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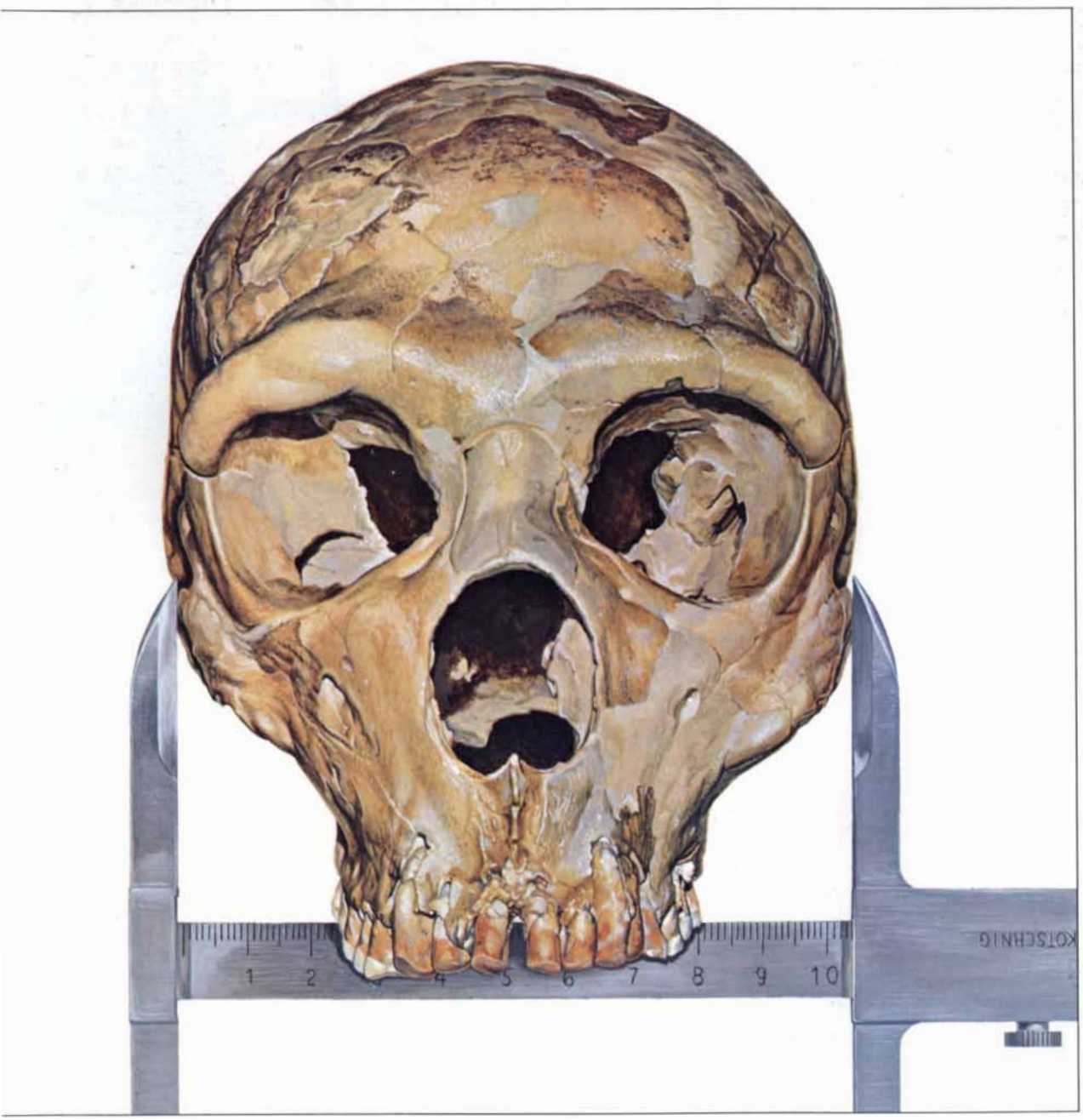

THE NEANDERTHALS

$2.00

December 1979

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Your friends will enjoy a toast of "Turkey" for the holiday celebrations. You'll find America's finest native whiskey, 101-Proof Wild Turkey,® dressed for the holiday season in a quietly elegant gift carton. It's a gift truly beyond duplication.

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*Price may vary by state.

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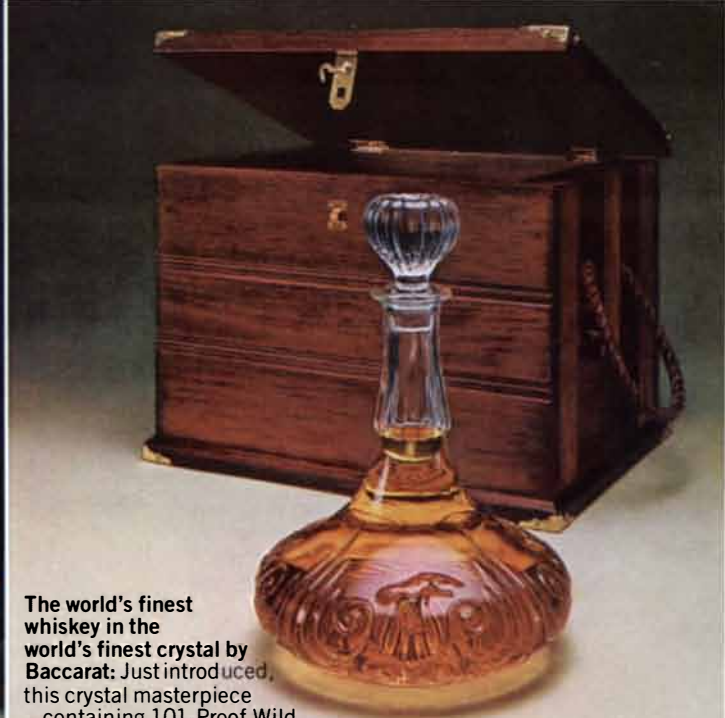


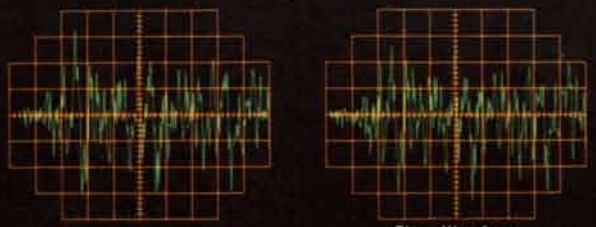
The world's finest whiskey in the world's finest crystal by Baccarat: Just introduced, this crystal masterpiece —containing 101-Proof Wild Turkey—was inspired by the decanters of early American sea captains. Each Baccarat decanter comes with a numbered certificate, in a "Captain's chest" of hand-hewn wood with a hand-rubbed finish. A true family heirloom. About $250.*

The first in an exciting new series of Wild Turkey ceramics: For collectors of Americana (and connoisseurs of Wild Turkey), America's great native bird is commemorated in this limited-edition decanter (in bisque finish) filled with 101-Proof Wild Turkey. It's a handsome "conversation piece" for the holiday season. Beautifully boxed for gift presentation.

When you hear Technics new Linear Phase Speaker Systems, you won't believe your ears.

Take a look at the two piano waveforms and you won't believe your eyes either. The waveform reproduced by Technics SB-L300 is virtually a mirror image of the original.

Technics



Live Piano Waveform.

Piano Waveform reproduced by SB-L300.

It's difficult to tell them apart. And how did we achieve this level of waveform fidelity? We started by giving each driver unit, including the wide-dispersion radial-horn tweeter, a frequency response that's as flat as it is wide. Then we developed a unique phase-controlled crossover network that compensates for the characteristics of each driver. Finally we staggered the driver units for optimum acoustic position.

Technics new Linear Phase Speaker Systems. Whether you choose the 3-way SB-L300 or SB-L200, or the 2-way SB-L100, you'll notice a big difference. Because, as you can see, there's very little difference between Technics Linear Phase and "live."

Cabinetry is simulated woodgrain.

Waveform Fidelity: The big difference is how little difference there is.

