which the diver leaves the springboard with nonzero angular momentum. Immediately after takeoff the diver is somersaulting without twisting, so that his angular-velocity and angular-momentum vectors are parallel. To initiate twisting he moves his arms and head until his somersaulting axis is no longer parallel to his angular-momentum vector. His body must twist in order to conserve angular momentum. Near the end of the dive the athlete moves his arms so that his somersaulting axis is once again parallel to the angular-momentum vector. That immediately stops the twisting motion. This illustration is based on a motion picture the author made at the 1979 U.S. Outdoor Diving Championships, held in Decatur, Ala.

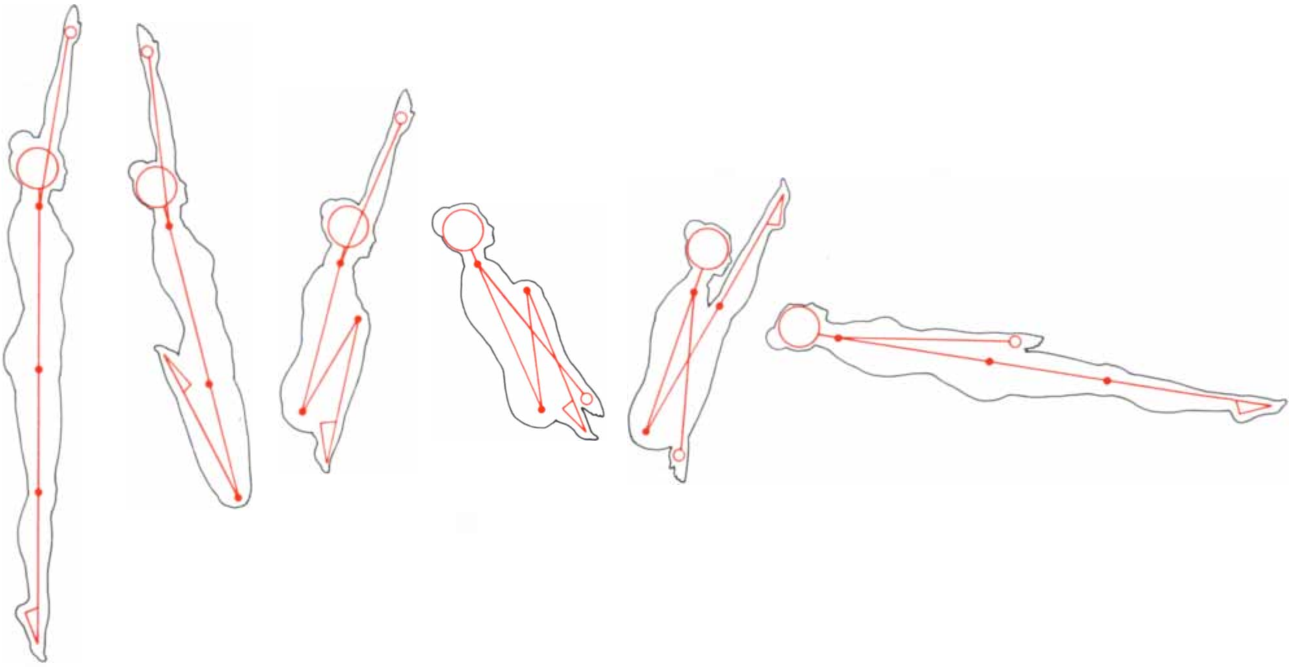
A FORWARD TWO-AND-A-HALF SOMERSAULT with two twists demonstrates unequivocally that divers can initiate continuous twisting in midair. In this maneuver the diver does more than one full somersault before he starts to twist. To maintain the twisting the diver does not have to move his legs with respect to his torso. Illustration is based on the film of the 1979 U.S. Outdoor Diving Championships.



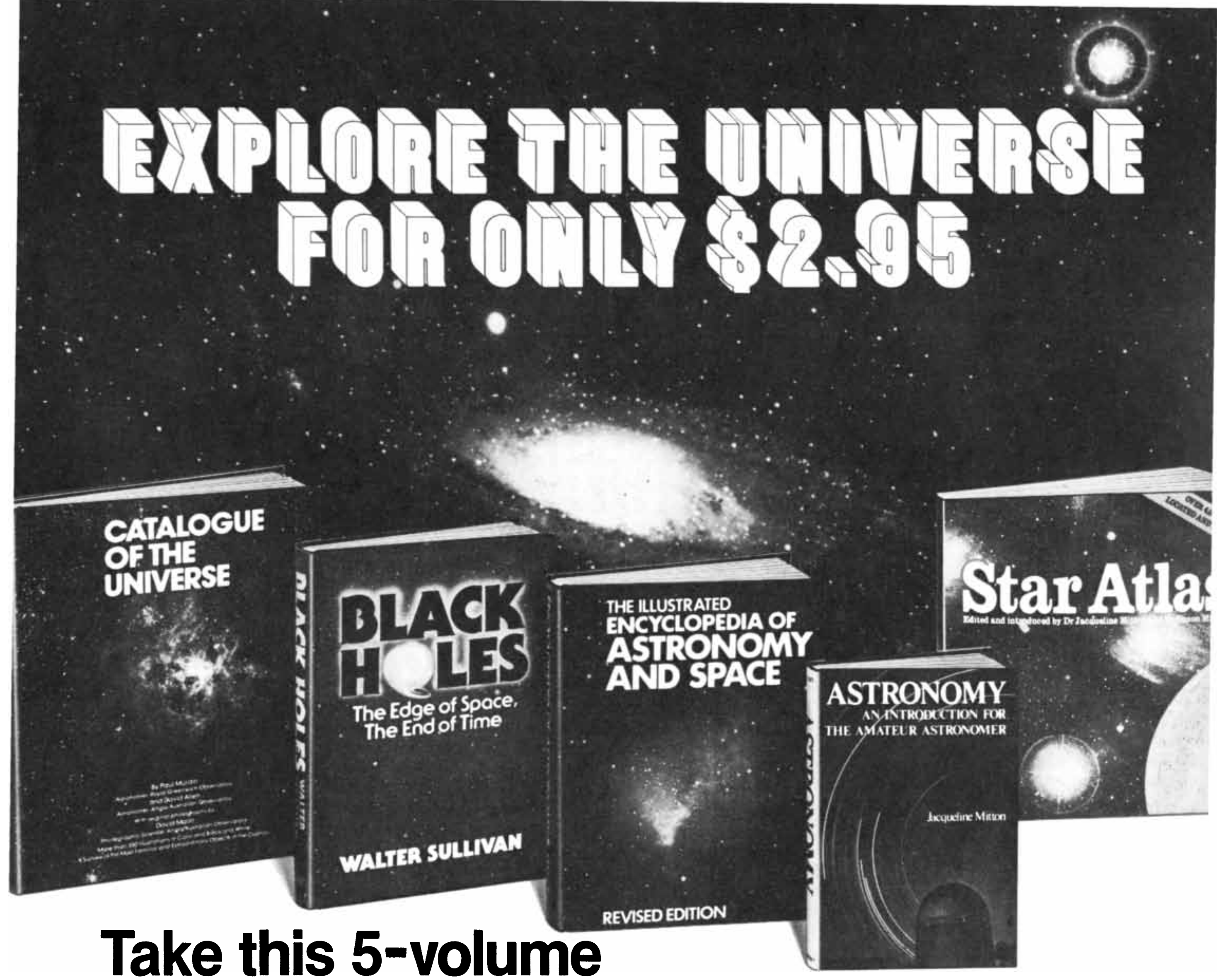
"SWIVEL HIPS" is a simple twisting maneuver executed by trampoliners that relies on zero-angular-momentum cat twists. By judiciously varying the relative moments of inertia of her upper body and lower body the trampoliner is able to twist half a revolution.

he wants? He can, and the underlying physics is the same for an astronaut as it is for a diver, since both men are moving in the absence of torques. From my discussion of diving it should be clear that an astronaut could reorient himself in any direction he chose by doing cat twists to rotate about his twisting axis and tuck drops to rotate about his somersaulting axis.

The work of Kane and Scher also demonstrates that an astronaut could easily control his motion, although the simple movements they recommend are quite different from the ones divers and gymnasts would execute in order to achieve the same reorientations. For example, they suggest that an astronaut could twist 70 degrees to the left by first moving his right leg forward and his left leg backward, then sweeping his right leg in a circle to the right and the rear and sweeping his left leg in a circle to the left and the front and finally bringing his legs back together. I believe once men actually start working regularly in space they will learn to achieve large reorientations of their bodies by making the same motions divers and gymnasts make.



"TUCK DROP" is a maneuver in which an athlete with zero angular momentum does somersaulting rotations. By repeated tuck drops he can rotate as much as he wants. An astronaut in space could easily reorient himself in any direction with swivel hips and tuck drops.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Horned Beetles

The formidable appendages of these insects look as though they were meant for stabbing or pinching an opponent. Actually most of the horns are used to pry up or lift a rival of the same species

by William G. Eberhard

On the visit of H.M.S. *Beagle* to Chile one of the most puzzling animals Charles Darwin encountered was the brightly colored stag beetle *Chiasognathus grandtii.* The males of this species have greatly elongated mandibles (vaguely resembling a stag's antlers) whose pincerlike configuration suggests that they function as weapons. When Darwin held one of these beetles in his hand, however, he found that its horns could not pinch his skin even hard enough to cause pain. If the horns did not serve as weapons for pinching adversaries, what was their function? The question presents an evolutionary puzzle that has baffled biologists for more than a century.

Horns are found in a wide variety of shapes and sizes on many different species of beetles. How did the horned beetles evolve? To put it another way, what selective advantage do horns confer? Darwin eventually decided that the horns serve to impress females, which presumably chose as mates those males with larger or more elaborate ones. More recently some biologists have argued that the structures do function as weapons, enhancing the reproductive capability of the beetles possessing them through their role in intraspecific fighting. And others have suggested that the horns serve as digging tools, as a defense against predators or simply as a deposit of excess body weight.

Still another argument is put forward by Gilbert J. Arrow in *Horned Beetles: A Study of the Fantastic in Nature.* In this book, the most comprehensive work on the subject to date, Arrow maintains that beetle horns are functionless, their evolution being somehow linked to that of increased body size. This hypothesis, which implies that the evolution of horns in beetles has run wild, free of the constraints of natural selection, is unacceptable to most evolutionary biologists, but until quite recently there was no way to refute it because horned beetles had almost never been studied in nature. It is only in the past decade that such "armchair" speculations on the function of beetle horns have begun to be replaced by conclusions drawn from accumulations of careful observations of horned beetles in their natural (or close to natural) environments.

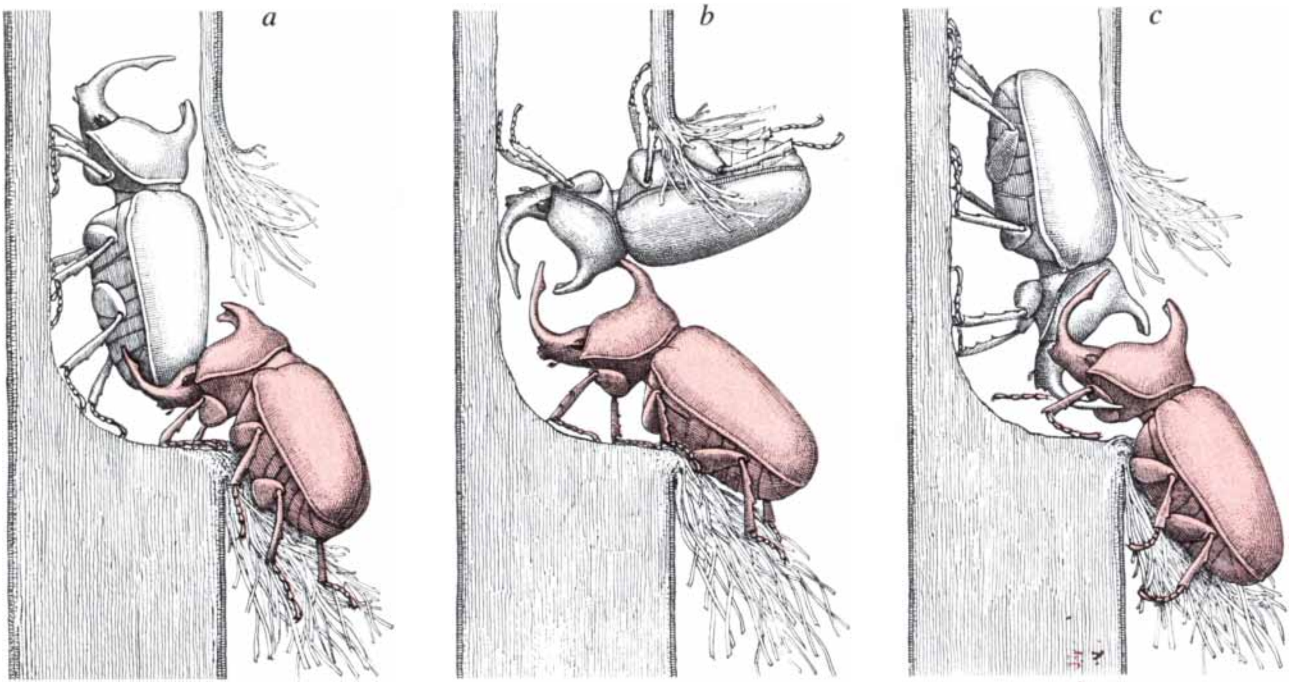
These recent studies have explored the functional morphology of beetle horns, attempting to assign functions to them in order to explain why a particular shape evolved in a particular species. Such assignments are made on the basis of a number of different criteria. Observers search for repeated and relatively stereotyped applications of horns in situations where their effective use has biologically significant benefits and also check to see whether the design of the horns seems to be compatible with the mechanical demands of the task to which they are applied. It is through efforts such as these that a new understanding of the evolution and behavior of horned beetles has begun to emerge.

It now appears that the early hypothesis that beetle horns generally function as weapons is correct. Indeed, in every species that has been carefully studied (a total of 17 so far) it has been established that far from being useless, beetle horns serve as effective weapons in contests between members of the same species over critical resources. The ways the horns are wielded in such contests, however, has turned out to be quite different from what was expected. For example, it has now been determined that the male *Chiasognathus grandtii* beetle usually employs the mandibles Darwin wondered about not as pincers for injuring rivals but as forceps for picking them up and dropping them from a tree to the ground below. In what follows I shall review some recent findings on the function and evolution of horns in some other species of horned beetles; I shall also discuss some objections that have been raised to the thesis that the horns of horned beetles function as weapons.

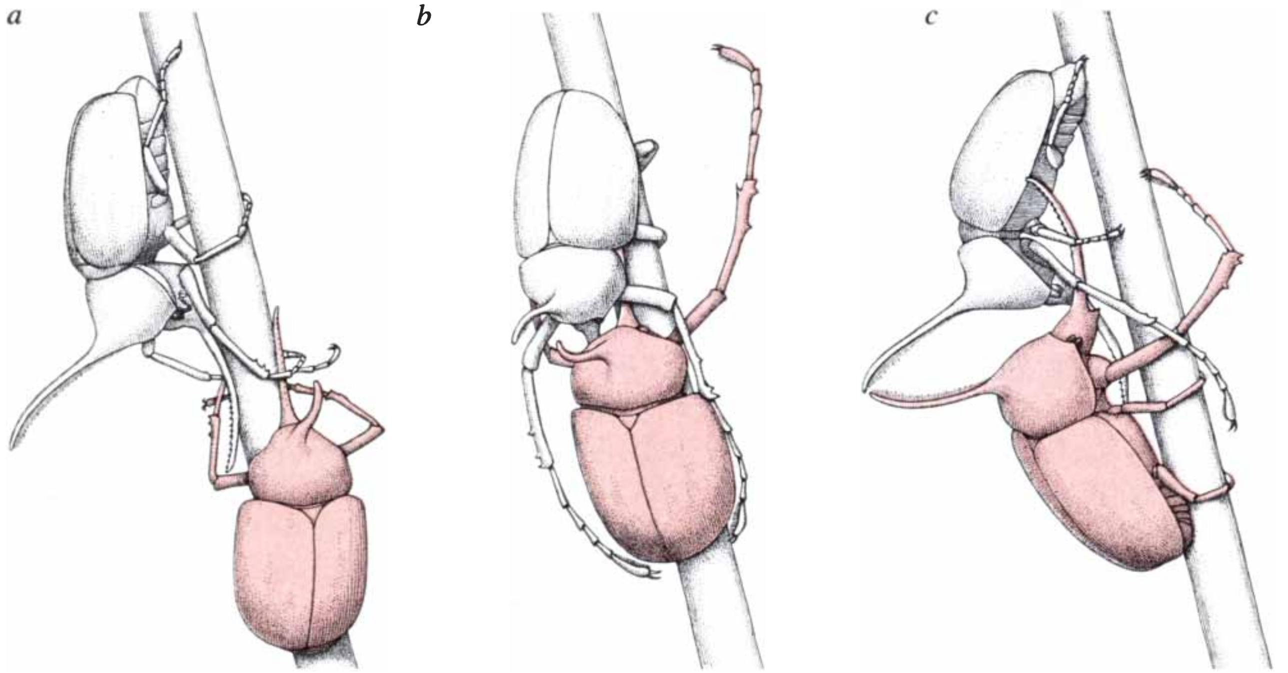
The lack of observations of living horned beetles is not the only reason biologists have had so much trouble determining the function of the horns. Consider the vast array of different types of structures that can be called horns. To begin with, the various parts of a beetle that are extended into horns include the head, the mandibles, the front legs, the top and front of the prothorax (the segment of the thorax immediately behind the head) and even the bottom of the thorax and the elytra (the wing covers that generally shield most of the upper surface of the abdomen). Moreover, the variety of the forms these projections take is staggering, ranging from single head horns and grotesquely elongated and spined front legs to a variety of polelike extensions pointing forward or backward and a multitude of pincerlike configurations formed either by a pair of elongated mandibles or by a backward-curving head horn working against one or more forward-curving thoracic horns. In some species these pincerlike horns mesh precisely; in others they do not.

This wealth of forms always made it seem unlikely that any single function for the horns could be discovered, particularly in view of the fact that they are found in many unrelated beetle families and therefore seem to have evolved a number of times independently. The recent observations of horned beetles indicate that the ways in which the horns are employed as weapons do in fact vary greatly from species to species, although the mechanical functions of the horns can be divided into two broad categories. The horns appear to serve either to pry an opponent away from a substrate so that it can more easily be pushed away from a contested resource or to lift an opponent off the substrate and drop it to the ground. (The second form of behavior probably evolved from the first.)

An example of a beetle that pries up opponents is *Golofa porteri,* a species of large, striking-looking scarab (belonging to the family Scarabaeidae) in which the male is endowed with a pair of monstrously elongated front legs, a long, thin horn rising from the prothorax and a sturdier horn with serrated edges curving forward from the head. High in the Andes of Colombia these beetles can be found battling for possession of single shoots of the bam-



PINCERLIKE CONFIGURATION OF HORNS on males of the horned beetle species *Podischnus agenor* is formed by a long horn curving up from the head and a shorter, sturdier horn projecting forward from the prothorax (the segment of the thorax immediately behind the head). In battles for possession of the blind burrows that these beetles dig in stalks of sugarcane the horns are wielded in several stereotyped ways. When one male invades the burrow of another, the resident may resist the attack by bracing itself against the walls at the entrance of the burrow. In response the invader (*color*) tries to insert its head horn under the resident and use it to pry the resident out (*a*). When the resident tries to turn and confront the invader head to head at the burrow entrance, the invader relies on its prothoracic horn to "punish" (and perhaps intimidate) the resident by repeatedly pushing it back into the burrow (*b*). As is shown here, the crescent-shaped tip of the invader's prothoracic horn fits snugly against the resident's prothorax and elytra (the horny wing covers that shield the upper surface of a beetle's abdomen). In struggles of this kind the invader eventually allows the resident to turn around in the burrow entrance, and in the ensuing head-to-head confrontation each beetle tries to wield its horns as pincers to clamp the other (*c*). In the contest shown here the resident has succeeded in the maneuver and is about to lift the invader off the sugarcane substrate and drop it to the ground.



LONG, GRACEFUL HEAD HORN and enormously elongated front legs of the male scarab beetle *Golofa porteri* serve as weapons in contests over single shoots of the bamboolike plants on which this species feeds in the Andes of Colombia. (Projections of almost any part of a beetle's body, including the legs and mandibles, can be considered as horns.) When two males of the species approach each other on a shoot or, as is shown here, a shootlike support (*a*), each one inserts its head horn under the body of the other, holds on to the support with its middle and hind legs and wraps its long front legs around the body of the other (*b*). The attacker (*color*) rakes its front legs sharply across its opponent's middle and hind legs and then an instant later jerks its head up to throw the opponent off the support (*c*). In this case the attacker was unsuccessful, since attacked beetle maintained a grip on support with its right hind leg (not visible) and was not thrown clear.

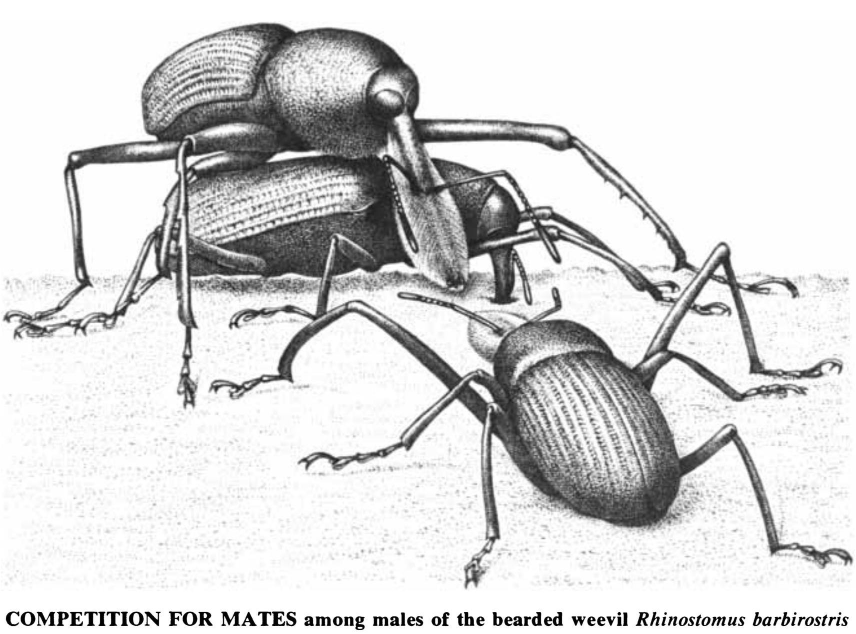
boolike plants on which they feed, and fights staged on similar supports in my laboratory at the Universidad del Valle in Colombia revealed that it is in these conflicts that the horns come into play.

When two males confront each other, each holds on to the support with its middle and hind legs, wraps its long front legs around the other male's body and then tilts its prothorax and lowers its head so that the head horn is inserted under the other male's body. To begin an attack one of the intertwined beetles rakes its front legs sharply across its opponent's middle and hind legs. This action apparently serves to tear the opponent's legs from the support, and an instant later the attacker jerks its head up to throw the opponent off the support. The function of the prothoracic horn in this species has not yet been determined.

A similar mode of behavior has been observed among males of the species *Rhinostomus barbirostris,* or bearded weevil. In this species the males have an elongated beak and front legs, and the beak is also distinguished by a thick covering of golden hairs. Male bearded weevils compete for females on the trunks of newly fallen palm trees, where the females, with their shorter beak, drill small holes in which to place their eggs. After a female has deposited an egg in a hole in the tree trunk she caps the hole with a quick-hardening fluid. The larva that hatches from the egg feeds as it bores through the trunk, finally pupating in a cell close to the surface of the tree.

Adult males patrol tree trunks where the females are depositing eggs, and when a male finds a female, he mates with her as she drills and then remains nearby to guard her against the advances of other males. If a rival male approaches, the defending male lowers his beak. When the two are sufficiently close, the defender snaps his head upward and simultaneously raises the front of his body on his two long front legs, attempting to deliver a hard blow that will knock his rival off the tree trunk. The top of a male bearded weevil's beak is covered with small knobs and spikes that may serve to reduce the possibility that the beak will slip when it hits the underside of an opponent's body, thereby wasting the force of the blow. (The hairs on the beak of the male seem to function not in intraspecific fighting but in maintaining contact between the male and the female; as the female drills and deposits her eggs the male strokes her assiduously with his hairy beak.)

Darwin and others objected to the hypothesis that horns function as weapons, reasoning that if beetle horns did function as weapons in intraspecific fighting, then it should be possible to find punctures or other marks on the body of horned species and scratches on the horns. Distinguished naturalists such as Henry Walter Bates, they pointed out, were unable to find such marks in most species that were examined. This situation is partly explained by the two examples I have discussed. Applying horns to pry an opponent off a substrate would not be likely to leave distinctive marks, and the same is true of the other principal application of horns: bodily lifting an opponent off a substrate. A good example of a beetle that lifts its opponents is the tropical scarab *Podischnus agenor.*

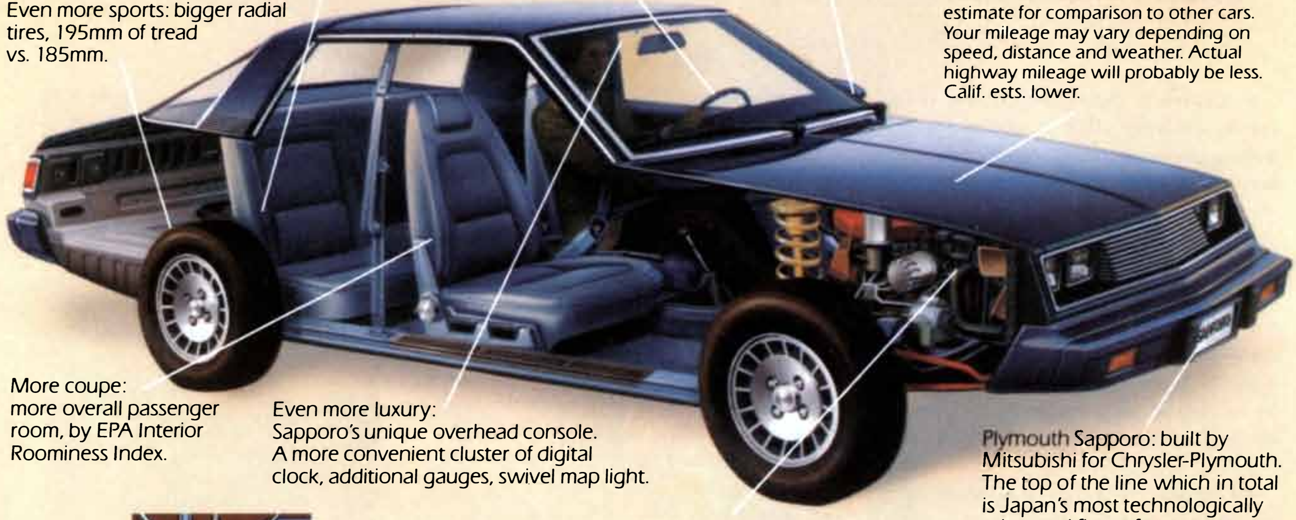


COMPETITION FOR MATES among males of the bearded weevil *Rhinostomus barbirostris* takes place on the trunk of a newly fallen palm tree, where the females drill holes in which to lay their eggs. A male mates with a female as she is drilling the hole and then remains nearby, in some cases straddling her, to defend her against the advances of other males. As is shown in this illustration, when a rival male approaches, the defending male lowers his head, so that with a flip of his elongated beak he will be able to throw the rival off the tree trunk.

The behavior of *P. agenor,* which inhabits burrows in the stalk of the sugarcane plant, has probably been studied more intensively than that of any other species of horned beetle. A relatively large species (with a body up to four centimeters long), this beetle has a pincerlike configuration of horns that is found in many horned beetles: a rather long head horn that curves upward and backward and a short prothoracic horn that projects forward. I shall discuss the behavior of the species in some detail, because it seems likely that the ways this beetle uses its horns will prove to be typical of many other species that live in burrows.

The life cycle of *P. agenor* begins in the rainy season (the period from September to December in Colombia, where I studied the species), when the female beetle lays her eggs individually in the soil. The beetles that hatch from the eggs spend their larval stage underground, eating soil and digesting its humus content; they also pupate there, emerging as adults at the beginning of the next rainy season. The males of the species tend to leave the soil earlier than the females, and locating a field of sugarcane they dig ragged, blind burrows up into the sugarcane stalks. To cut through the tough cane fibers a *P. agenor* beetle relies not on its horns but on its mandibles and a small pair of protuberances near its mouth, and as it digs it feeds, squeezing sweet juice from the plant tissue. Once a burrow is well under way the *P. agenor* male turns to the task of finding a mate.