Established 1845 **SCIENTIFIC AMERICAN** December 1979 Volume 241 Number 6

ARTICLES

DEPARTMENTS

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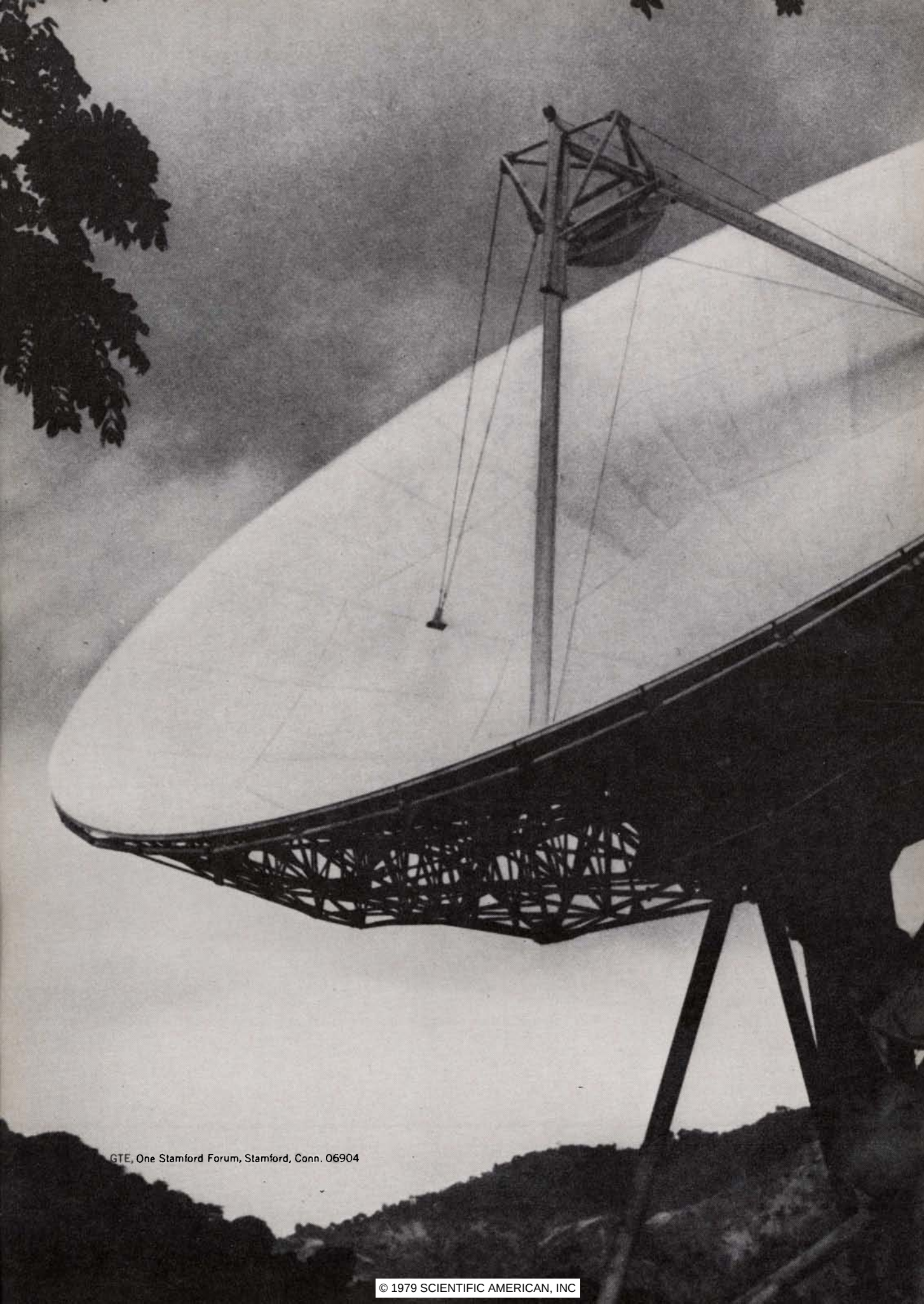
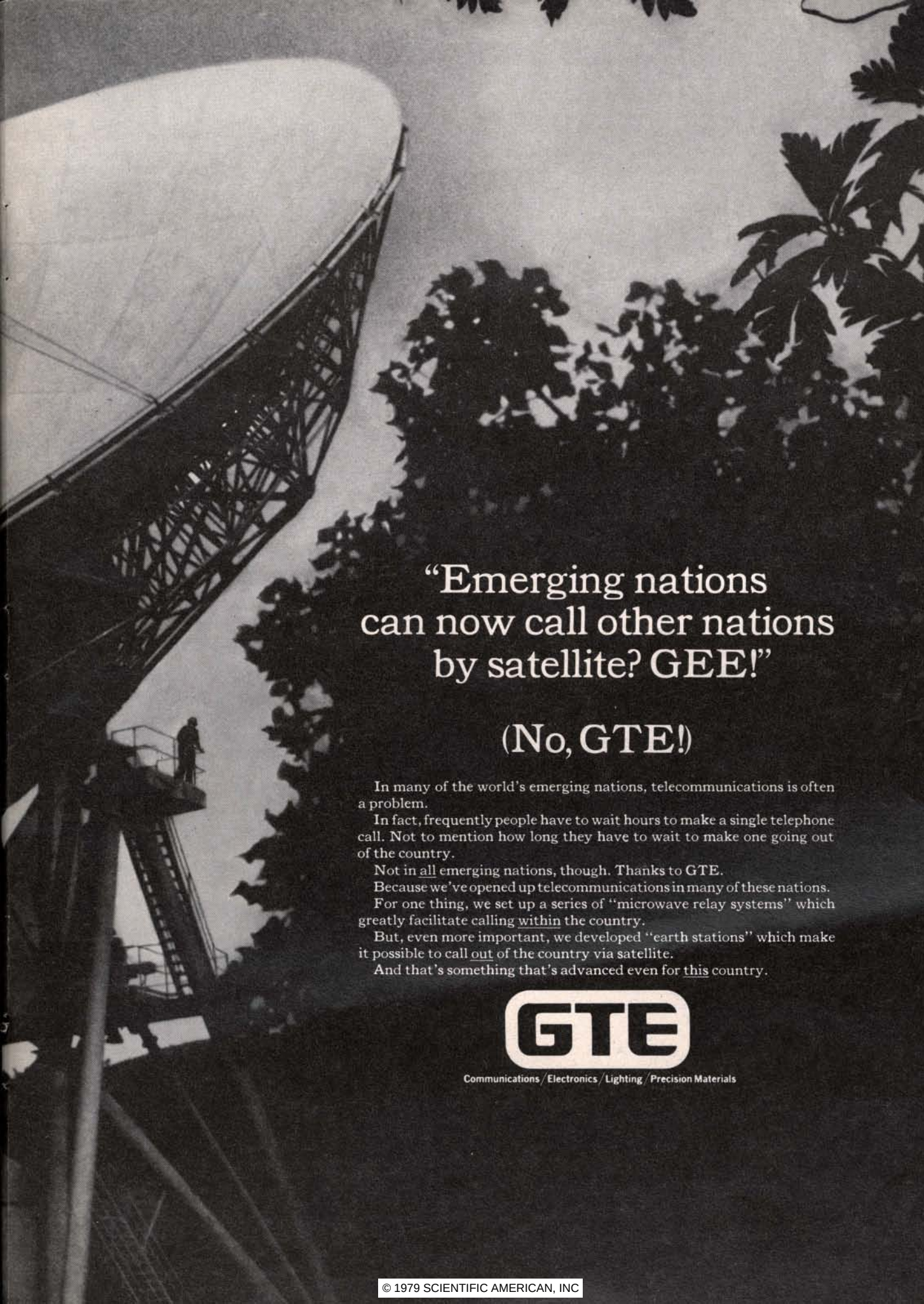


GTE, One Stamford Forum, Stamford, Conn. 06904



"Emerging nations can now call other nations by satellite? GEE!"

(No, GTE!)

In many of the world's emerging nations, telecommunications is often a problem.

In fact, frequently people have to wait hours to make a single telephone call. Not to mention how long they have to wait to make one going out of the country.

Not in all emerging nations, though. Thanks to GTE.

Because we've opened up telecommunications in many of these nations.

For one thing, we set up a series of "microwave relay systems" which greatly facilitate calling within the country.

But, even more important, we developed "earth stations" which make it possible to call out of the country via satellite.

And that's something that's advanced even for this country.

GTE

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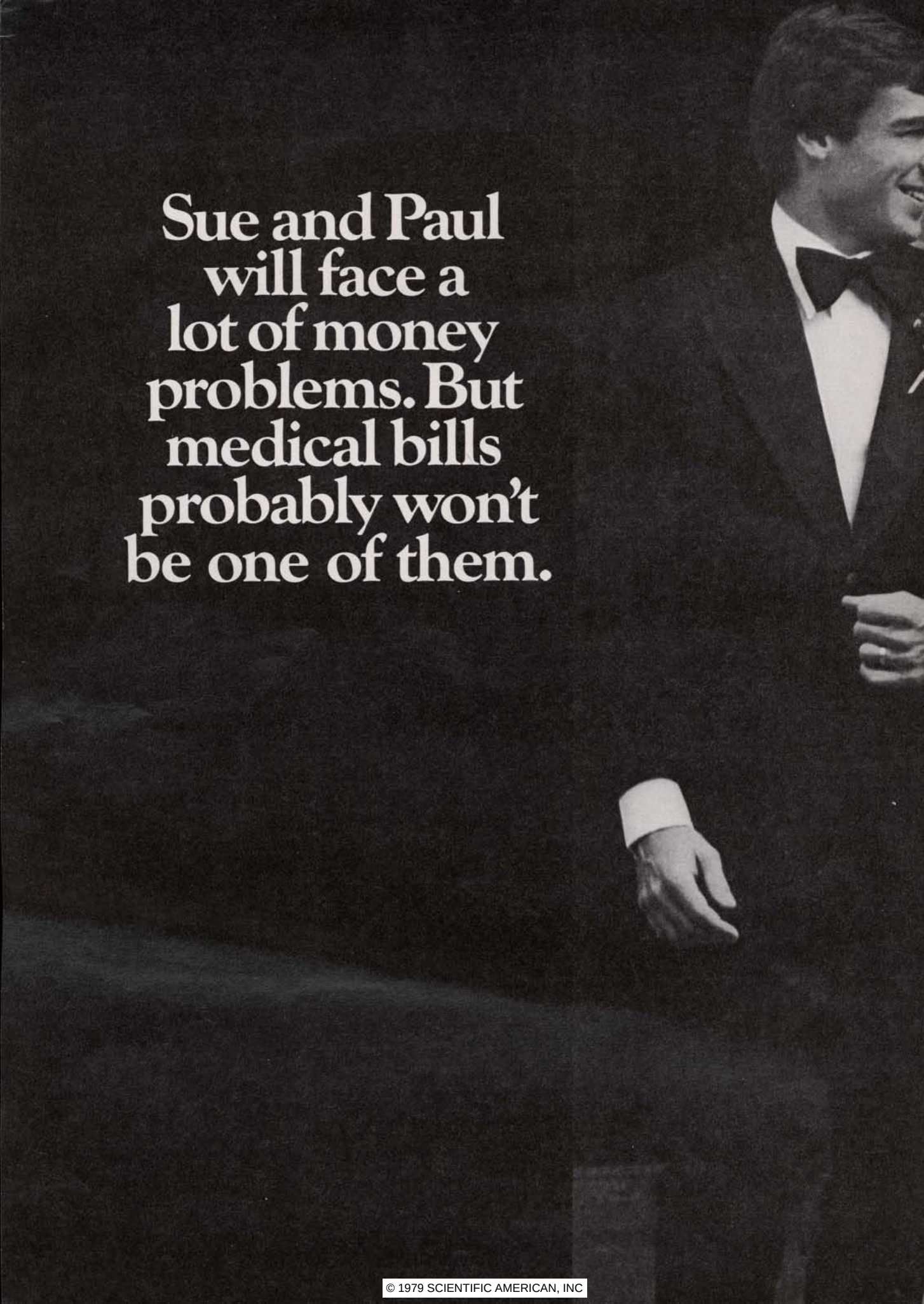

They're two of 179,000,000 people protected by health insurance.