The beetle positions itself in the entrance of its burrow at night and emits a pheromone, or message-bearing chemical, whose pungent odor apparently serves to attract females. (The odor is so pungent that it can be smelled by a human being at a distance of 15 meters, thereby attracting coleopterists as well.) A female that flies to the burrow in response to the pheromone is allowed by the male to enter, and in many cases the two mate near the entrance before the female moves to the blind end of the burrow and begins to feed. At this point the male stops emitting pheromone but generally remains close to the entrance of the burrow. At any time during the process another male *P. agenor* beetle may be attracted to the burrow and may enter to challenge the resident for possession of it. It is in these confrontations over burrows that the beetles' horns are



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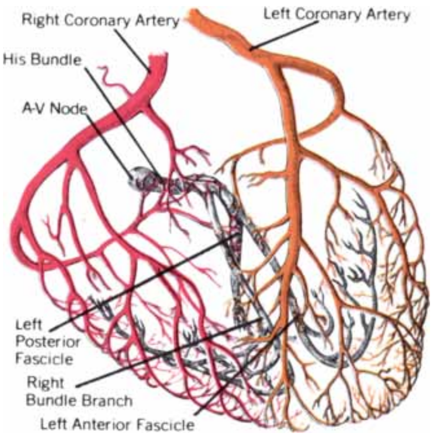

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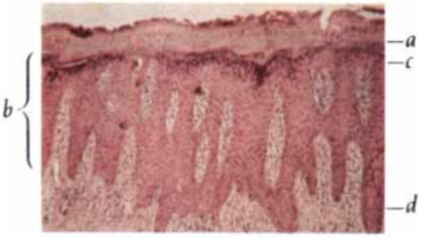

Histopathologic changes in psoriasis.

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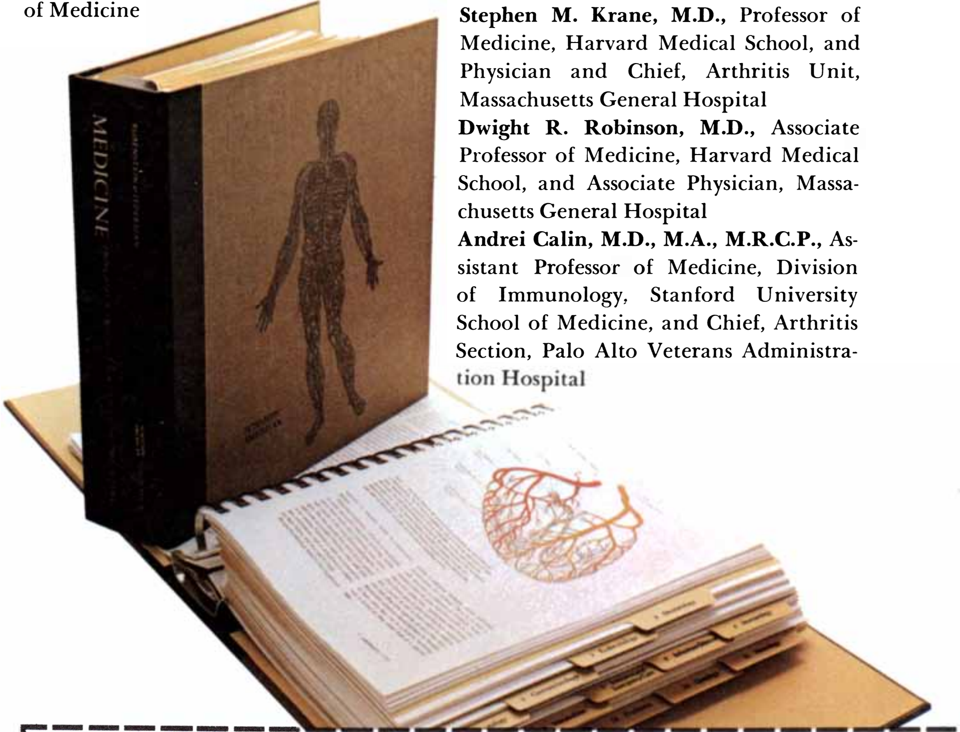

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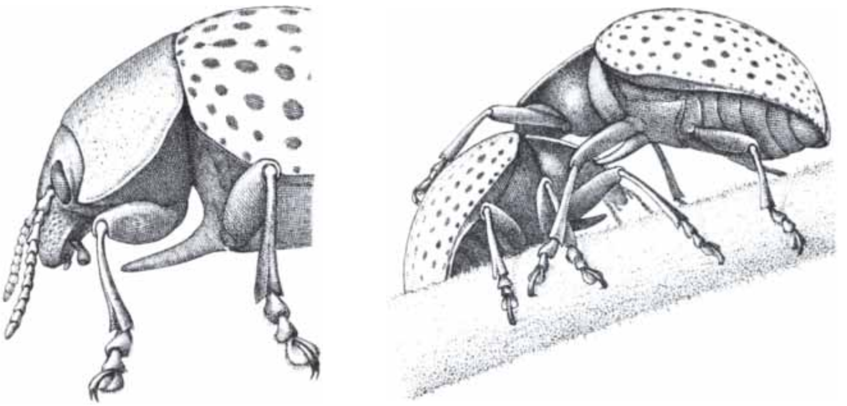
effectively employed in a number of relatively stereotyped ways.

A male that invades the burrow of another male begins by trying to push the resident farther up into it. The resident, with its rear end to the invader, may resist the attack by bracing itself against the walls of the tunnel to block the way with its body [*see top illustration on page 167*]. To displace a resident behaving in this way the invader tries to insert its head horn under the resident's body and pry the resident out. The resident may also move or be pushed into the interior of the burrow, where a sometimes protracted pushing match ensues, but eventually the two beetles move to the entrance of the burrow. As the invader backs out of the tunnel onto the surface of the sugarcane stalk below, the resident attempts to turn in the mouth of the burrow to confront the invader head to head. At this point the invader uses its prothoracic horn as a ram to "punish" (and perhaps intimidate) the resident by driving the resident repeatedly back into the tunnel. The crescent-shaped tip of the invader's horn fits snugly against the resident's elytra and prothorax.

The invader eventually allows the resident to complete its turn (otherwise the invader cannot gain sole possession of the blind burrow), and the two beetles finally confront each other head to head. In the last phase of the battle each beetle tries to use its horns as a clamp, inserting the head horn under the other beetle's body and the prothoracic horn over it. Usually each beetle succeeds in getting a clamp hold on the other and in the ensuing test of strength each attempts to lift the other off the sugarcane substrate and drop it onto the ground.

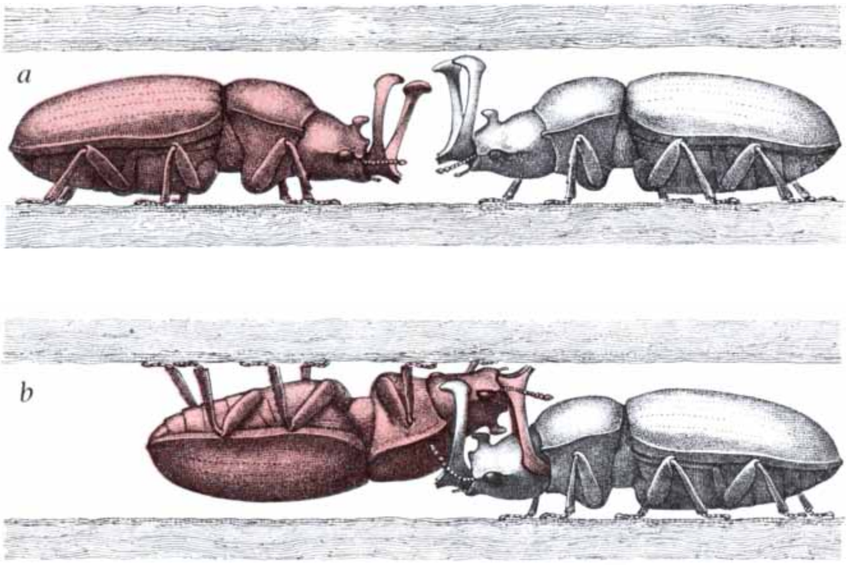


SMALL HORN projecting from the ventral surface of a beetle closely related to the species *Doryphora punctissima* (*left*) serves to pry opponents off a contested food plant. Beetles of this species engage in pushing matches for the possession of a leaf or a stem of the small vines on which they feed in eastern Colombia. The beetles defend themselves against such pushing attacks by lowering themselves to the surface of the leaf or stem, where their round, smooth body makes them difficult to dislodge. The defense can be overcome, however, if the attacking beetle hooks its curved horn under edge of other's body and pushes forward and upward (*right*).

There are many other types of behavior associated with horns that could be described here, but to conclude this list of examples I shall discuss two species that promised to be exceptions to the tendency for beetle horns to function as weapons. In the past one of the most convincing arguments against the thesis that beetle horns serve as weapons was the fact that certain species have horns that appear to be mechanically useless. In particular some horns are placed on the beetle's body in such a manner that there would seem to be no way for them to be brought to bear effectively on an opponent or a substrate. In the species that have been studied, however, all such horns have proved to be well positioned for use in combat.

For example, both males and females of a large speckled plant beetle closely related to the species *Doryphora punctissima* are endowed with a short horn curving forward from a most unlikely part of the body, the underside of the thorax, which gives the beetle the look of a simplified bottle opener. Careful observations showed that the horn is not involved in mating or feeding activities, but when pairs of males were placed together on the small vines on which they feed in eastern Colombia, contests ensued in which each beetle tried to push the other off the substrate. To defend itself against pushing attacks a beetle of this species lowers itself to the surface of the leaf, where its smooth, nearly hemispherical body makes dislodging it quite difficult.

It is in this situation that good use is made of the bizarre horn. The attacking beetle hooks its horn under the edge of the other beetle's body and by pushing forward and upward pries the other one away from the leaf like a bottle top. The presence of horns in the females of the species as well as the males may have to do with the relatively small size of the host plants. The vines where the females lay their clusters of eggs and where their larvae feed may sometimes be too small to accommodate more than a single



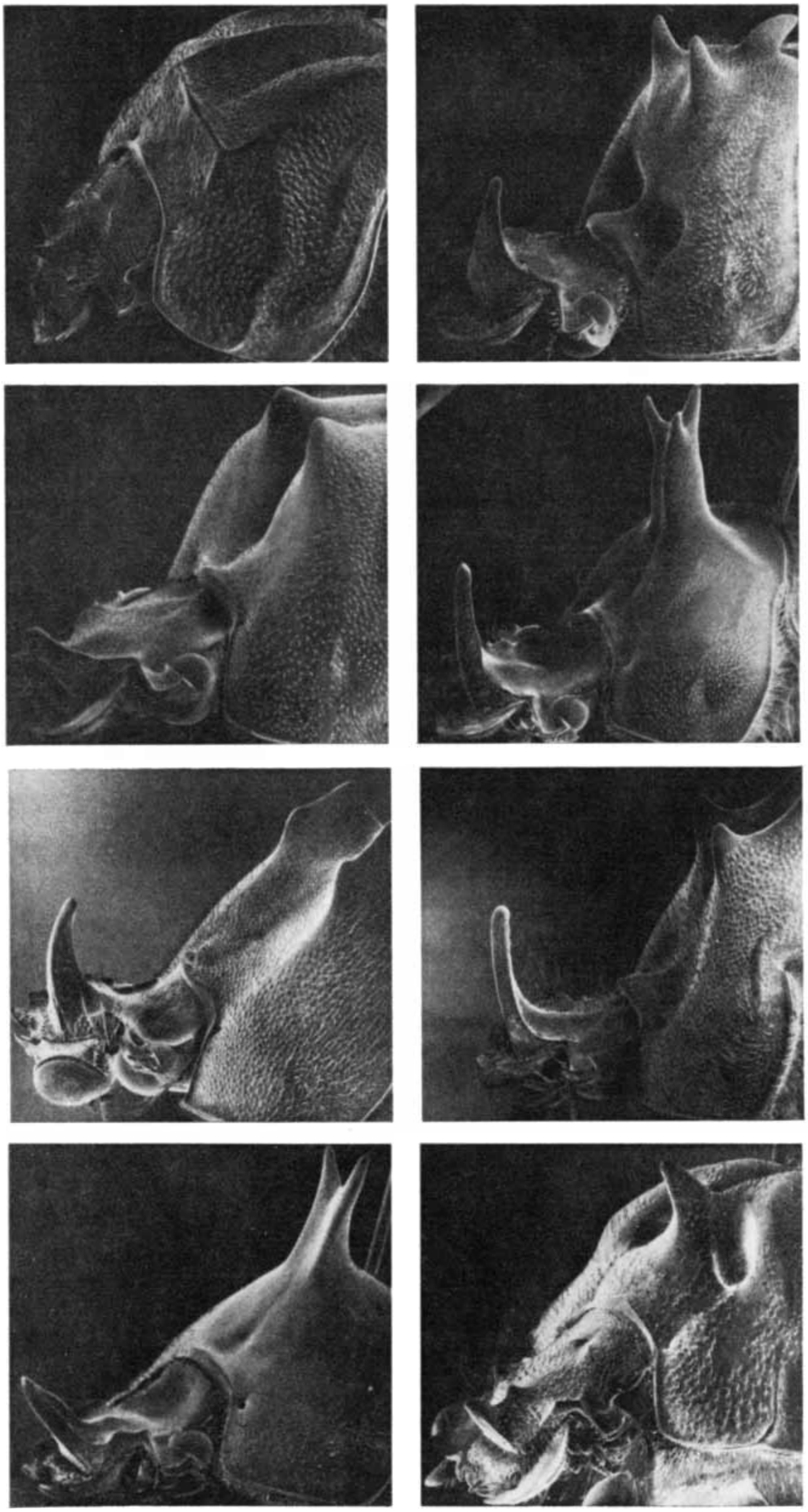
ANTLERLIKE HORNS of a darkling beetle closely related to the species *Molion muelleri* are elongated mandibles that can be opened and closed. Because the beetle inhabits narrow tunnels in fallen logs and can hardly move its head there appeared to be no way for it to bring its horns to bear on an opponent, and they were thought to be mechanically useless. When the beetles were studied in glass-sided tunnels, however, it was discovered that when two individuals meet head to head in a burrow (*a*), the more aggressive one (*color*) turns 180 degrees so that its horns are well positioned as pincers for clamping the other beetle behind the head (*b*). Even the small, pointed extensions at the tip of the horns seem to be functional: they have been observed to penetrate membrane between head and prothorax of an opponent, as is shown here.

brood. At present, however, there are not enough data to properly evaluate this hypothesis.

The small darkling beetles of a species closely related to *Molion muelleri* have even more improbable weapons, which they wield in an even more ingenious manner. Both the males and the females of the species are endowed with a small head horn that hooks forward and a pair of sturdy elongated mandibles that look somewhat like antlers, rising up and curving slightly out from the head to end in flattened tips that point forward and slightly inward. These structures can be opened and closed, but because the beetles live in narrow burrows in logs and cannot bend their head down there does not seem to be any way for them to bring their horns to bear on opponents. It was not until the beetles were studied in glass-sided tunnels that the utility of these strange structures became apparent.

When two darkling beetles meet head to head in a burrow tunnel, the more aggressive of the two rolls over 180 degrees, and in this position its "antlers" become efficient, well-positioned pincers for grasping its opponent behind the head. Even the flat tips of the horns appear to be functional; in two instances they were observed to penetrate the membrane between the head and the thorax of the attacked beetle and draw blood. Obviously when a beetle rolls over to bring its pincers into play, it exposes itself to the same kind of clamping attack from its opponent, and in nature pairs of the beetles have been found interlocked in this manner. The ecology of these beetles is not well understood, and it is not known what they fight over or why both the males and the females have horns.

It would therefore appear that horns function as weapons in intraspecific fighting and have evolved because winning such fights is selectively advantageous. It is necessary to be somewhat cautious in making sweeping generalizations about horned beetles, however, since certain questions about horns and their function remain unanswered. There are hundreds, perhaps thousands, of horned species whose behavior has yet to be studied. One puzzle they present is the bewildering spectrum of horn designs that are sometimes found within a single beetle genus [*see illustration at left*]. Why do species that presumably live in similar conditions develop such dissimilar horns? It is evident that much more work is needed before questions such as this one can be answered. On the other hand, there is a closely related problem that seems now to be at least partly solved: the paradox of the beetle species in which "minor," or small, males nearly devoid of horns coexist



HORN DESIGNS CAN VARY GREATLY even within a single genus. Each of the scanning electron micrographs in this array shows the horns of a male of a different species of the dung beetle genus *Athyreus*. Almost nothing is known about the natural history and behavior of these beetles (in part because all specimens have been captured near lights at night), and it is not known why species that presumably live under similar conditions have evolved such dissimilar horns. Micrographs were made by Henry F. Howden of Carleton University in Ottawa and Antonio Martínez of National Council of Scientific and Technical Research in Buenos Aires.

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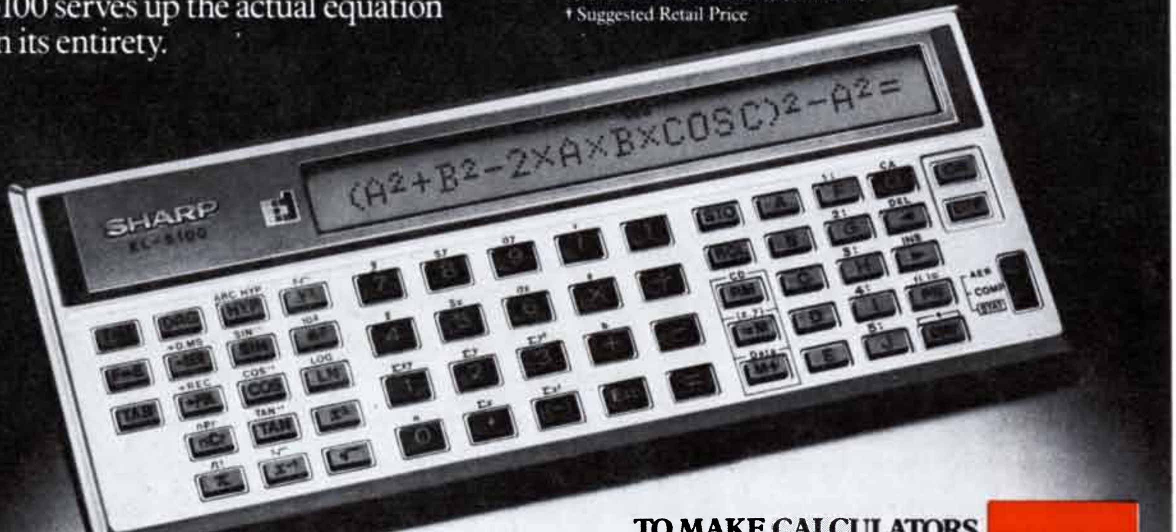

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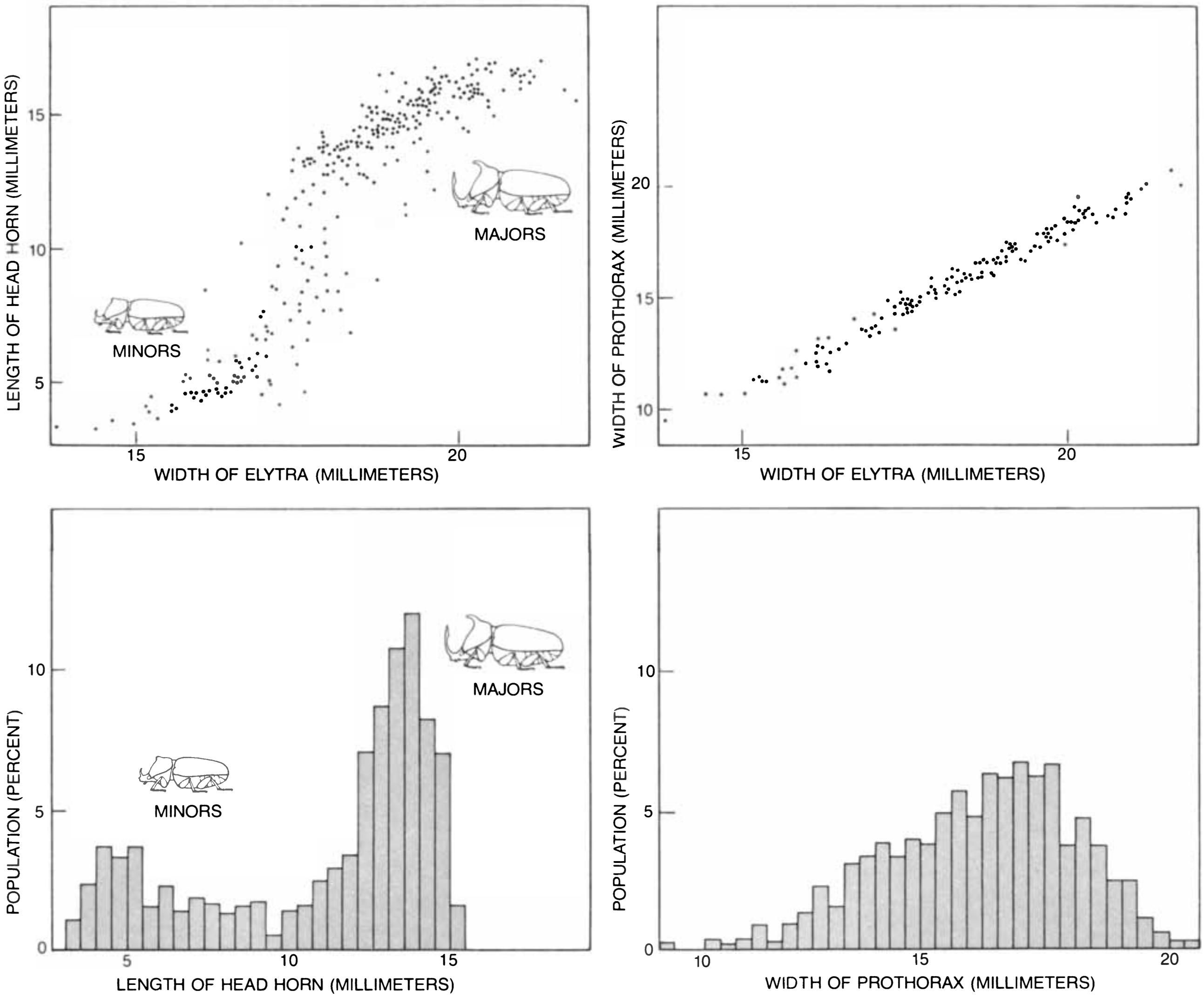
Sharp Electronics Corp., 10 Keystone Place, Paramus, N.J. 07652 with "major," or large, males endowed with elaborate horns.

Beetles do not grow after achieving adulthood, and so minor males remain small and hornless throughout their life. It is therefore difficult to understand how minors manage without horns. These unarmed beetles should lose fights and fail to reproduce, and the genes for hornlessness should be quickly eliminated from the population. The explanation of why unarmed males persist has been worked out for only two horned species, but it seems that similar reasoning will apply to other species with hornless forms. The simpler case is that of the bearded weevil *Rhinostomus barbirostris.*

Bearded weevils exhibit a continuous and remarkably wide range of sizes. For example, in one sample of 65 males the largest one was four times longer than the smallest and 20 times heavier. (Such differences in size are probably due to differences in the feeding conditions of the larvae.) The tiniest males have only a very short beak, but they compensate for their lack of fighting ability by adopting a completely nonaggressive mode of behavior. They avoid contests with other males and try to capitalize on their small size by sneaking past larger males to mate with the females those males are defending. Hence when a large male is distracted by, say, a fight with another male, a nearby small male will move quickly to the side of the female and begin to edge slowly back alongside her to position himself for mating. In some cases the larger male notices the smaller one and flips him away with his elongated beak, but in others the small male succeeds in mating with the female while the larger male maintains his guard, apparently unaware of the presence of the interloper.

The persistence of minor males in the sugarcane beetle species *Podischnus agenor* is a more complex matter, as can be seen by considering the graph at the upper left in the illustration below, in which the body size of *P. agenor* males



"MINOR," OR SMALL, MALES that have minimal horns coexist with "major," or large, males that have substantial horns in several horned species, including the sugarcane beetle *Podischnus agenor*. In *P. agenor* the minor and major males appear to represent two distinct morphologies rather than extremes of a continuous range of body sizes. As is shown at the upper left, when body size (measured as the width of the elytra at the widest point) is plotted against horn size (measured as the length of the head horn) for the males of a *P. agenor* population, the resulting graph has two distinct linear segments: one corresponding to minor, hornless individuals and the other to major, horned ones. For comparison the graph at the upper right shows how in the same beetles the width of the prothorax increases as a simple linear function of body size, a relation that is typical of the growth of many other body parts. The bar charts at the lower left and lower right respectively show the distribution of horn lengths and prothorax widths for the same group of beetles. The first chart displays two distinct groupings corresponding to minor and major forms, whereas the second is simply skewed toward larger sizes. The minor males in this species seem to display altered behavior that may compensate for their lack of fighting ability (*see illustration on page 178*).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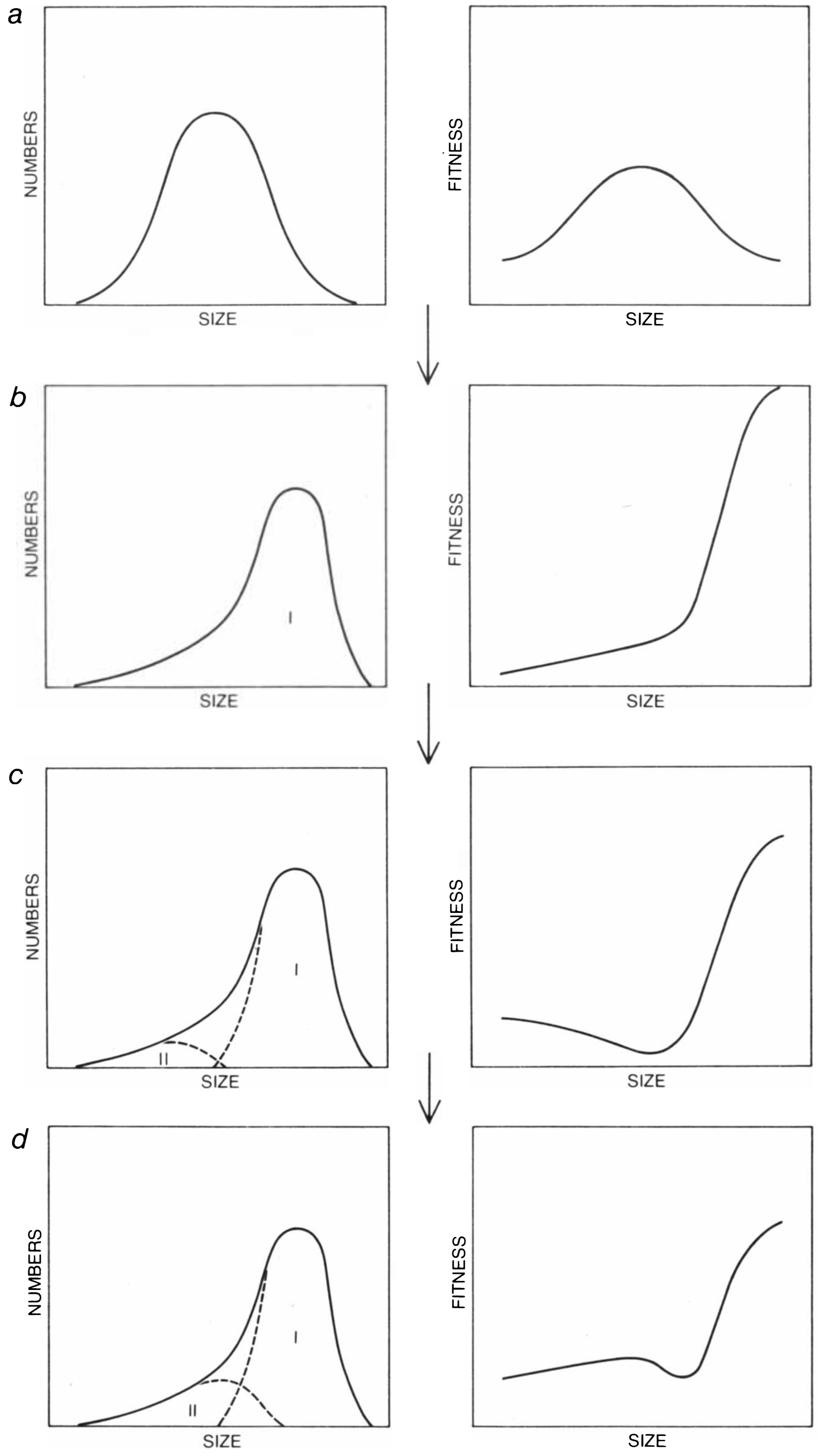
DATSUN ENGINE SAVES GAS

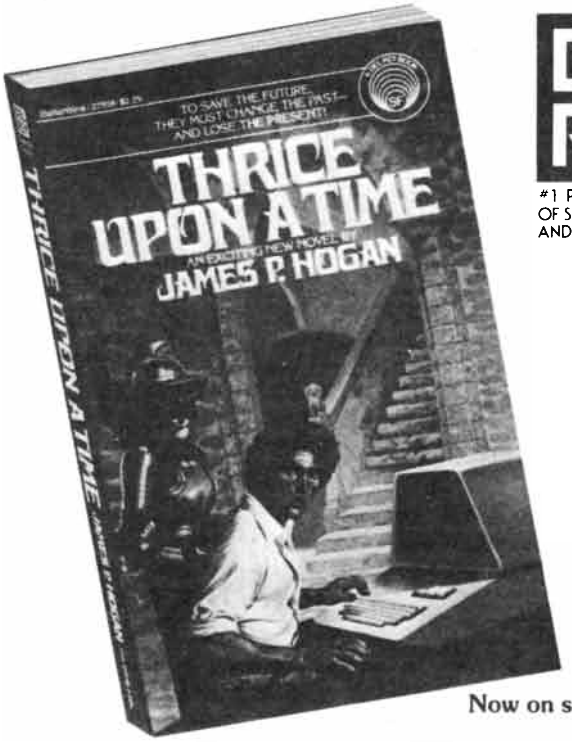


EVOLUTION OF HORNLESS MINOR MALES characterized by diminished fighting behavior could have occurred gradually within a horned species. Given a typical population of beetles (*a*) with a normal size distribution and with the highest fitness, or reproductive capacity, associated with intermediate sizes, selection for Strategy I (featuring both horns and an associated fighting behavior) could result in a generally large-sized population in which smaller males would be virtually excluded from reproduction (*b*). If environmental conditions (such as suboptimal nutrition for larvae) nonetheless persisted in causing production of smaller males, then for those males selection might favor alternative strategies such as Strategy II, characterized at first only by different fighting behavior but eventually by morphological adaptations such as hornlessness (*c*). If appropriate conditions persisted, minor caste with distinct morphology and fighting behavior would be established and intermediate forms would disappear (*d*).