Just about everybody faces medical expenses sooner or later. But that's much less of a worry for some people than others. For 9 out of 10 people in this country, as a matter of fact. The ones protected by health insurance.

And the 142,000,000 major medical policy holders who are protected against extreme medical expenses have even less to worry about.

Health insurance is meeting the needs of the times in other ways, too.

Like expanded coverage. Now more and more policies cover dentistry, psychiatry, home and preventive care, and second opinions for surgery.

And we're confronting the pressing problem of costs. Health insurance people are enthusiastically behind money-saving ideas like better planning of facilities and services, alternate methods of treatment, review of hospital budgets. And we're active in programs for preventive care and health education.

A lot's been accomplished. But there's still a lot to do. So we'll keep working till the promise of "good health care for everyone that everyone can afford" becomes a reality.

If you'd like to know more about the ways health insurance meets family needs, we've put together a booklet called *All About Health Insurance.* For a free copy, write the Health Insurance Institute, Dept. 18, 1850 K Street NW, Washington, DC 20006.

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THE COVER

The painting on the cover is symbolic of revived interest in the immediate predecessor of modern man, the Middle Paleolithic subspecies known as *Homo sapiens neanderthalensis*. The painting shows a Neanderthal skull being measured. The arms of the calipers indicate a facial dimension, the distance separating the two cheekbones at the widest point. The specimen is an idealized reconstruction of Shanidar 1, the skull of a Neanderthal male unearthed at a cave site of the same name in Iraq in 1957. During the lifetime of the Shanidar 1 male his left eye socket and the adjacent part of his skull had been fractured and had remained distorted after the bone had reknitted. Here the undistorted right side of the skull has been mirrored to reconstruct the left side without distortion. Shanidar 1 is some 45,000 years old. Discovered by Ralph S. Solecki of Columbia University and his colleagues, it was one of several Neanderthal specimens found at Shanidar. The remains of more than 300 other Neanderthals have been uncovered from Portugal to central Asia; the majority are in France (see "The Neanderthals," by Erik Trinkaus and William W. Howells, page 118).

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Cover painting by Enid Kotschnig

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These and other technological

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The look and feel of luxury, and a 41% improvement in EPA estimated miles per gallon over last year.

The 1980 Lincoln Continental Town Car
Automatic Overdrive Transmission Standard

The front seat has more headroom, hiproom and legroom than last year.

advances combine to produce a 41% improvement in EPA estimated miles per gallon over last year.

And a new automatic overdrive transmission helps improve highway fuel economy.

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Luxury in the Lincoln tradition, with very contemporary fuel efficiency.

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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 how fast you drive, weather conditions and trip length. Actual highway mileage will probably be less than the estimated highway fuel economy. California estimates and percentages are different.

†Based on EPA interior volume index.

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EATON

LETTERS

Sirs:

After reading Roberta J. M. Olson's "Giotto's Portrait of Halley's Comet" [SCIENTIFIC AMERICAN, May] I happened to reread Chapter 43 of Edward Gibbon's *The History of the Decline and Fall of the Roman Empire,* in which he discusses, among other things, a comet seen for 20 days in September of the fifth year of the reign of Justinian, A.D. 531. On the basis, he says, of investigations by Flamsteed, Cassini, Bernoulli, Newton and Halley he concludes that the comet had a period of 575 years, appearing in 1767 B.C., 1193 B.C., 618 B.C., 44 B.C., A.D. 531, A.D. 1106 and A.D. 1680 and due to reappear in A.D. 2355.

I remember reading somewhere, however, that Halley's Comet's period of 76 years is the longest period fully established by observation of one or more returns, and I wonder whether Justinian's comet of September, A.D. 531, could not have been the return of Halley's Comet in September, A.D. 530, listed in the table on page 165 of Professor Olson's article.

SAMUEL F. HOWARD, JR.

Brooklyn, N.Y.

Sirs:

There are several misconceptions in Gibbon's speculations concerning the comet said to have appeared "in the fifth year of Justinian's reign." In order for this to have been Halley's Comet some mistake must be found in Gibbon's dating to explain how A.D. 530 could have been the fifth year of the reign of a man said to have become emperor in A.D. 527. From what is known of the calendar available to Justinian (the Julian) and the one available to Gibbon (the Gregorian, as adopted in England just a few years before this study of his in 1752) it could be argued that an error of one year could have been made and that Justinian's comet was Halley's Comet (perihelion in September, A.D. 530).

As for Gibbon's other apparition dates for this comet (a long-period comet appearing once every 575 years), it is possible that such a comet exists but not on the evidence presented by Gibbon: myth, metaphor, folklore and other sources that do not meet today's standards. The idea of periodic comets was fresh in Gibbon's day, when the appearance of Halley's Comet in 1759 had ushered in a new, exacting era in cometology. Perhaps Gibbon in his enthusiasm sought to elevate the importance of Justinian's comet by contending that it was not only the comet said to have appeared at Caesar's death (44 B.C.) but also the great comet of 1680, which

terrified Europe. Incidentally, the 1680 comet occasioned a caustic exchange of letters between John Flamsteed, the first Astronomer Royal of England, and Isaac Newton. Although Newton incorrectly regarded the passage of the 1680 comet before and after perihelion as being two comets, the episode aroused his interest in these objects. The apparition of Halley's Comet two years later played an important part in the studies that led to *Principia Mathematica*.

Mr. Howard's letter points up the wide-open nature of comet dating. There has yet to appear a modern, informed chronological listing of cometary appearances throughout history that can be said to have eliminated such things as folklore, misdatings, meteors, auroras, novas and Newton's seeing two comets where there was only one. There is a current project to do just that, and it is described by D. J. Schove in "Comet Chronology, A.D. 200–1882," a paper published in *Journal of the British Astronomical Association* (Vol. 85, No. 5, pages 401–407; 1975). In any event there are several comets whose periods are longer than 575 years. One is Donati's Comet (with a period of 2,040 years), which appeared in 1858. Another is Humason's Comet (with a period of 2,900 years), which appeared in 1961.

ROBERTA J. M. OLSON

Wheaton College
Norton, Mass.

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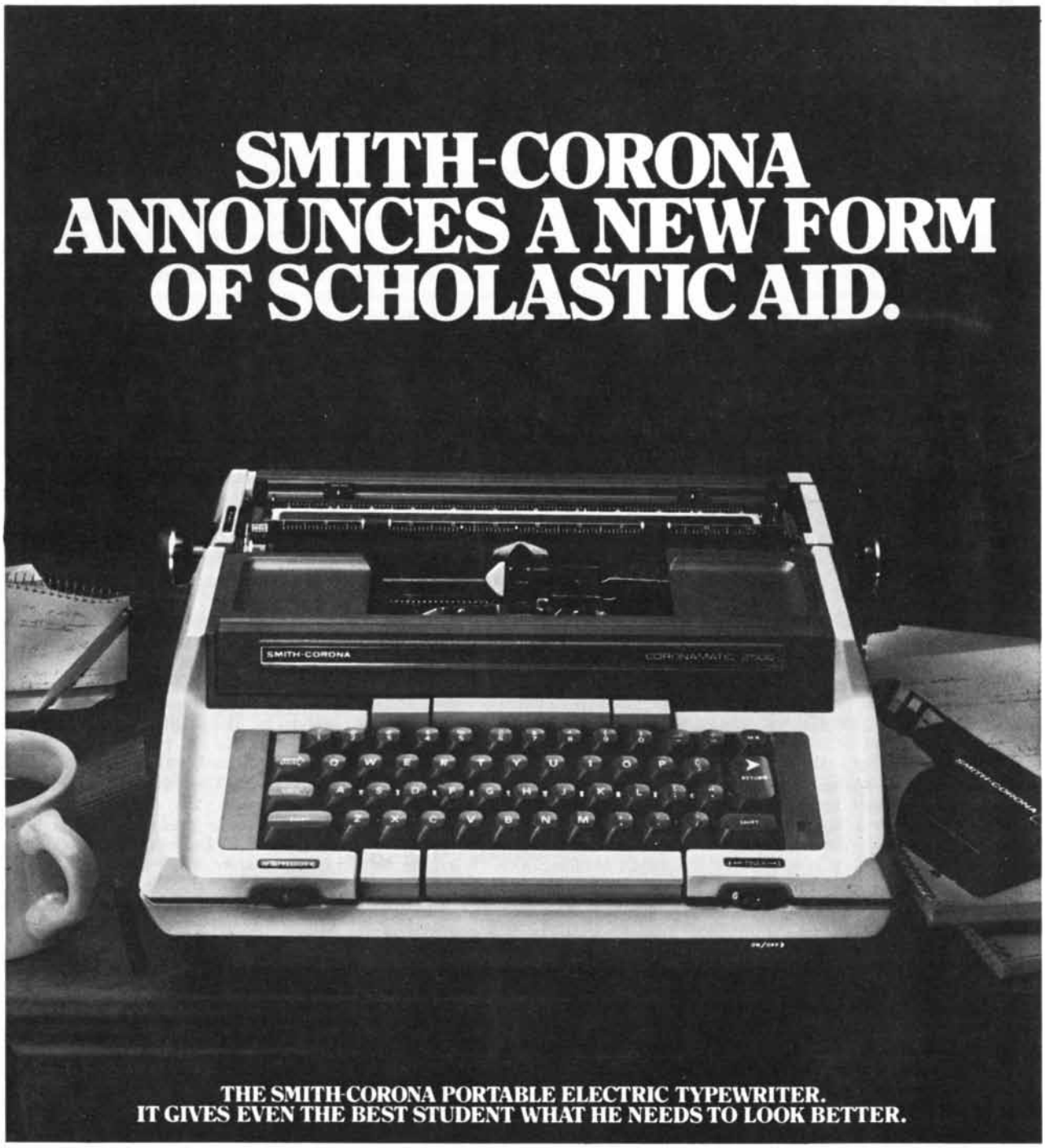

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SCIENTIFIC AMERICAN

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"Of all marine salvage feats no other will compare in magnitude with the raising of the scuttled German fleet from the bottom of Scapa Flow in the Orkneys. Mr. E. H. Cox bought 27 of the wrecks and has since raised 25. He grappled with the cruiser *Moltke* for more than a year and got her in the end. Then he tackled the battleship *Seydlitz,* and after a titanic struggle got her too. In November of last year he turned his attention to the overturned battleship *Kaiser,* which has now been raised to the surface after being filled with air."

"Flying over a section of Yucatán, Mexico, which is entirely blank on the maps, Colonel Lindbergh has discovered from the air and located on the map several hitherto unknown ancient Mayan cities. It is the first time archaeological flights have been made in this hemisphere, although Roman ruins have been found in England by the same modern method. While some 1,200 archaeologically important sites in Mexico are known, it is believed dozens, perhaps hundreds, more are hidden in the densely matted jungle. An expedition might pass within a few feet of important ruins and be unaware of their existence. From the air, however, the story is different. Columns and masonry stand out clearly, and where they are overgrown entirely, temple sites and even paved Mayan pathways may be patterned in the coloring or relative growth of the trees and other plants that cover them. On one flight it is reported that Colonel Lindbergh and his party, which included Dr. A. V. Kidder of the Carnegie Institution of Washington, found four ancient city sites and located them on the maps so that ground expeditions can cut their way directly to them."

"If you could rub Aladdin's lamp and be transported miraculously to the southern part of Europe as it was 50,000 years ago, you might get a glimpse of the Mousterian cave man, or Neanderthal man. In reconstructing his physical form anthropologists have studied more than 20 skeletons, some of them in excellent condition. From these it is possible to derive his posture with accuracy. The bent knees and short, thick neck, the large forward-inclined head and chunky body are as scientific as a fact in physics or chemistry, for the shape and angle of the contact surfaces at the joints provide the data, and similar measurable data are provided by other skeletal details. When we come to supplying the superficial features, however, we find greater difficulty, because there are no fossils of the fleshy parts. Some anthropologists have given Neanderthal man a fierce, wild aspect. Others have made him appear stupid. There is considerable reason to doubt whether in the main he was either. The evidences of his workmanship in flint show us he was a savage, but not all savages are fierce. These evidences also show that he possessed a fair intelligence. Let the reader attempt to fashion even such crude weapons as Mousterian man made and used and his respect for the 'rude cave man' will undergo a rapid rise."

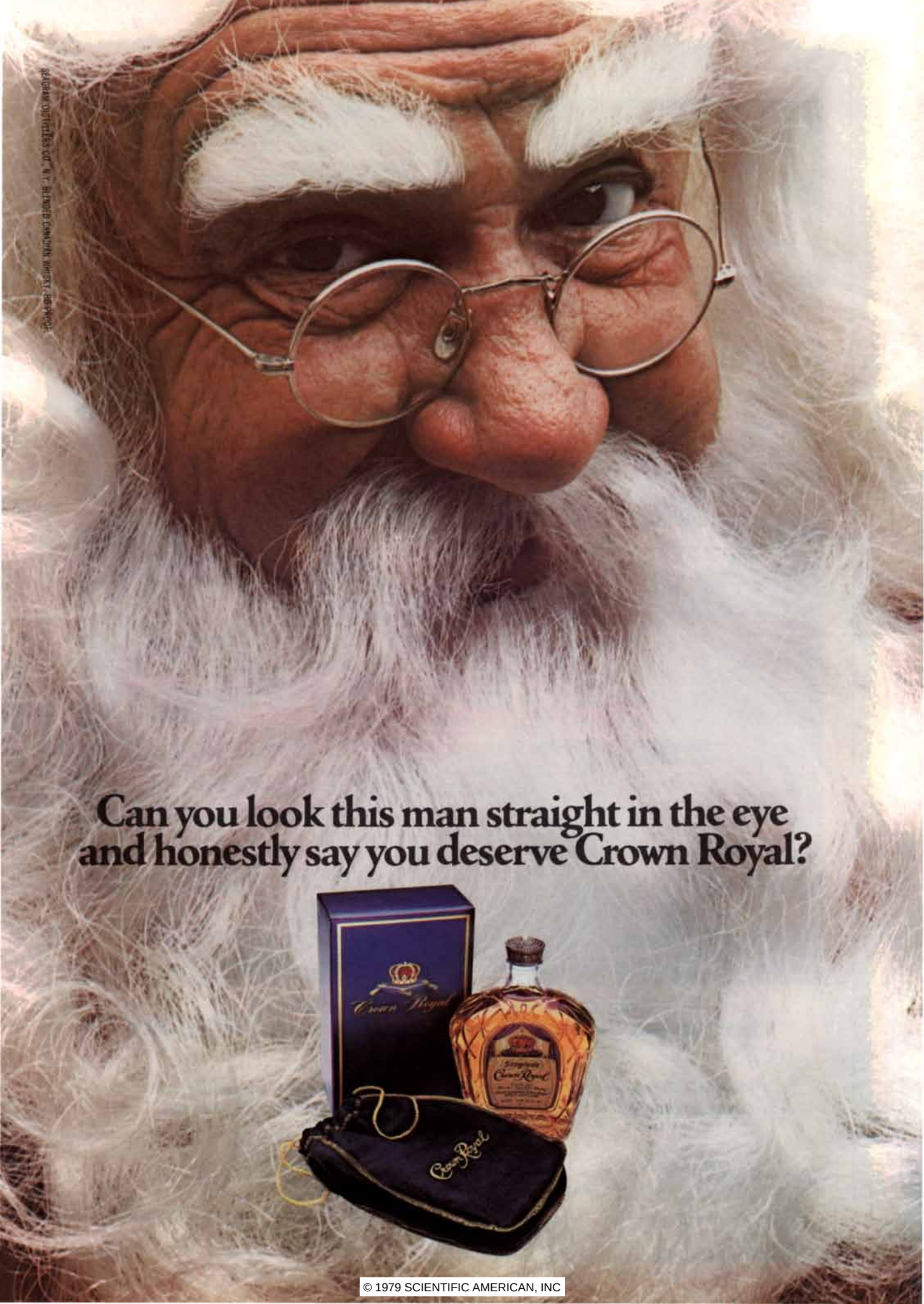
DECEMBER, 1879: "What the 18th and 19th centuries have done for America the 20th is likely to do for Africa. Civilization is attacking her ancient fastnesses from all sides. Europe is specially alive to the enormous capacities of the continent for trade. What with telegraphs along the coast, steamers and railways pushing inward along with steamship lines and traffic, the suppression of its external slave trade, the pluck and energy of scientific, missionary and commercial explorers and the great wealth of the national and international societies bent upon the early evangelizing of the African peoples and the commercial development of the enormous natural capacity of the country, we may reasonably expect in the near future an awakening of Africa as marvelous as anything the world has yet witnessed."

"A dispatch from California reports the discovery of uranium in the Sacramento mining district. This mineral is found in Bohemia, but never before has it been discovered in this country as far as is known. The present discovery was made by H. L. Rice. The ore runs 60 per cent. Uranium is worth $1,000 per ton. One of its principal uses is as a coloring substance in the manufacture of glass."

"Which is the most powerful telescope in existence? Everyone has heard of the two giant telescopes that were constructed nearly 40 years ago by the late Lord Rosse. The second of these telescopes has a metal speculum six feet in diameter and 54 feet in focal length. Experienced observers, however, know that the real power of a telescope can be ascertained only by a study of what it has done. Tried by this test, the giant telescope of Lord Rosse breaks down. It has not the accuracy of definition that constitutes the real power of a telescope. It is only in observing the dull, ill-defined nebulae that Lord Rosse's great telescope has any exceptional advantage. The most powerful telescope in existence is the magnificent new reflecting telescope that has just been finished by Mr. A. Ainslie Common and is erected at his residence at Ealing. This telescope has a silver-on-glass speculum 37½ inches in diameter and a focal length of just over 20 feet. When in 1877 the astronomical world was electrified by the announcement of Professor Asaph Hall's discovery of the two satellites of Mars, it was to Ealing that astronomers looked for systematic observations of these faint objects."