(measured as the width of the elytra at the widest point) is plotted against their horn size (measured as the length of the head horn). The graph has two distinct linear segments corresponding to small and large body sizes with an irregular distribution of values in between, indicating that in this species the small male represents not simply one extreme of a continuous range of body sizes but a distinct morphology. In other words, there seem to be two basic body plans coded by two distinct sets of genes: a minor, or small, version with minimal horns and a major, or large, one with substantial horns. Further evidence suggests that each male is genetically capable of developing either morphology and that it is the nutrients supplied to the *P. agenor* larvae that determine which set of genes is expressed.

The sugarcane beetle minors differ from the small bearded weevils in that they display many of the behavior patterns of major males: excavating a burrow in sugarcane stalks, calling (with pheromone) females from the burrow entrance and trying (generally without success) to defend their burrow against other males. The minors compensate for their inferior fighting ability, however, by emerging from the soil (where they pass their larval and pupal stages) earlier in the season than most major males. Furthermore, the results of a two-year study in which *P. agenor* males were followed in the field (after identification numbers were scratched on their elytra) suggest that the minor males also disperse over a wider area than the major males and so the possibility of their coming in contact with (and being forced to compete with) major males is minimized in terms of space as well as time.

These two examples in which small, unarmed males exhibit altered behavior that compensates for their lack of fighting ability may provide a general explanation of how minor males persist in horned species. It is not difficult to see how a dimorphism such as that exhibited by *Podischnus agenor* in both body structure and behavior could have evolved by gradual steps. Consider a species for which the direct competition for vital resources is so intense that smaller individuals are virtually excluded from reproduction but for which environmental conditions (such as suboptimal feeding conditions for larvae) continue to give rise to small individuals. Such circumstances could favor the facultative adoption by the individuals that happen to be small of alternative adaptations, at first behavioral but eventually morphological. In at least some situations such alternative "strategies" could result in the salvaging of sufficient reproductive capability to maintain in the



species the genes associated with the strategies.

Another aspect of the function of beetle horns that still remains to be explained is the fact that in many unrelated groups of horned beetles the horns of larger species tend to be larger with respect to body size. Such differences have been thought to be a consequence of the phenomenon of allometric growth rates, where the growth of a part of an organism is an exponential function of the growth of the whole. In some, and perhaps many, species of horned beetles, however, horn size has a linear relation to body size rather than a geometric one. Daniel Otte and Katherine Stayman of the Academy of Natural Sciences of Philadelphia have recently shown this to be true for a number of species of stag beetles (members of the family Lucanidae), and it also holds for the species *Podischnus agenor* and *Rhinostomus barbirostris.* (In the case of *P. agenor,* of course, there are two linear relations, one for minor males and one for major males.)

It might seem that the presence of relatively larger horns in larger beetles could be explained by the fact that the larger species are proportionately heavier and stronger than the smaller ones. (The cross section and so the strength of the muscles increase as a function of the square of the body length.) The larger species are therefore able to effectively manipulate proportionately longer horns. The trouble with this explanation is that it works only within a taxonomic group such as a genus or a family. Comparing different groups, one finds that small beetle species that are large in relation to the other species in their group have relatively large horns, whereas larger species that are small in relation to the others in their group have relatively small horns or even none. For example, the largest species of the family Ciidae are only two to three millimeters long but have quite spectacular horns. The fact that this pattern is found in many groups of horned beetles suggests there is some underlying physical relation, but it has yet to be identified.

Beetles are of course not the only animals with horns. Many species of ungulates, or hoofed mammals, also have well-developed horns, and a comparison of the functional morphology of these structures with that of beetle horns points up important differences between the two groups. To begin with, however, there are certain important similarities. In ungulates as in beetles a variety of hornlike structures (antlers, tusks and so on) have evolved independently in many different species. Like beetle horns, many of these structures are larger in relation to body size in larger species, they are often limited to the males of a particular species and in some instances they are missing from certain males of a horned species. (For example, male "hummels" of the red deer lack the regularly branched antlers found on other males of the same species.) There has also been much speculation about the function of ungulate horns, but here the behavior of many species has been observed. Once again the most reasonable conclusion to be drawn from the available evidence is that the structures evolved primarily as weapons for intraspecific combat.

When one turns to the specific way in which ungulate horns function as weapons, however, all resemblances between ungulates and beetles end. To put it very generally, it would appear that ungulates and beetles have developed more or less similar structures they employ in completely different ways to accomplish similar ends. Consider the following summary of a general scheme of the function and evolution of ungulate horns that has been proposed by Valerius Geist of the University of Calgary.

The most primitive ungulate horns are small and in many instances sharp structures that serve to concentrate the force of stabbing or ripping blows directed to the body of an opponent. In many species these horns can inflict severe wounds: the commonest protection against them is heavy hair (as in mountain goats) or a thick hide (as in boars). Some species have evolved a different type of defense: the tactic of parrying an opponent's thrusts with the head or the horns. In these species (which include such diverse ungulates as cattle, or members of the genus *Bos,* the small Asiatic deer *Muntjac* and several species of wart hogs) the horns have acquired the additional function of receiving and controlling the attacks of horned opponents. These animals fight head to head, trading blows to the head and horns, each combatant trying to push the other off balance so that a damaging blow can be delivered to the body.

The most complex horns in ungulates are associated with two other tactics that have evolved from this parrying behavior: ramming and wrestling. Ramming species such as the spiral-horned mountain sheep *Ovis dalli* fight by charging at each other from a distance and crashing their blunt horns together. In this type of attack the horns serve not to stab or rip but only to concentrate the force of the blow delivered and to absorb the impact of the blow received. The commoner type of behavior, however, is wrestling, where animals fight by locking their horns together and then twisting and/or pushing against each other.

In some ungulates that employ this tactic, such as the cervids (deer, elk and caribou) and elephants, the horns or

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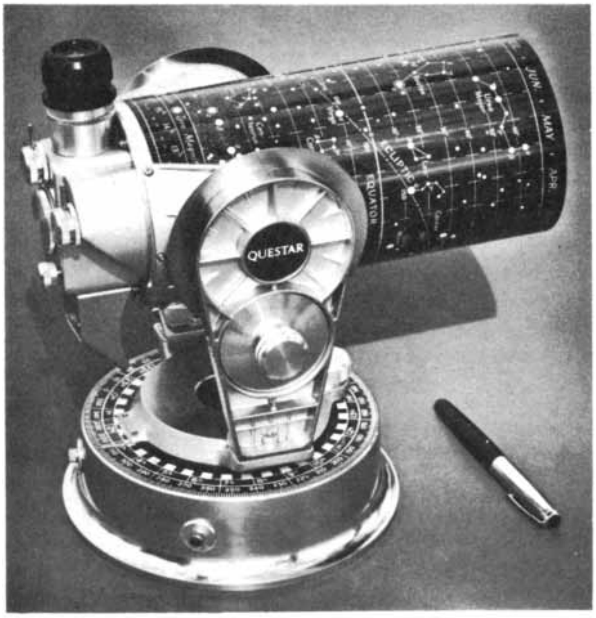

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tusks have retained their stabbing function and a wrestling match may end in a goring; in others, such as many species of African antelopes, the horns serve only to lock opponents together in contests of strength. In addition the use of horns for intimidation in prefight displays has probably been involved to some extent in the evolution of certain complex horn designs, although data bearing on this hypothesis are difficult to gather. Geist's study of mountain sheep makes the most convincing case to date. Stephen Jay Gould of Harvard University has also argued that the largest of all mammalian horns, the gigantic horns of the extinct Irish elk, served mainly for display.

Hence ungulate horns function very differently from beetle horns, which seldom serve to deliver stabbing blows, to intercept opponents' attacks or to ram opponents. Moreover, the commonest applications of beetle horns—to pry up or lift opponents—are rarely observed among ungulates. There are probably several reasons for these differences.

To begin with, the hard, armorlike covering that shields a beetle's body makes stabbing (the original function of the earliest ungulate horns) a largely ineffective form of attack for beetles. Conversely, the vulnerability of the mammalian body makes prying (probably the most primitive function in the evolution of beetle horns) less advantageous for ungulates. After all, if an ungulate can maneuver its horns into the kind of contact with an opponent's body that is necessary for prying, an immediate stabbing or gashing attack would generally be far more effective.

It also seems reasonable that ramming has not evolved as an important tactic among horned beetles. Ramming is only likely to be advantageous behavior for animals capable of rapid, well-directed movements on the ground, and whereas horned ungulates arose from a stock whose basic defense against predators was swift, agile movement, beetles are generally slow and clumsy.

In conclusion it seems fitting to return to the problem that has long been basic to the study of horned beetles: the surprising lack of observations of these creatures, some of the most magnificent organisms ever to evolve. As Darwin pointed out, if a male beetle of the genus *Chalcosoma* were magnified to the size of a dog or a horse, "with its polished bronzed coat of mail and its vast complex horns... it would be one of the most imposing animals in the world." That horned beetles have been so often the subject of speculation but so seldom the subject of serious study is curious. Surely there is time for the contemplation of these splendid animals with which we share the earth.

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THE AMATEUR SCIENTIST

Stalking the fossil trilobite, crinoid and seed fern in Ohio

by Jearl Walker

For several months I have been collecting fossils in Ohio, working over both shale and limestone. Ohio has a wide variety of fossils in an excellent state of preservation. Here I shall concentrate on marine fossils, in particular trilobites and crinoids, but I shall also discuss some plant fossils I found in eastern central Ohio. My emphasis will be on the fundamentals of fossil collecting: how to find a good site, how to remove the fossils and how to clean and display what you have found.

Many amateur collectors particularly prize trilobite and crinoid fossils. The trilobite was an arthropod distinguished by the division of its body into three lobes, one lobe on each side and one in the middle. The body was further divided into cephalon (head), thorax (central section of the body) and pygidium (tail). Trilobites probably were scavengers that crawled over the ocean bottom, feeding on biological debris. They had jointed legs, but the legs and other appendages are rarely preserved in the fossils. The harder exoskeleton is well preserved in the shales of Ohio.

The crinoids were an ancient group of echinoderms. Some were free-floating but most were attached to the bottom by a stem and some rootlike branches. These crinoids must have appeared to be more plant than animal; they resembled lilies and grew in stands as though in a garden. The body was cup-shaped and had a mouth on top surrounded by five branched and flexible arms. The cup, arms and stem are preserved in fossils, but a whole crinoid is difficult first to find and then to get out of the rock without damage. Usually a collector uncovers only parts of a crinoid, but even they can reveal much about the nature of these animals.

An easy way to find a fossil site is to have an experienced collector lead you there. When that opportunity is not open, you must seek out the sites through detective work. Since most sites will be on private property, you should always get permission before you enter the area. Failure to do so may lead to prosecution, particularly if you enter private mines and quarries. The owners of some quarries in Ohio automatically have anyone caught on their property jailed.

Some of the most likely places to find fossils are cuts through hills for roads or railroads. Scout through such a cut, watching for fossils weathered out of the rocks; dig into any likely looking outcroppings of sedimentary rocks. If you see pieces of fossils, explore the site with further digging. Fresh road construction is also promising (although here again permission may be needed). For example, when an interstate highway was being built in Cleveland a few years ago, the crews clearing the ground broke into a magnificent deposit of fossilized fishes that was only a few minutes from my office near the downtown area. The Cleveland Museum of Natural History carefully unearthed the fossils and now has a fine collection of fossil fishes. The deposit was small, and although I and others have searched through the nearby shale (the site of the deposit is now covered by the highway), we have not found any more fossil fish.

Another likely place to investigate is along a stream bed that cuts through the soil and down into the bedrock. As you walk along the stream watch for fossils embedded in the rock. You might also occasionally crack open a piece of rock. If you do find a fossil in such a rock, investigate the shores of the stream to find the outcropping of shale or limestone from which the rock came.

My friend Edgar Roeser took me to a stream near Cincinnati where parts of trilobites could be found in the walls of the stream bed and various other fossils were visible in the hard limestone slabs along the stream. Still, most of the rock exposed at low water proved to be nearly barren, yielding only common specimens or poor ones. We were looking for a particular type of trilobite known as a flexicalymene. After we had discovered some fossils in a particular layer, Roeser showed me how the layer continued upstream and disappeared into the water. After mentally extrapolating the level of the layer we waded into the stream at an appropriate place and began to pry up slabs of shale from the bottom, groping in the water we had muddied. Within a few hours we each had pulled up about five "flexis," some in very good condition. (To find this place Roeser marched me through several miles of poison ivy and poison oak. The resulting rash nearly drove me crazy for two weeks, but the flexis were worth it.)