"The Chinese in California have begun to go. The steamer that sailed from San Francisco for Hong Kong on December 15 took 901 of them to their native land. The port statistics of San Francisco show that the arrivals of Chinese during the year ending November 1 were 6,128 and the departures were 8,746, of whom 6,229 went to China and 2,517 to Honolulu, the excess of departures over arrivals being 2,618. It is estimated that there are 62,000 Chinese on the Pacific coast, which shows that this population is decreasing instead of increasing, for when the anti-Chinese agitation was begun a few years ago, the estimate was 100,000."

"Like all the rest of American institutions, SCIENTIFIC AMERICAN closes the year with the most assuring prospects of prosperity in the year to come. The country has entered upon a period of successful activity that has made the past year profitable beyond precedent, and the coming year bids fair to surpass it in solid gains. Having taken possession of the vast and varied markets of our own land, our farmers, manufacturers and merchants are reaching out to the earth's remotest ends, with every prospect of retaining and increasing their hold upon the world's most profitable trade. With a circulation of 50,000 copies every week among the most intelligent and active men in the country SCIENTIFIC AMERICAN has a basis of permanent prosperity."



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THE AUTHORS

FRITZ R. KALHAMMER ("Energy-Storage Systems") is director of the Department of Energy Management and Utilization Technology at the Electric Power Research Institute (EPRI) in Palo Alto, Calif. A native of Bavaria, he studied at the University of Munich, where he obtained his bachelor's and master's degrees in physics and his Ph.D. in physical chemistry, the last in 1957. After a year as a staff scientist at Farbwerke Hoechst, the German chemical company, he emigrated to the U.S. in 1958. For three years he worked as a project scientist at the Philco Research and Development Center in Philadelphia and assisted in the development of photogalvanic cells and photoconductors. He then joined the southern California laboratories of the Stanford Research Institute as a senior physical chemist, and in 1969 he was transferred to its headquarters as manager of the electrochemistry program. Kalhammer went to EPRI in 1973 to manage the Electrochemical Energy Conversion and Storage Program; he was appointed to his present position in 1976.

PERRY J. BLACKSHEAR ("Implantable Drug-Delivery Systems") is clinical and research fellow in endocrinology at the Massachusetts General Hospital. He did his undergraduate work at the universities of Minnesota and Wisconsin and then spent three years as a Rhodes Scholar at Trinity College, Oxford, earning his D.Phil. in 1974. While he was a graduate student at Oxford he worked in the Metabolic Research Laboratory of the Radcliffe Infirmary. He returned to the U.S. to attend the Harvard Medical School and received his M.D. in 1977. After a residency in internal medicine at the Massachusetts General Hospital, Blackshear joined the staff of its Endocrine Unit.

E. M. DE ROBERTIS and J. B. GURDON ("Gene Transplantation and the Analysis of Development") are both on the staff of the Medical Research Council Laboratory of Molecular Biology in Cambridge, England. De Robertis obtained his M.D. at the University of Uruguay in 1971 and his Ph.D. in chemistry from the University of Buenos Aires in 1974. The following year he moved to Cambridge. In addition to his research De Robertis is currently devoting much of his time to revising a textbook of cell biology of which he is coauthor and which is published in English, Spanish and Italian. Gurdon was educated at Christ Church, Oxford, where he did his undergraduate work in zoology and received his D.Phil. in embryology in 1960. After fellowships at Oxford and at the California Institute of Technology he joined the Oxford faculty. He moved to the Laboratory of Molecular Biology in 1972.

JEROME A. FELDMAN ("Programming Languages") is professor and chairman of the computer science department at the University of Rochester. He obtained his bachelor's degree in physics at Rochester, his master's degree in mathematics at the University of Pittsburgh and his Ph.D. in mathematics and computer science from Carnegie-Mellon University in 1964. After working for a year as an assistant research scientist at Carnegie-Mellon he joined the staff of the Lincoln Laboratory of the Massachusetts Institute of Technology. In 1966 he moved to Stanford University, and in 1972 he was made associate director of the Stanford Artificial Intelligence Laboratory. He returned to Rochester in 1974. His research has focused on both artificial intelligence and programming languages and systems. Recently Feldman has been attempting to formulate a detailed theory of human memory consistent with known facts of biology, psychology and computation.

ERIK TRINKAUS and WILLIAM W. HOWELLS ("The Neanderthals") are physical anthropologists at Harvard University. Trinkaus, who is associate professor of anthropology, is primarily interested in fossil human remains from Europe and the Near East and more recent human skeletal material from coastal Peru. He did his undergraduate work at the University of Wisconsin and received his Ph.D. in 1975 from the University of Pennsylvania. Trinkaus writes: "There are enough Neanderthal remains to make possible the kind of functional anatomical studies that allow behavioral inferences. I hope that through such studies we shall not only be able to determine the sequence of events in later human evolution but also get a good idea as to why certain events took place." Howells is professor emeritus of anthropology at Harvard. He obtained his bachelor's degree at Harvard in 1930 and his Ph.D. in 1934. From 1939 to 1954 he was on the faculty of the University of Wisconsin; he returned to Harvard in 1954. Howells' research has combined the study of morphological variation in recent human populations with an interest in early hominids. The authors would like to thank J. K. Melentis of the University of Thessalonike, Yves Coppens of the Musée de l'Homme in Paris and B. Vandermeersch of the Rockefeller Museum in Jerusalem for access to specimens.

DAVID REGAN ("Electrical Responses Evoked from the Human Brain") is Killam Research Professor and director of the Centre for Research in Sensory Psychology and Medical Physics at Dalhousie University in Nova Scotia. A native of England, he obtained his Ph.D. from the Imperial College of Science and Technology in 1964 and his D.Sc. from the University of London in 1974. After teaching physics in London for a few years, he worked in the department of communication at the University of Keele in England. He moved to Canada in 1976. Regan's major research interests are the application of visual and auditory psychophysics to the diagnosis and management of brain damage and to the piloting of aircraft.

LEWIS P. FULCHER, JOHANN RAFELSKI and ABRAHAM KLEIN ("The Decay of the Vacuum") are theoretical physicists working at the interface between relativity theory and quantum mechanics. Fulcher is associate professor of physics at Bowling Green State University in Ohio. He did his undergraduate work at the Virginia Polytechnic Institute and State University and received his Ph.D. from the University of Virginia in 1969. After postdoctoral work at the University of Frankfurt and the University of Maryland, Fulcher joined the faculty at Bowling Green. Rafelski is a fellow of the European Organization for Nuclear Research (CERN) in Geneva. Born in Poland but of German nationality, he studied physics and mathematics at the J. W. von Goethe University in Frankfurt, obtaining his Ph.D. in 1973. After working at the University of Pennsylvania, Rafelski joined the staff of the Argonne National Laboratory; he moved to CERN in 1977. Klein is professor of physics at the University of Pennsylvania. He received his Ph.D. in theoretical physics from Harvard University in 1950 and after five years on the Harvard faculty moved to Pennsylvania. In the summer of 1971 Klein visited the University of Frankfurt, where he met his coauthors for the first time.

LAURENCE R. KITTLEMAN ("Tephra") is a practicing geologist in Eugene, Ore., and adjunct associate professor of geology at Southern Oregon State College in Ashland. He received his B.S. at Colorado College, his M.S. at the University of Colorado and his Ph.D. from the University of Oregon in 1962, all in geology. He worked for a time as a geologist for the U.S. Atomic Energy Commission, and in 1962 he joined the faculty of the Museum of Natural History at the University of Oregon, serving as curator of geology until 1977. He has done research on Upper Cenozoic volcanic rocks in Oregon and on the stratigraphy and petrology of volcanic rocks. Kittleman is also interested in the geology of prehistoric human habitations.

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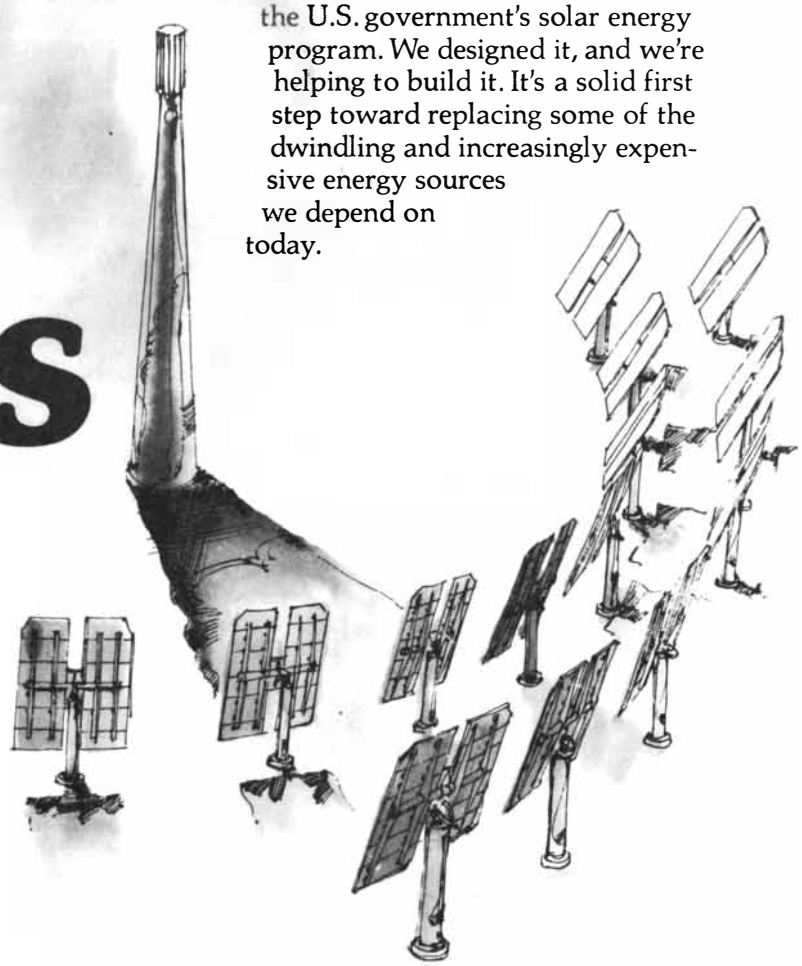

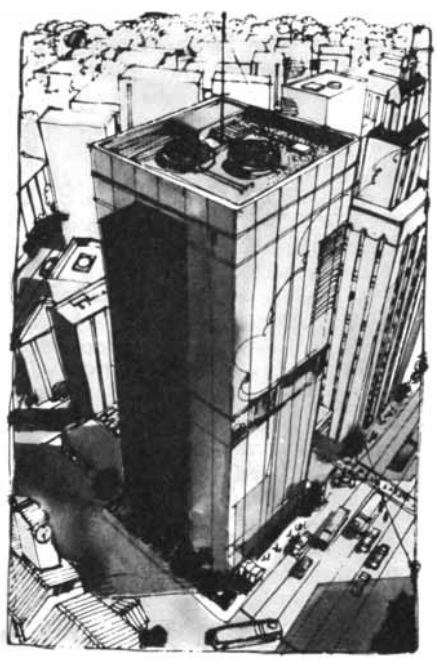

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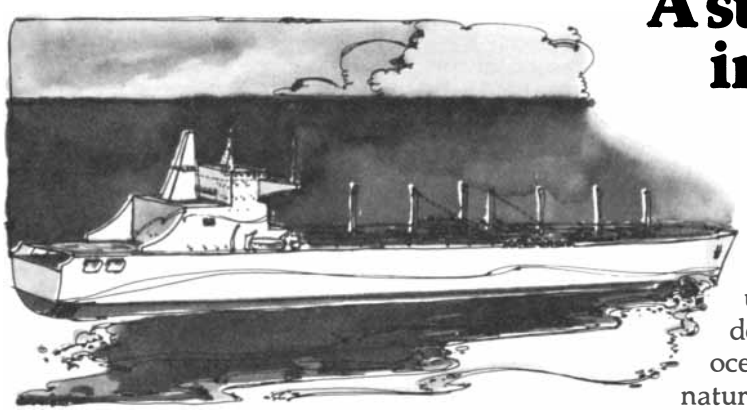

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MATHEMATICAL GAMES

A pride of problems, including one that is virtually impossible

by Martin Gardner

It is hoped that the following unrelated short problems will be new and challenging to most readers. Problem No. 1 is so difficult, with a solution that would take up an inordinate amount of space next month, that it is answered at the end of the column. Readers who relish a tough challenge are urged to work on the problem before they read the solution. If there is a simpler solution to the problem than the one given, I should like to know about it. The other problems will be answered at the end of next month's column.

1. The Impossible Problem. This beautiful problem, which I call "impossible" because it seems to lack sufficient information for a solution, began making the rounds of mathematics meetings a year or so ago. I do not know its origin. Mel Stover of Winnipeg was the first to call it to my attention.

Two numbers (not necessarily different) are chosen from the range of positive integers greater than 1 and not greater than 20. Only the sum of the two numbers is given to mathematician *S*. Only the product of the two is given to mathematician *P*.

On the telephone *S* says to *P*: "I see no way you can determine my sum."

An hour later *P* calls back to say: "I know your sum."

Later *S* calls *P* again to report: "Now I know your product."

What are the two numbers?

To simplify the problem, I have given it here with an upper bound of 20 for each of the two numbers. This means that the sum cannot be greater than 40 or the product greater than 400. If you succeed in finding the unique solution, you will see how easily the problem can be extended by raising the upper bound. Surprisingly, if the bound is raised to 100, the answer remains the same. Stover tells me that a computer program in Israel checked on all numbers up to two million without finding a second solution. It may be possible to prove that the solution is unique even if there is no upper bound whatever.

2. Poker Puzzle. As every poker player knows, a straight flush [*card hand at left in illustration below*] beats four of a kind [*card hand at right*].

How many different straight flushes are there? In each suit a straight flush can start with an ace, a deuce or any other card up to a 10 (the ace may rank either high or low), making 10 possibilities in all. Since there are four suits, there are four times 10, or 40, different hands that are straight flushes.

How many different four-of-a-kind hands are there? There are only 13. If there are 13 four-of-a-kind hands and 40 straight flushes, why does a straight flush beat four of a kind?

3. The Indian Chess Mystery. Raymond M. Smullyan's long-awaited collection of chess problems has been published by Knopf with the title *The Chess Mysteries of Sherlock Holmes*. Just as there has never been a book of logic puzzles quite like Smullyan's *What Is the Name of This Book?* (reviewed in this department in March, 1978, and now available in paperback), so there has never been a book of chess problems as brilliant, original, funny and profound as this one.

Although a knowledge of chess rules is necessary, as Smullyan says in his introduction the problems in the book actually lie on the borderline between chess and logic. Most chess problems deal with the future, such as how can White move and mate in three. Smullyan's problems belong to a field known as retrograde analysis (retro analysis for short), in which it is necessary to reconstruct the past. This can be done only by careful deductive reasoning, by applying what Smullyan calls "chess logic."

Sherlock Holmes would have had a passion for such problems, and his enthusiasm would surely have aroused the interest of Dr. Watson, particularly after Watson had learned from Holmes some of the rudiments of chess logic. Each problem in Smullyan's book is at the center of a Sherlockian pastiche narrated by Watson in his familiar style. Some of the problems are so singular that it is difficult to believe they have answers. In one, for example, Holmes proves that White has a mate in two but that it is not possible to show the actual mate. In another problem Holmes shows that in the days when chess rules allowed a promoted pawn to be replaced by a piece of the opposite color, a position could arise in which it is impossible to decide if castling is legal even when all the preceding moves are known.

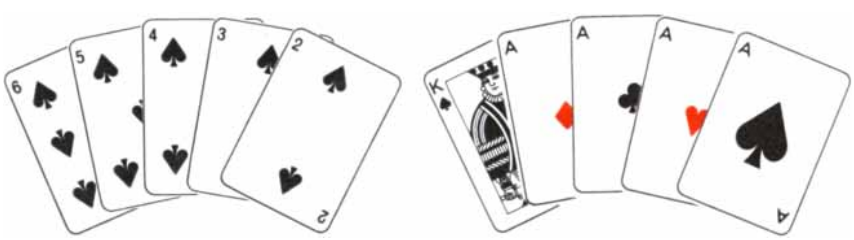
In the second half of the book Holmes and Watson set sail for an island in the East Indies where they hope to find a buried treasure by combining cryptography with retrograde chess analysis. Their first adventure takes place on the ship. Two men from India have been playing a game with pieces that are colored red and green instead of the usual black and white or black and red.

The players have temporarily abandoned the game to stroll around the deck when Holmes and Watson arrive on the scene. The position of the game is shown in the illustration on page 27. Several chess enthusiasts are studying the position and trying to decide which color corresponds to white, that is, which side had made the first move.

"Gentlemen," says Holmes, "it turns out to be quite unnecessary to guess about the matter. It is *deducible* which color corresponds to White."

In retro-chess problems it is not required that one side or the other play good chess, only that they make legal moves. Your task is to decide which color moved first and prove it by ironclad logic.

4. Redistribution in Oilaria. "Redistributive justice" is a phrase much heard these days in arguments among political philosophers. Should the ideal modern industrial state tax the rich for the purpose of redistributing wealth to the poor? Yes, says Harvard philosopher John Rawls in his influential book *The Theory of Justice*. No, says his colleague (they have adjoining offices) Robert



Why does a straight flush beat four of a kind?

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Nozick in his controversial defense of extreme libertarianism, *Anarchism, State and Utopia*. It is hard to imagine how two respected political theorists, both believing in democracy and free enterprise, could hold such opposing views on the desirable powers of government.

The Sheik of Oilaria, in this problem devised by Walter Penney of Greenbelt, Md., has never heard of Rawls or Nozick, but he has proposed the following share-the-wealth program for his sheikdom. The population is divided into five economic classes. Class 1 is the poorest, class 2 is the next-poorest and so on to class 5, which is the richest. The plan is to average the wealth by pairs, starting with classes 1 and 2, then 2 and 3, then 3 and 4 and finally 4 and 5. Averaging means that the total wealth of the two classes is redistributed evenly to everyone in the two classes.

The Sheik's Grand Vizier approves the plan but suggests that averaging begin with the two richest classes, then proceed down the scale instead of up.

Which plan would the poorest class prefer? Which would the richest class prefer?

5. Fifty Miles per Hour. A train goes 500 miles along a straight track, completing the trip with an average speed of exactly 50 miles per hour. It travels, however, at different speeds along the way, making numerous stops, even at times backing up. It seems plausible that nowhere along the 500 miles of track is there a segment of 50 miles that the train traverses in precisely one hour.