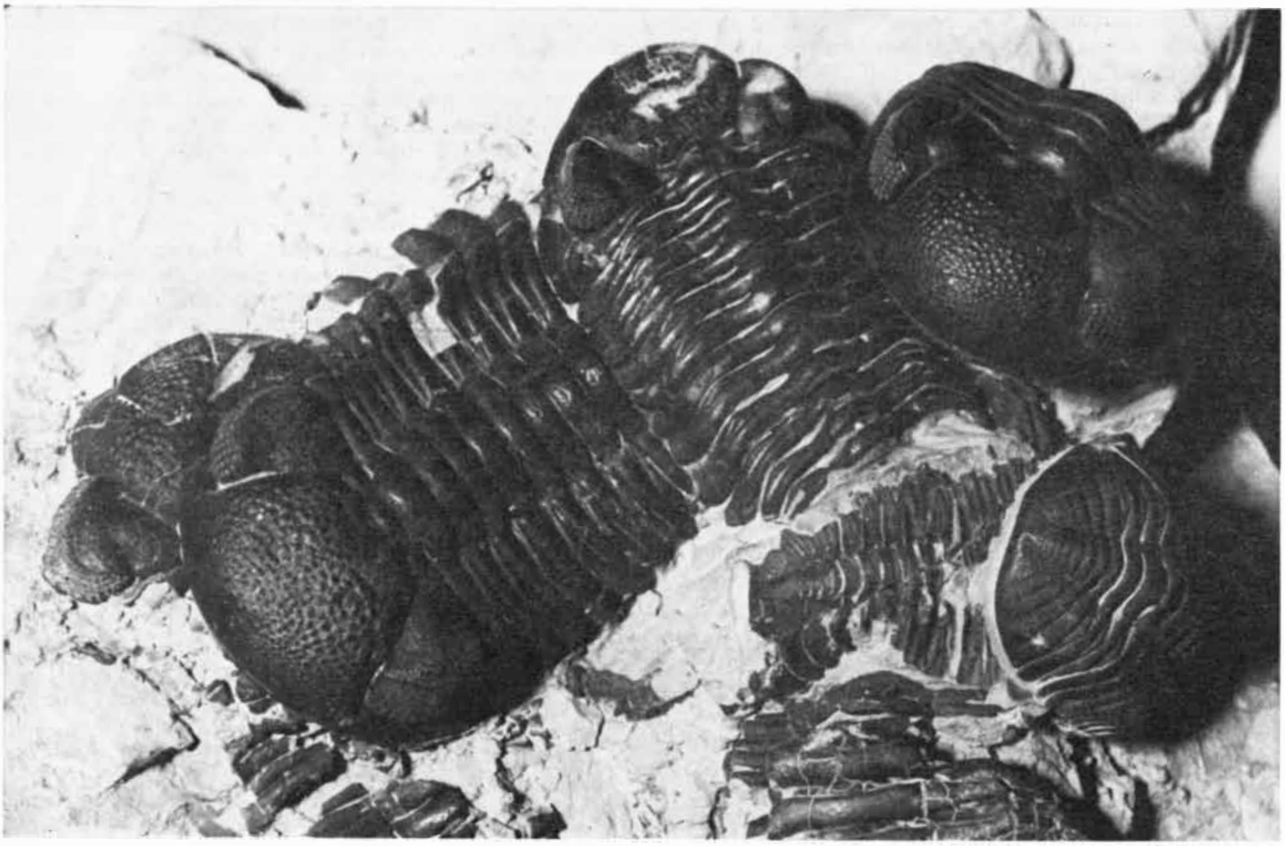
Another good prospect for fossils is a mine dump or a quarry. (Never enter an abandoned mine tunnel!) The rock there is often broken up by the mining operations and weathered by exposure. Many people prefer this type of location because it requires little digging. In a quarry near Toledo I met a collector who is particularly adept at this kind of hunting. He was marvelous at spotting "rollers"—rolled-up trilobites—lying partially weathered in the dump piles around the quarry. I suspect he took keen pleasure in showing us his huge rollers (each two inches or so in diameter) after my friends and I had spent half the day rummaging in the quarry in the hot summer sun, usually finding only a few odds and ends of small trilobites.

The best trilobite I found all summer was one I picked up from the dumps within the first hour of my first trip to hunt for fossils. It was a small roller about an inch in diameter and in almost perfect condition. The individual facets of its compound eyes could be seen clearly. All the other trilobites I found in the area had to be pried out of the walls of the quarry with exhausting effort.

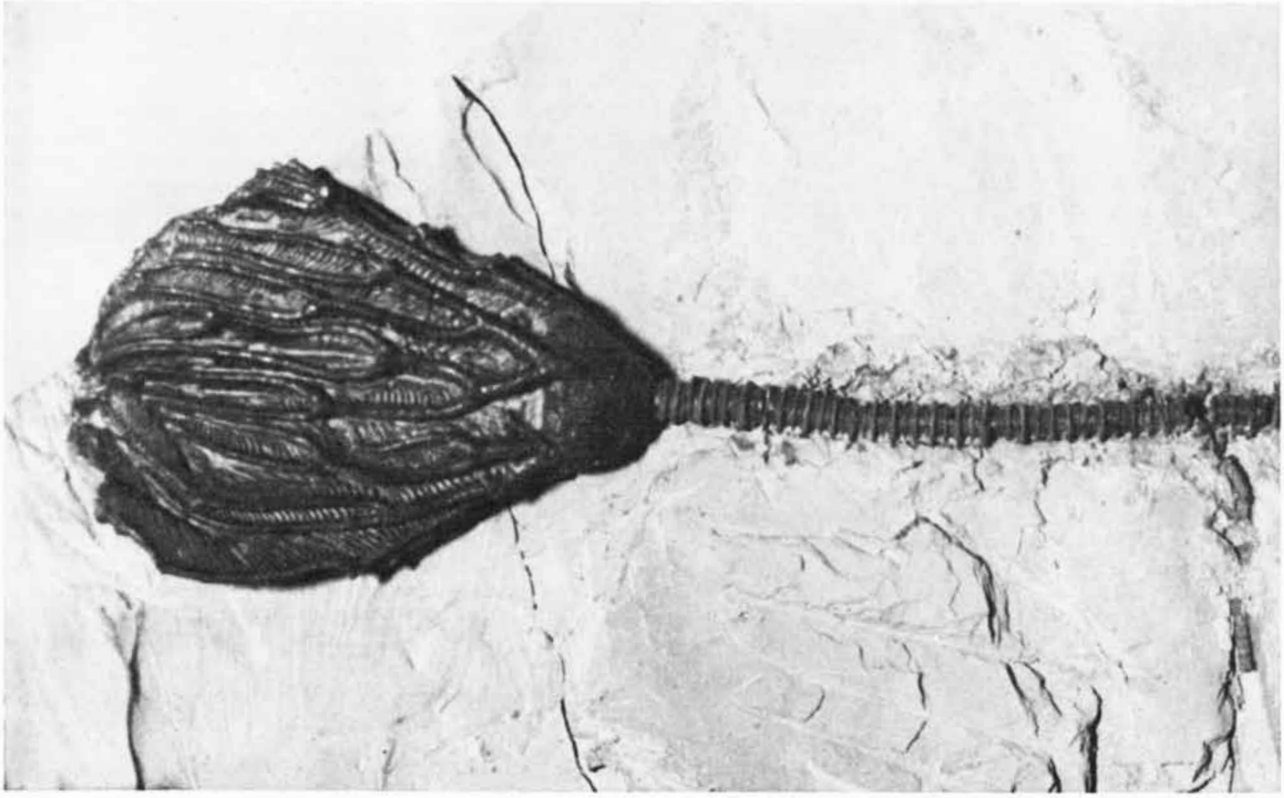
Once a fossil location is found you should make a map of the area or identify the site on a large-scale map. This procedure not only will help you to remember the site but also will enable others to follow your map to the location. With many sites on a map you may also be able to correlate the type and abundance of fossils at several sites. If the map is topographical or geological, you might be able to predict the location of other fossil-bearing sites in the area.

For the purpose of correlation you should label each fossil when you collect it. Write the name of the site and the date on the container in which you put the fossil. You probably should also indicate the depth or level from which the fossil came. When you return to that site, you can then continue to work at the same level rather than wasting time on unrewarding levels.

Fossils are found in sedimentary rocks, some of which are easier to deal with than others. The limestones in Ohio sometimes yield good specimens, but in general I find their hardness an obstacle to fossil collecting. The Ohio shales are softer and much easier to open up to expose fossils, and so one can work through a lot more shale than limestone



A group of fossil trilobites collected in Ohio



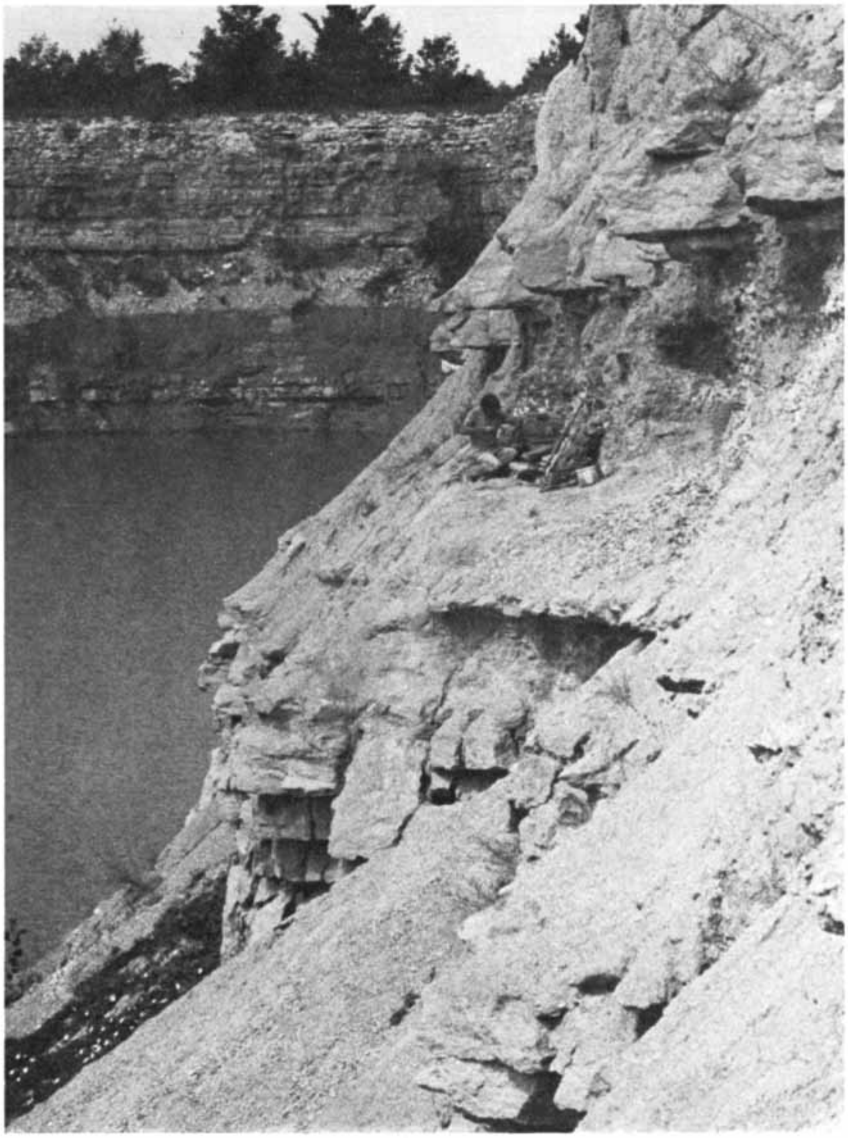
A fossil crinoid

in a day. It is also far easier to remove a specimen from soft shale than it is from harder rock.

If the fossil-bearing rock lies in the side of a cut such as one made for a road, you should be able to see the continuation of the stratum on the opposite side of the cut. If the stratum is straight and contains fossils, you may be able to find fossils all through it. If it is strongly folded or fractured, it is not promising, because even if it once contained fossils, they would probably have been destroyed by the folding or fracturing.

I have collected most of my fossils on the slopes above stream beds or in quarries. Either kind of site can be dangerous if there is much loose rock above the collection level. Mining operations in a quarry often leave heavy boulders overhanging shale that looks promising. Jeff Aubry, who is widely known for his collection of fossils from Ohio and the surrounding states, was once hit by a rock in the quarry I frequented this summer. He was unconscious for several hours. If more rock had come down the slope, he might have been killed. Even if you have had experience with collecting, do not dig below a large overhang of rock no matter how tempting the place may seem.

The general strategy for digging on a slope is to level a section so that slabs of rock can be lifted and examined. When I worked on a slope, I began digging well above the stratum in which I was interested. My initial cut was high enough so that a straight line downward would cross through the stratum at least a meter in from the slope. Digging out the overburden took hours and considerable effort with a pick and shovel. Sometimes the overburden itself yielded interesting fossils, but usually this stage of the digging was simply tiring.



Amateur fossil hunter on a ledge in a quarry near Toledo

When I finally had the overburden cleared away, the shale at the level I was interested in was exposed for several square meters. Along the sides and the back of the exposed area I pounded long chisels to a depth of four or five centimeters with a sledgehammer, rocked them slightly and then removed them. Next I carefully drove a long chisel horizontally into the side of the shale layer several centimeters below the top surface in order to pry up a slab. The chisel holes at the rear and the sides facilitated the proper fracturing of the slab.

After lifting the slab I examined the bottom of it and the top of the layer of shale under it. If I saw no fossils, I stood the slab on one edge and split it further by tapping a small chisel or screwdriver into the other edge with my hammer. Although the shale is easily split, the splitting should be done with restraint. I have destroyed some beautiful trilobites by heavy-handed hammering.

Digging out the overhang and the slabs this way is hard work and can take hours or even days. Some people prefer to dig directly into the wall. The advantage of the longer and more careful work becomes apparent if you open up a slab that holds several good fossils. Single fossils can be recovered by digging straight into the wall, but the chances are slim that you can avoid damaging the delicate types such as the flat trilobites or the complex crinoids. On the other hand, if you can lift out a slab with several good fossils in it, you have a valuable discovery because the slab will be far more impressive than a single fossil cleaned and removed from its matrix.

Scott Vergiels of Temperance, Mich., recently showed me a slab he had wrestled out of the quarry near Toledo. It contained a complete crinoid and seven trilobites. I was impressed. Vergiels told me of a remarkable slab Aubry had dug out of the quarry: it had 26 complete trilobites in it.

Unless the fossil you uncover is notably solid (some of the brachiopods may be solid enough) the specimen should be left in its matrix until you have carried it home. I recommend that you avoid cleaning the specimen while you are in the field. If part of the specimen is chipped when the fossil is exposed, gather up the chips. I prefer gluing them to the matrix so that I can reconstruct the fossil at home. A dilute white glue (which is water soluble and so can be loosened easily) will do. If the fossil seems to be in danger of falling apart, I apply a small amount of glue near the loose edges. Capillary action pulls some of the glue under the loose pieces and secures them after a few minutes.