Prove that this is not the case.

6. A Counter-Jump "Aha!" Draw a five-by-six array of spots on a sheet of paper, then rule a line as is shown in the top illustration on page 30 to divide the array into two triangular halves of 15 spots each. On the spots above the line [*shown shaded*] place 15 pennies or any other kind of small object.

The task is to move all the pennies from above the line to the spots below the line. Each move is a jump of one counter over an adjacent counter to an unoccupied spot immediately beyond it on the other side. Jumps may be to the left or the right and up or down but not diagonal. For example, as a first move the penny at the fourth spot on the top row may jump to the top unshaded spot, or it may jump down to the third spot from the top of its column. All the jumps are like the jumps in checkers except that they are confined to horizontal and vertical directions and the jumped pieces are not removed.

We are not concerned with transferring the pennies to the unshaded spots in a minimum number of moves, only with whether the transfer can be made at all. There are three questions:

A. Can the task be accomplished?

B. If a penny is removed from a shaded spot, can the 14 pennies that remain be jumped to unshaded spots?

C. If two pennies are removed from shaded spots, can the remaining 13 be jumped to unshaded spots?

This new problem was devised recently by Mark Wegman of the Thomas J. Watson Research Center of the International Business Machines Corporation. It is of special interest because all three questions can be answered quickly by an "Aha!" insight well within the grasp of a 10-year-old.

7. Toroidal Paradox. Two topologists were discussing at lunch the two linked surfaces shown at the left in the bottom illustration on page 30, which one of them had drawn on a paper napkin. You must not think of these objects as solids, like ropes or solid rubber rings. They are the surfaces of toruses, one surface of genus 1 (one hole), the other of genus 2 (two holes).

Thinking in the mode of "rubber-sheet geometry," assume that the surfaces in the illustration can be stretched or shrunk in any desired way provided there is no tearing or sticking together of separate parts. Can the two-hole torus be deformed so that one hole becomes unlinked as is shown at the right in the illustration?

Topologist *X* offers the following impossibility proof. Paint a ring on each torus as is shown by the colored lines. At the left the rings are linked. At the right they are unlinked.

"You will agree," says *X*, "that it is impossible by continuous deformation to unlink two linked rings embedded in three-dimensional space. It therefore follows that the transformation is impossible."

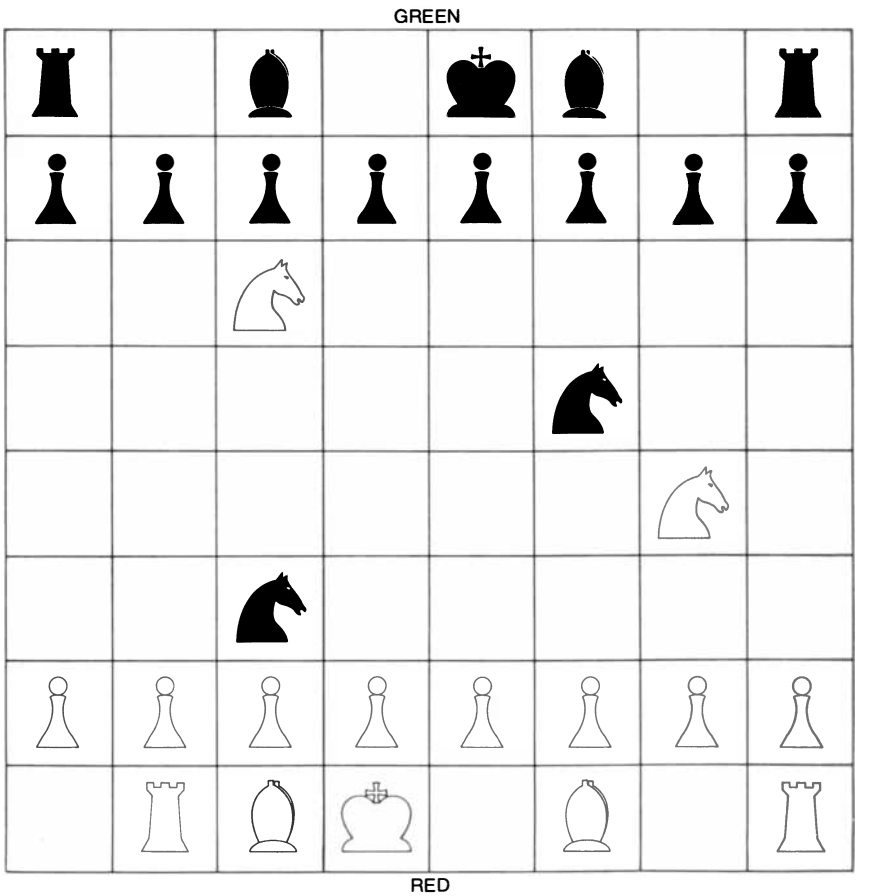
"But it doesn't follow at all," says *Y*.

Who is right? I am indebted to Herbert Taylor for discovering and sending this mystifying problem.

The solution to problem No. 1, the "impossible" problem, is as follows. The two numbers are 4 and 13, easy to remember because a deck of cards has four suits each with 13 values. Thus *S*'s sum is 17 and *P*'s product is 52. Here is one solution procedure.

After *S* said "I see no way you can determine my sum," *P* quickly realized that the sum cannot be a sum of two primes. To understand why, suppose the sum is 14. *S* would reason as follows: "Perhaps the two numbers are the primes 3 and 11. Since their product, 33, has only the one pair of factors 3 and 11 (the factors 1 and 33 can be ignored because each number must be greater than 1), *P* would know at once that my sum is 3 plus 11, or 14." Therefore when *S* says *P* cannot know his sum, that tells *P* the sum cannot be the sum of two primes.

There is a famous conjecture in number theory called Goldbach's conjecture, which states that every even num-



Which color moved first?

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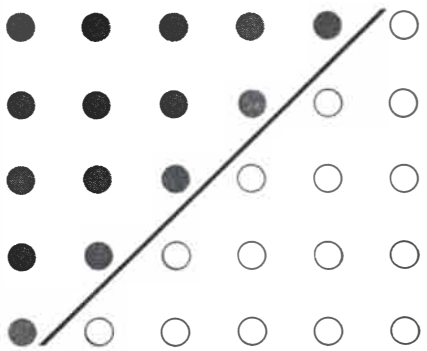


An "Aha!" problem

ber is the sum of two primes. This has not been proved in general, but it has been established for all even numbers up to 100 million, so that one can safely eliminate all even sums within the given range of 4 through 40. We can do more. Since 2 is a prime, one also can eliminate all odd sums that are a prime plus 2. After making these eliminations one is left with seven possible sums: 11, 17, 23, 27, 29, 35 and 37. These are the only odd numbers within the range that are sums of a composite number plus 2.

Could the sum be 11? No. If *P*'s product were 24, he would immediately conclude the numbers were 3 and 8, since only those factors of 24 have a sum, namely 11, that is among the seven numbers that are possible. On the other hand, if *P*'s product were 28, he would also know the sum was 11, because only the factors 4 and 7 add up to a number on the list. *S* would then not be able to make his final statement that he knows *P*'s product because he would have no way of deciding between the products 24 and 28. As a result 11 is eliminated as a possible sum.

Could the sum be 23? No. *S*, unable to decide between $4 + 19$ and $16 + 7$, both of which add up to 23, would not know whether the product was 76 or 112. In the same way 27 is eliminated by $4 + 23 = 8 + 19 = 16 + 11 = 27$; 29 is eliminated by $16 + 13 = 4 + 25 = 29$; 35 is eliminated by $4 + 31 = 16 + 19 = 35$, and 37 is eliminated by $8 + 29 = 32 + 5 = 37$. There is only one possible sum left: 17.

Seven possible pairs of numbers add up to 17, as follows:

$2 + 15$. The product 30 could be taken by *P* as being the product of 5×6, and since this adds up to 11, a possible sum, *P* would not be able to decide which sum was correct, 17 or 11.

$3 + 14$. The product 42 could be taken by *P* as being 2×21. This adds up to 23, another possible sum, creating the same ambiguity as before.

$5 + 12$. The product 60 could be 3×20, which has the possible sum of 23.

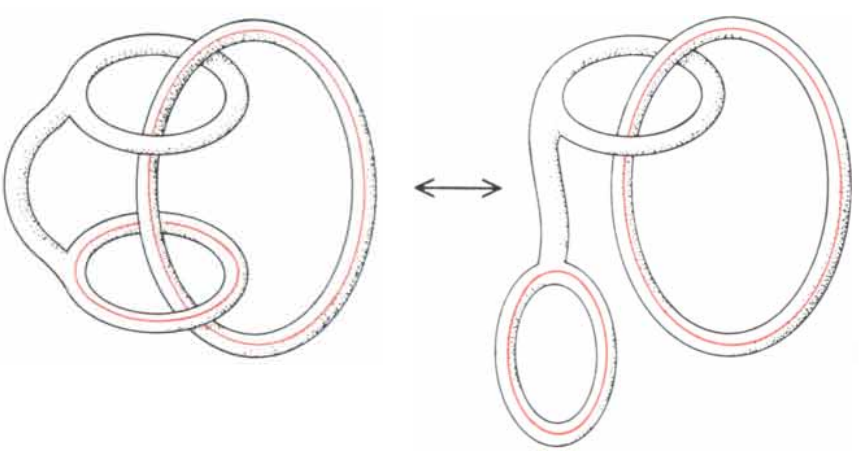
$6 + 11$. The product 66 could be 2×33, which has the possible sum of 35.