Many fossil collectors prefer to carry out all but the largest slabs in small baskets. If you use a basket or a box, avoid packing one specimen on top of another; the specimens can easily damage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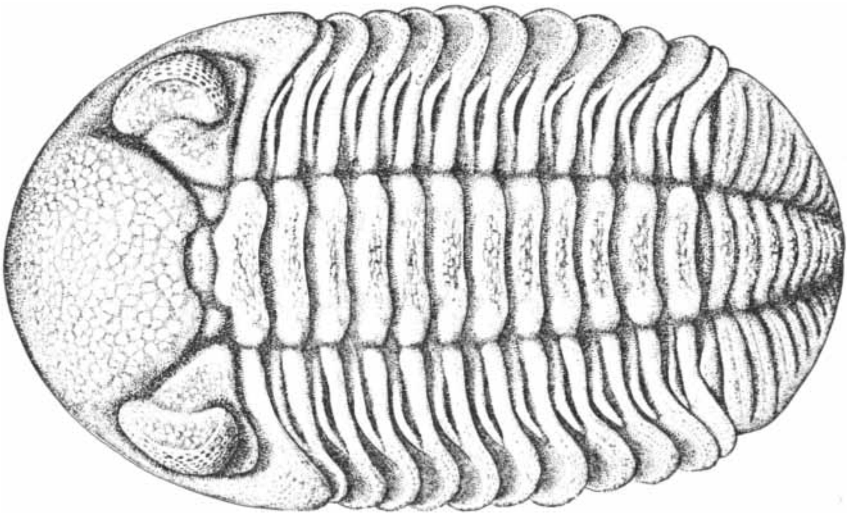


The Middle Devonian trilobite **Phacops rana milleri**

each other. If you wrap your specimens in newspaper, paper towels or plastic foam, you can carry them in a backpack.

Many fossil specimens can be cleaned roughly with an old dental tool or even a safety pin. With a trilobite fossil I pick at the shale, being careful not to flick away any of the fossil itself. Fine metal points are needed to remove the shale in the narrow crevices of the trilobite and to expose the arms of a crinoid.

Excellent cleaning can be done with an air gun (a miniature "sand blaster") that many avid fossil collectors have bought, although the cost is now more than $1,000. The gun blows a fine powder from a small nozzle that one directs at a glancing angle to the specimen, removing the matrix without damaging the fossil. Different powders are available for different types of fossil. For example, a harder powder (aluminum oxide) may work best for a hard brachiopod and a softer powder (sodium bicarbonate) for the delicate work needed to expose a crinoid. If the fossil is harder than the surrounding matrix, the stream of powder is directed at the fossil surface at a glancing angle; the matrix is flicked away by the impact. If the fossil is softer than the matrix, the stream must be directed at the matrix or the fossil will be damaged. The air gun is useful only if there is a difference in hardness between the matrix and the fossil so that the impact of the powder can fracture the shale at the interface.

Dental tools are handy for the reconstruction of broken fossils. A loose piece of fossil can be lightly coated with dilute glue and then positioned on the fossil with a dental pick. I lick the tip of the tool in order to provide a little adhesion between the tool and a dry surface on the loose piece.

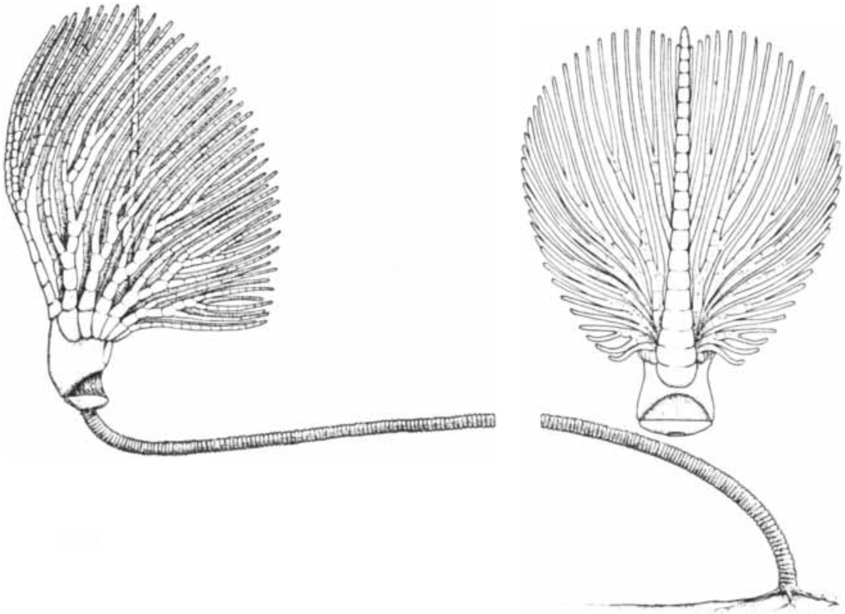
Some chemicals will remove shale or limestone through a reaction that leaves the fossilized material unaltered. For example, some acids will eat away limestone without damaging a fossil that is composed of silicon dioxide. With specimens in shale I prefer to avoid chemicals, since I get better results with a dental pick and an air gun. If the specimen is in limestone, however, one often must resort to chemicals.

The matrix in which a fossil is found can be cut down to a convenient size and then flattened on the back with an abrasive masonry disk (sold in hardware stores). The disk is mounted on an electric drill the same way a drill bit is. Flattening the back of a rock (the matrix, not the fossil) enables you to glue it to a mounting board. Roeser has assembled displays of some of his fossils by gluing the flattened back of the rocks to canvas stretched on a frame as for a painting. Fossils can also be put in a display case.

My most rewarding digging was done in the stone quarry near Toledo. The quarry contains part of the rock unit known to fossil collectors as the Silica Formation, which was formed 350 million years ago in the Middle Devonian period. It was part of the sea in what is termed the Michigan Basin. The basin held a saltwater sea that extended into Ontario and for a while into New York. After the sea had receded and disappeared uplifting, warping and erosion of the ground exposed and removed much of the Silica Formation. What remains is rich in fossils.

Six zones of sediment deposition have been identified in the Michigan Basin. Only two of them are important in the Toledo quarry. One zone is called the coral-brachiopod zone; it consists of limestone and calcareous shale holding fossils of corals and large brachiopods and a few bryozoans, crinoids and blastoids. The other zone is called the diverse-fauna zone. It was originally mud flats and now consists of clay stone or shale with little calcareous content. It holds fossils of bryozoans, brachiopods, ostracods, trilobites, corals and other marine animals.

Some people believe the ancient sea at the site of the quarry must have been no deeper than about 150 feet. If it had been deeper, the corals would not have received enough sunlight for growth. If it had been considerably shallower, evidence of turbulence from the surface waves would appear among the fossils. Very shallow water would probably have been too rough for crinoids and other rather frail animals. Much information about the fossils of the quarry has been collected in a book, *Strata and*



The crinoid **Cunctocrinus fortunatus** *in side* **(left)** *and rear views*

"Chess Challenger-10 Wins Microchess Tourney"
—Personal Computing Magazine
February, 1979

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			OPPONENTS												
	CONTESTANTS		#1	2	3	4	5	6	7	8	9	Games Won	Games Drawn	Games Lost	FINAL SCORE	FINAL POSITION
1	MICRO-CHESS 1.0 (Heath H-8)	W	X	½	0	1	0	0	0	—	—	1	3	8	2½	7*
		B		½	½	0	0	0	0							
2	MICRO-CHESS 1.5 (TRS-80)	W	½	X	½	½	0	0	0	—	—	0	5	7	2½	6*
		B	½		0	0	0	½	0							
3	MICRO-CHESS 2.0 (PET)	W	½	1	X	1	0	0	½	—	—	3	4	5	5	4
		B	1	½		½	0	0	0							
4	CHESS CHALLENGER (3 Level)	W	1	1	½	X	0	½	½	—	—	2	5	5	4½	5
		B	0	½	0		0	0	½							
5	CHESS CHALLENGER (10 Level)	W	1	1	1	1	X	1	½	—	—	10	2	0	11	1
		B	1	1	1	1		1	½							
6	BORIS	W	1	½	1	1	0	X	1	—	—	7	2	3	8	3
		B	1	1	1	½	0		0							
7	SARGON I (TRS-80)	W	1	1	1	½	½	1	X	—	—	6	5	1	8½	2
		B	1	1	½	½	½	0								
8	ATARI *Did not play*	W	—	—	—	—	—	—	—	X	—					
		B														

* Note: Microchess 1.5 wins 6th place over Microchess 1.0 by virtue of the tie breaking analysis of relative strength of opponents

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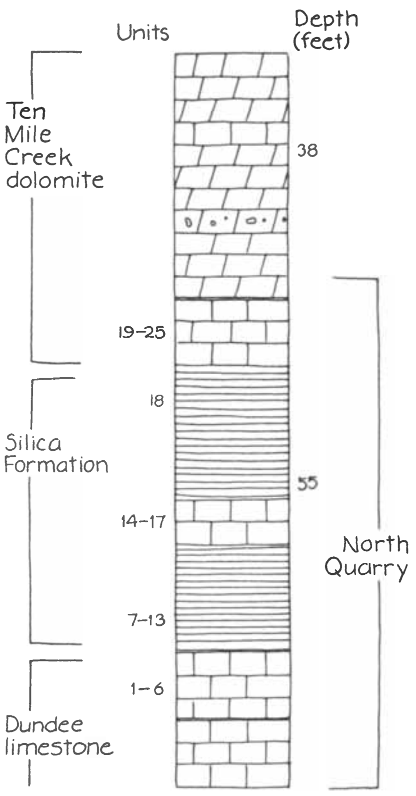
Megafossils of the Middle Devonian Silica Formation, by Robert V. Kesling and Ruth B. Chilman, published at $10.50 by the University of Michigan Museum of Paleontology, Ann Arbor, Mich. 48104.

The quarry is divided into a northern and a southern section by a county road. The southern section is closed to collectors because it is still being mined. The northern section has not been mined in years and is open to amateur collectors, although I have heard a rumor that new owners will soon close it. The northern section is partly filled with water that has run off from the surrounding land. At the sides of the quarry are steep cliffs where the fossil-containing strata of limestone and shale are exposed.

Fossils can also be found in the piles of shale and limestone mined and then dumped on the surrounding land. Corals and shells turn up in quantity on flat land at the northern end of the quarry, where layers of fossils formerly underground have been exposed by uplifting and weathering. Although I explored the dump piles and the ancient reefs, I spent most of my time working with friends (Roeser, Vergiels, Dave Watson and Mike Walsh) on a ledge about halfway up one of the cliffs.

The rock layers along the cliffs have been labeled and connected geologically with layers in the southern section of the quarry and with layers elsewhere in the Michigan Basin. The labels are numbered units that begin in the limestone under the shale. Unit 11, an easily workable layer of shale, was approximately at eye level when I stood on the ledge. Under it was a narrow stratum of hard limestone, Unit 10, about six inches thick. (The thicknesses of the units are not constant throughout the quarry.) Near belt level was a thicker layer of shale, Unit 9B, which extended downward some six feet, ending on more limestone under the floor of the ledge. Although various types of fossils were below and above me, I concentrated on Unit 9B. Toward the top of the unit several good specimens of trilobites had been collected. Toward the bottom of the unit the trilobites were rarer but usually larger.



Stratigraphy in the quarry

Two types of trilobite are predominant in the Silica Formation. *Phacops rana crassituberculata* is normally found in units 8 (shale) and 10 (limestone). *P. rana milleri* is usually in units 7 and 9. Since the "crassies" are farther down, they must have existed at an earlier time than the *milleri,* although some slabs dug out of the Silica Formation contain both types of trilobite, indicating that for a time they coexisted.

My procedure for digging on the cliff was first to remove the overburden above the preferred level and then to split out large slabs of shale. Early in the morning I dug into the wall at about face level, chopping and shoveling my way back for about two feet. The cut was about four feet wide. Then I extended the cut downward, chopping out the hard limestone as fast as I could but being more careful with the shale. Most of the shale was weathered because it was near the surface. Water seepage had made some of it so fragile that it crumbled in my hands. The only fossils I recovered from this shale were the harder brachiopods.

By midafternoon I had reached a level between my belt and my knees. Now the cut was much deeper into the wall because of the slope. The shale was less weathered and could be split off in large slabs. Here I worked slower for fear of damaging the fossils. Some of my stronger friends managed to pry out slabs weighing 100 pounds or more. Although these large slabs are difficult to handle, they eventually save the collector much time. An old dictum of fossil collecting is that the more you can dig out in a promising spot, the better your chance is of finding rare and prized specimens. Some of my friends work like human power shovels, clearing out large cuts into the slope in a day.

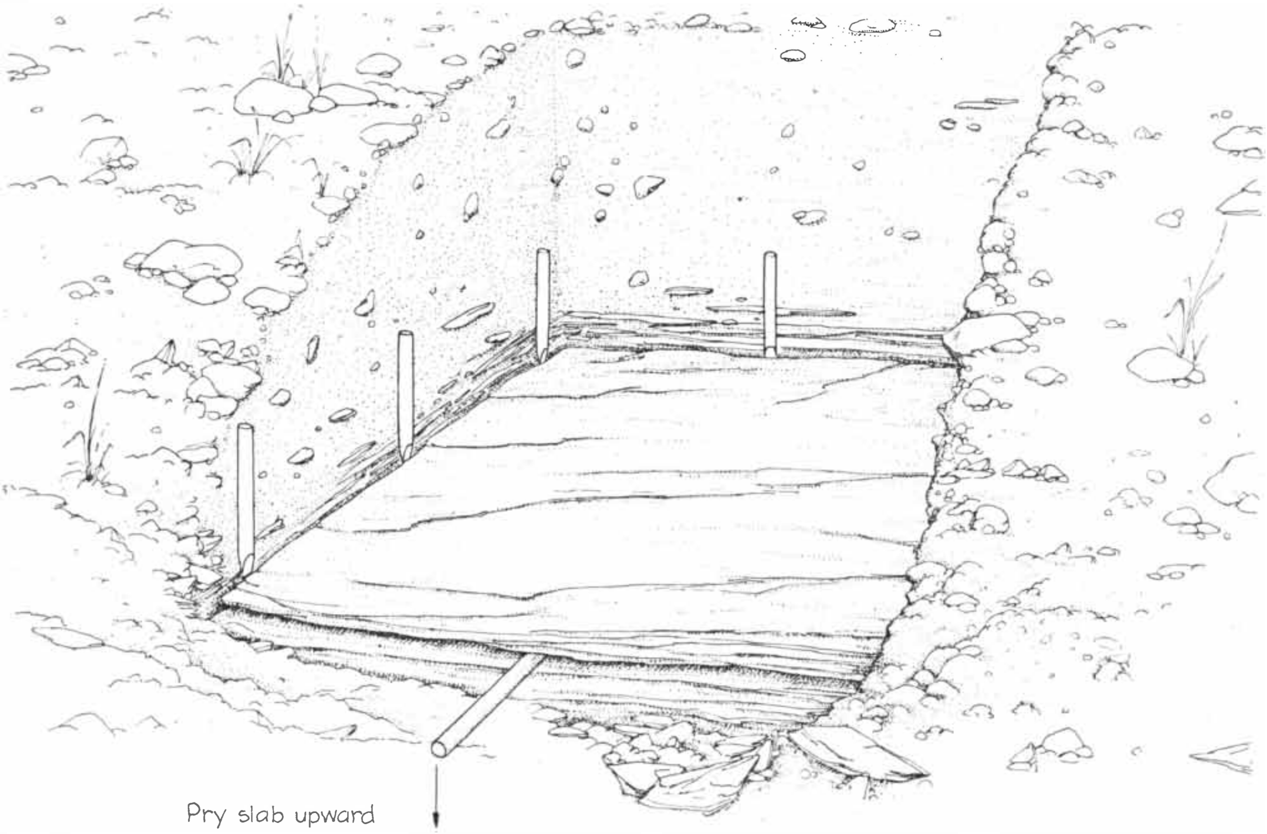
If I reached a promising specimen, I naturally slowed down considerably. Ordinarily a rolled trilobite was firm enough so that it and its surrounding matrix could be chipped out of a larger slab without much concern that it would be damaged. Flat trilobites and all crinoids required more attention. Usually a bit of dilute white glue had to be applied to a flat trilobite before its surrounding matrix could be safely chipped out of a slab. Crinoids are difficult to recover without damage unless one is extraordinarily lucky in splitting open a slab just the right way. Without such luck one must work patiently with small chisels and delicate taps of a hammer to follow the full length of a crinoid and then free the slab in which it lies. One of the saddest sights in the world is a fracture line running directly across a good crinoid or trilobite specimen.

Trilobites molted periodically during their lives, shedding their exoskeleton in order to form a new and larger one. These molts are relatively abundant in the shale, sometimes frustratingly abundant when they appear to be a whole trilobite. I found one trilobite that had died after it had molted and before a larger exoskeleton had hardened. These specimens, called soft-shells by collectors, are difficult to spot because they blend into the color of the shale more than the normal trilobite fossils do. The soft-shells are also difficult to recover intact because the fossil is quite fragile. Fossils of the appendages and soft underside of trilobites are rare, and they are not found at all in the Silica Formation. The preserved exoskeleton consists of calcium carbonate and calcium phosphate that had hardened the original chitinous covering.

In addition to trilobites Unit 9 contains phyllocarids, clams, large brachiopods and many other fossils. One of my friends, Zarko Ljuboja, dug a slab containing nine fossil starfish out of the rock unit. I have witnessed several large trilobites, both rolled and flat, being split out of the shale. Alas, I was always working next to the person who found the large specimen, never at the right place to get one for myself.

Of all the fossils I have found or seen the trilobites remain the most fascinating, particularly because of the evolution that apparently shaped them. Many different types of trilobite have been identified around the world. The animals had a variety of shapes and sizes, the length of adults ranging from six millimeters to 75 centimeters. They first appear in the fossil record from earliest Cambrian times (some 600 million years ago); by middle Paleozoic times they had become specialized, and by the end of Permian times (225 million years ago) they had waned and disappeared. During their peak period they were apparently abundant in fairly shallow waters, feeding on small organisms and organic waste on the muddy bottoms. Judging from the many rollers found at fossil sites, many trilobites died at a time when they were rolled up.

The adaptations of trilobites led into a variety of evolutionary paths. For



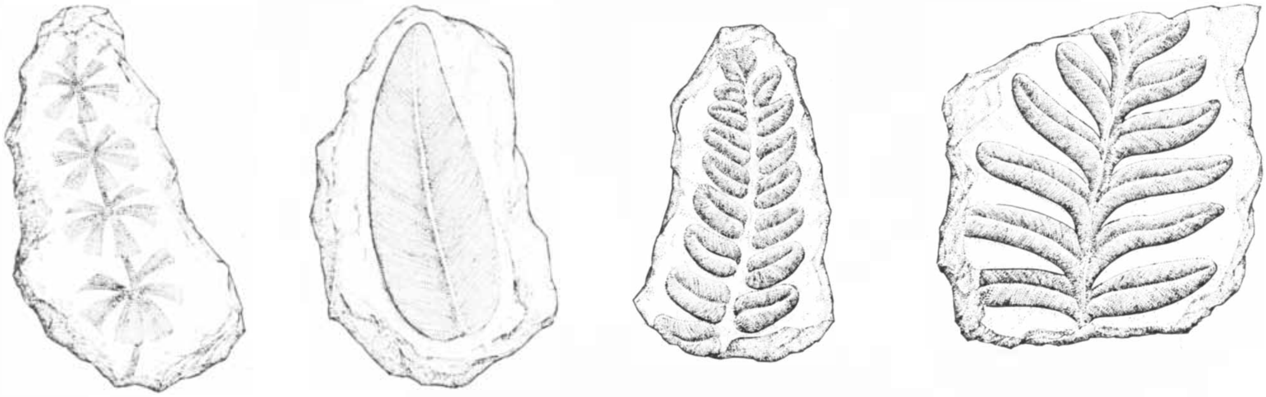
How to remove a flat shelf of shale

example, the eyes of different species of trilobites were noticeably different. Some of the trilobites had small crescent-shaped eyes, some had large eyes that dominated their cheeks, some had small eyes mounted on stalks that extended from their cheeks and some had no eyes at all. One can guess at why the eyes evolved in these different ways. The large eyes may have been for trilobites that lived in deep water where the light was dim. The blind trilobites may not have needed eyes because they spent their lives burrowed in the mud.

The trilobites I saw at the Toledo quarry had compound eyes with the facets arranged differently in the two subspecies. The *P. rana milleri* specimens had eyes with eight facets in each vertical row and an average of 104 facets per eye. The *P. rana crassituberculata* specimens had eyes with six or seven facets in a vertical row and only 77 per eye.

In some of the trilobites each facet of the compound eye consisted of two layers of material, arranged so that the outside and inside surfaces were simple convex shapes and the surface between the layers was a more complex shape. According to research done by the paleontologist Euan N. K. Clarkson of the University of Edinburgh and the physicist Riccardo Levi-Setti of the University of Chicago, the form of the composite lens is approximately the ideal one for the elimination of spherical aberration.

The outer layer of the trilobite's eye consisted of calcite, a birefringent mineral of the kind I discussed in this department for December, 1977. In general when light travels through a birefringent crystal, it is split into two rays



Seed-fern fossils: **Sphenophyllum, Neuropteris** *and* **Alethopteris**

according to the polarization of the rays with respect to the crystal axes. Such a splitting of light rays would have made an interpretation of the environment by a trilobite virtually impossible, but evolution gave rise to a lens with the calcite crystal oriented advantageously. When light entered the lens, it traveled along the optical axis of the crystal and was not affected by birefringence. Hence the trilobite saw only a single image.

I also collected a number of plant fossils from a strip-mining operation in the hills of eastern central Ohio. Large amounts of shale had been put in dumps on the surface, but all of it was barren of fossils. At one end of the mined area, on the side of a gentle hill, a small stream had cut its way into a lower layer of shale. Along the slopes of the stream the shale was full of plant fossils.

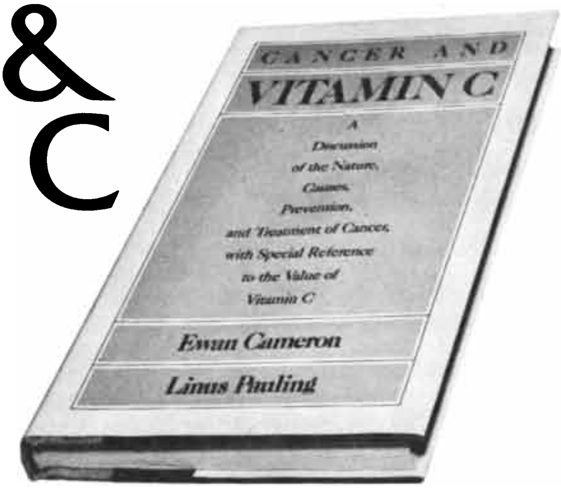
Roeser and I dug into the slopes, cleared the overburden and finally got a flat working area on the shale layer. Although the plant fossils were abundant, recovering a whole specimen was difficult because of the orientation of the fossils and the nature of the surrounding rock. Where the marine fossils from the Silica Formation were usually nicely exposed when I split open a slab of shale, the plant fossils were almost randomly oriented in the slab. When I split such a slab open, the fracture was likely to cut through several specimens. Nevertheless, the fossils were so abundant that by the end of the day Roeser and I each had plenty.

Most of the plant fossils from the site appear to be seed ferns, which are fernlike plants that bear seeds rather than spores as true ferns do. We found examples of *Sphenophyllum,* which had a circular array of fan-shaped leaves on the end of a slender stem. There was also *Alethopteris,* which had long leaflets extending to the sides from a central rib with a prominent central vein. Various other fernlike plants (*Pecopteris* and *Neuropteris*) were dug out of the walls. Roeser discovered a layer of *Sphenophyllum* that extended along the slope at a slight slant for at least 10 feet.

All these plants were deposited in a stagnant muddy lagoon some 230 to 320 million years ago. Since the plants were not hardened by mineral matter, their preservation depended critically on the absence of oxygen and aerobic bacteria. Apparently the plants Roeser and I uncovered had dropped into the stagnant waters and had been covered with mud before decay could set in.

Ohio is rich in fossils, yielding specimens from several of the ancient ages. Many other areas of North America, however, are equally rich in these specimens and others as well. Why not take a walk along a stream bed or a road cut and see what kind of animals and plants lived in your area long ago? You are likely to wind up with a pleasant addiction: fossil collecting.

CANCER & VITAMIN C



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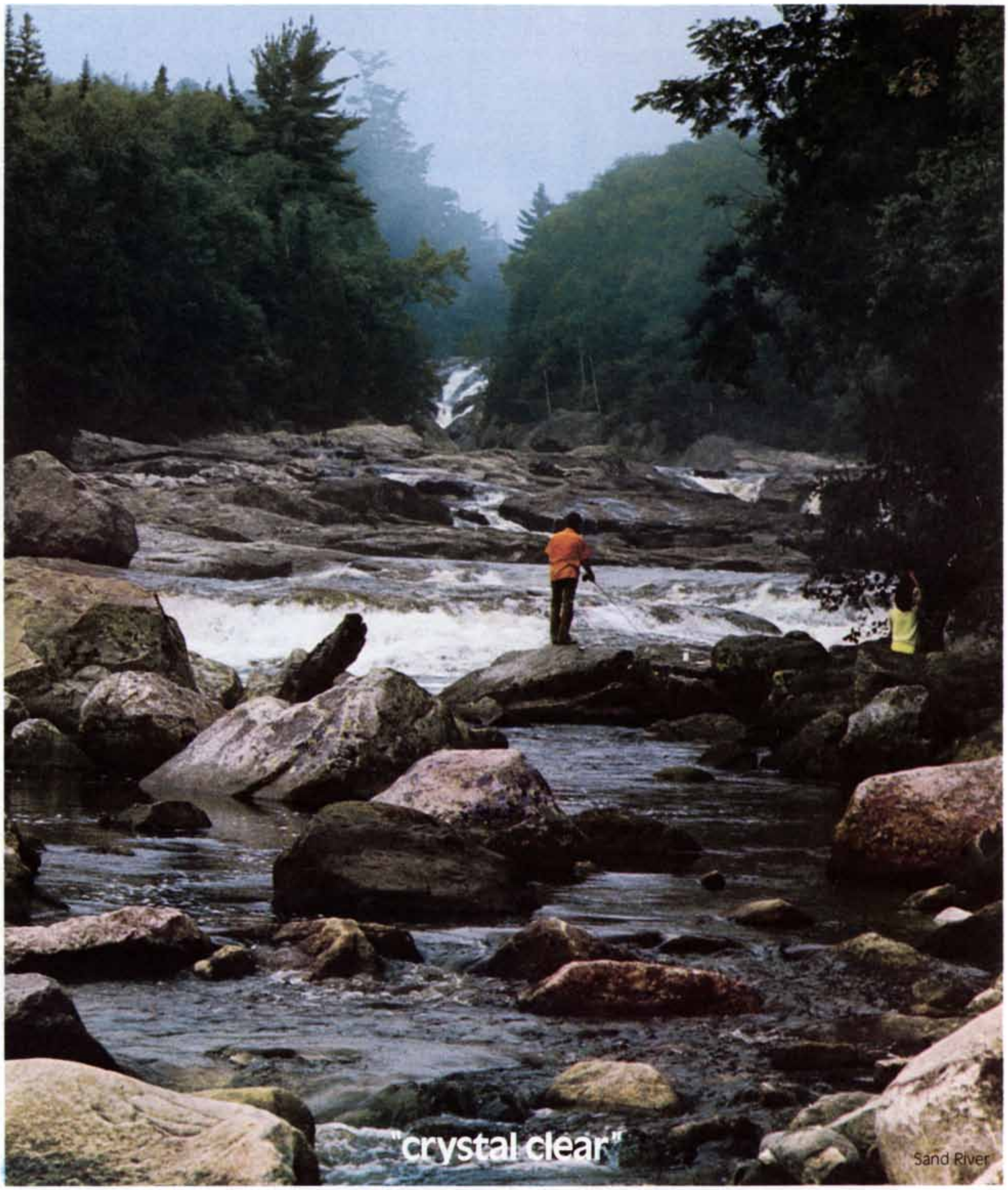
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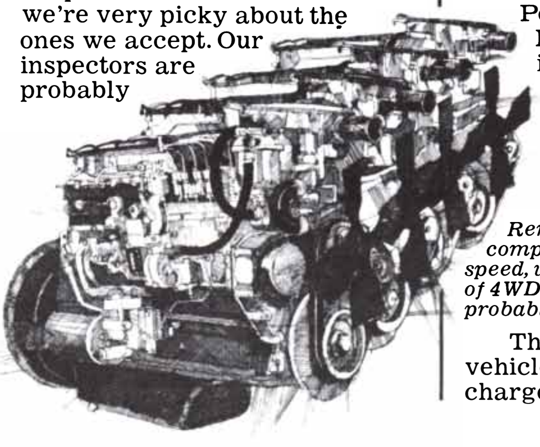

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