$7 + 10$. The product 70 could be 2×35, which has the possible sum of 37.

$8 + 9$. The product 72 could be 3×24, which has the possible sum of 27.

Only one pair of numbers remains, $4 + 13$. The product 52 has only one other pair of factors, 2×26, and they add up to 28, which is not a possible sum. Therefore only if the numbers were 4 and 13 would *P* know for certain that *S*'s sum is 17. From the fact that *P* knew this sum *S* could then deduce that *P*'s product is $4 \times 13 = 52$. Any other pair of numbers has ambiguities that do not allow both *S* and *P* to know the numbers. Since ambiguity increases as numbers get larger, it is reasonable to conjecture that there may be no other solution even when the upper bound is removed.

For readers who may want to prove that this result also holds when the bound is raised to 100, I shall add that the higher possible sums are 41, 47, 51 and 53. If the bound is raised still higher, computer programs seem necessary to rule out other solutions. I would be interested in hearing from anyone who knows the origin of this remarkable problem, or whether anyone has shown that the answer is unique when there is no upper limit to the two numbers.



Herbert Taylor's toroidal paradox

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BOOKS

An annual Christmas survey of books for younger readers

by Philip and Phylis Morrison

The steady increase in the number of worthwhile books about science for younger readers continues. We are both pleased and rueful that there are so many we could not cover more of them.

Animal and Plant

DINOSAURS, by David Lambert. Illustrations in color. Crown Publishers, Inc. ($10). ARCHOSAURIA: A NEW LOOK AT THE OLD DINOSAUR, by John C. McLoughlin. Illustrations by the author in black and white. The Viking Press ($10.95). The giant brontosaur and its sauropod kind fill a canonical niche in our visions: the heavy beasts float or lumber slowly on the oozy swamp bottom, buoyed up by the waters, their long necks holding their tiny air-breathing heads high above the surface. Their peg teeth were not very good for cropping or grinding tough grass; they seem to have had outsize gizzard stones. Recent finds and new thought have changed this picture radically. These up-to-date books on the dinosaurs concur. There is a new sauropod abroad in the Jurassic landscape. A group of them plod heavily on the dry land of the forest, towering conifers and cycads all around. Like the giraffe of the modern world, but heavier and as gregarious as the elephants of today, the beasts surround their young ones, holding high long necks to browse on the needles of the ever higher branches of the Mesozoic trees, ancestors of the sequoia. The animals' tails do not drag; they too are held high. The neck is "a living crane," flexible, strong, articulated, light-boned, its ligaments artfully spanning the joints. Alert upland herds have replaced the mired beasts of not so long ago.

These two excellent books bring us a valuable look at the new dinosaur. *Dinosaurs* is a fine example of the familiar encyclopedic treatment: maps, species names, skeletal diagrams, carefully painted color reconstructions everywhere, nature red in tooth and claw. The work is a British corporate production, created by a group of artists and designers, including the simple and informative text, and issued by Italian color printers. The endpapers bear a marvelous color photograph of a crowd of fossil ammonites, the frontispiece is a color shot of the Grand Canyon in full glory. We see expeditions at work, simple family trees and some modern habitats of relevance. The big paintings of reconstruction scenes dominate the pages, and most satisfyingly. The text is not mere scissors work; as the sauropod story shows, it is aware of the changes new data and new conjecture are making of our old dinosaur friends.

Archosauria is very much a one-man product. Its author is a feisty and talented writer/artist, and all the figures are his work, pen-and-ink drawings in a variety of techniques that bring the reader dinosaurs in a definitely revisionist mode. The "great fossil lizard," slothful, low-bellied and dumb, is replaced by a somehow warm-blooded beast, more birdlike than lizardly. That great old brainy predator is no "hulking tripodal lizard," impeded by a heavy dragging tail, but a "bright-eyed, five-meter-tall, eaglelike tyrannosaur... hunting his prey in packs,... quite a problem, even to the handsomest and most machismo-rich movie hero."

McLoughlin is most useful for good readers, eager to follow argument and conjecture, who can absorb the detail. Anyone can gain from his careful drawings showing the progress of comparative reconstructions, in all of which, including his own, there remains a considerable element of uncertainty. Numbers have not yet entered the texts; how far the dinosaur should be revised is not yet clear. At least the creature is not static; the dinosaur of these books is not the same beast you grew up with.

How did dinosaurs end? Worldwide climate change, both books have it. Lambert sees a cold climate alone as being enough; not many of the beasts, even if they were warm-blooded, were furry or could burrow. McLoughlin thinks they would have beaten the cold; some insufficiency in the plant basis of their life is what he reckons, with the sun dimmed by dust and the bigger forms in decline everywhere.

THE PUMPKIN PEOPLE, by David Cavagnaro and Maggie Cavagnaro. Sierra Club Books/Charles Scribner's Sons ($8.95). THE GOURD BOOK, by Charles B. Heiser, Jr. Illustrated in color and in black and white. University of Oklahoma Press ($14.95). It begins with a seed planted in the family garden. Pointed end down, the big white seed would grow into a handsome orange pumpkin there by Bolinas Lagoon. They planted many more related seeds, to yield squashes and gourds of every size, color and shape. At harvesttime friends came by, and the diverse jacks were carved with faces, fitted with candles lighted under the crescent moon and grew to glowing life. "Lined up in front of us were congressmen, actors, generals, workers and poets.... We looked at the squash people and saw ourselves." The faces ended on the compost heap, and by the time of the winter rains to "congressmen and actors, generals, workers and poets, one and all, old age had come at last." Just as it began with a seed, so it ends with one. A vigorous sprout came from "the eye of one... old sage" to promise a new adventure in the cycle of life. The simple, lyric text and the color photographs as luminous as jack-o'-lanterns offer delight to early readers in a small work with a sense of depth and beauty.

The Gourd Book is an agreeable, modest foray into ethnobotany. Meant for the general reader, it is certainly rewarding for readers of high school age. The author is a botanist at Indiana University; his botany is catholic and critical. His offerings of history and folklore are wide-ranging and full of interest, but they dig perhaps less deeply into primary sources and appropriate interpretations than professionals might expect. He opens a wide and curiously winding path to the appreciation of the interaction of human beings and the hard-shelled hollow gourds, an old symbiosis indeed. True gourds include the tree gourd (*Crescentia cujete*), whose huge pumpkinlike fruits hanging high on a tree are sure to startle the newcomer to the Tropics, and the bottle gourd, a cucurbit vine cultivated in great variety in our latitudes, as it is worldwide. We learn the facts of cucurbit life, the two sexes of the flowers, the unstable mutants that give the curious color patterns of the fruit and a good deal more. The big tree gourd, the calabash, is a post-Columbian migrant from tropical America to the Tropics everywhere.

The African bottle gourd was an authentic domesticate on both sides of the Atlantic long before Columbus, but the form is not old enough to predate the continental drift that opened the Atlantic. Like most modern students, Professor Heiser favors the natural dispersion of the gourd over human agency; the fruit floats, is self-seeding and prospers as a weed in places disturbed by human habitation. Made from the gourds are cups and pots, floats and storage jars, pipes and snuffboxes, the remark-

able New Guinea penis sheaths, cricket cages, masks, lutes, rattles and the noble sitar. Decoration of the gourd anciently reached the level of fine art, and the gourd plays no small part in myth and legend. All of this is shown in word and picture, with a good list of references, and the author (who is no mean raiser of bottle gourds himself) offers a few pages on their culture, including how to grow a gourd with a knot in its long neck. The other plants called gourds are also treated, particularly the loofah, the vegetable sponge. Gourd craft is outside the scope of the work, but contact is offered with the American Gourd Society. This lighthearted book is a fine start toward braving the sea of plant and social science that is today's ethnobotany.

FISHING FOR SUNFISH, by Robert Bartram. J. B. Lippincott Company ($6.95). PACIFIC SALMON & STEELHEAD TROUT, by R. J. Childerhose and Marj Trim. Color photographs by Marj Trim, paintings by Harry Heine, drawings and maps by Joey Morgan. University of Washington Press ($25.95). Human beings have pulled up finny fish as prey for a very long time. The least of the fisheries for sport and food is that of the little sunnies, fishes no bigger than a small person's hand. Invariant are a long pole, a bobber light on the water, a shaded weed bed near the shore, a boy or girl still and expectant at one end of a line and one of the eight species of panfish cruising warily near the baited end. Many readers will remember summer hours passed long ago in just that way. Pumpkinseed or bluegill, these little freshwater fishes are found in every state of the contiguous 48. This small book of watercolors and clear text embodies the entire craft in written form, a sure prop for the usual folk tradition passed from the expert 12-year-old to the novice. It is all here save the experience: from hook, line and sinker to bait, dislodging, cleaning, cooking and eating. Barbless hooks are not forgotten, but sunfish multiply rapidly, and at the right spot you can catch a family dinner; in many states there is no limit on sunnies except the end of summer. The drawings distinguishing the eight species would have been helped by the color detail found on some other pages.

Among the greatest of all fisheries is that of the Pacific salmon. Five salmon species and their cousin the steelhead trout forage in the cold, rich seas from the Aleutians to California. The sockeyes still leap the falls and press up the coastal rivers to spawn along the sunlit rocks of the icy streams. Once "shimmering hordes of salmon thrashed their way upstream" in nearly every coastal river from California to Alaska. Once the wealthy tribes of the Northwest proudly called themselves the Salmon People. Then a new people came, powerful and careless. The run is ruined

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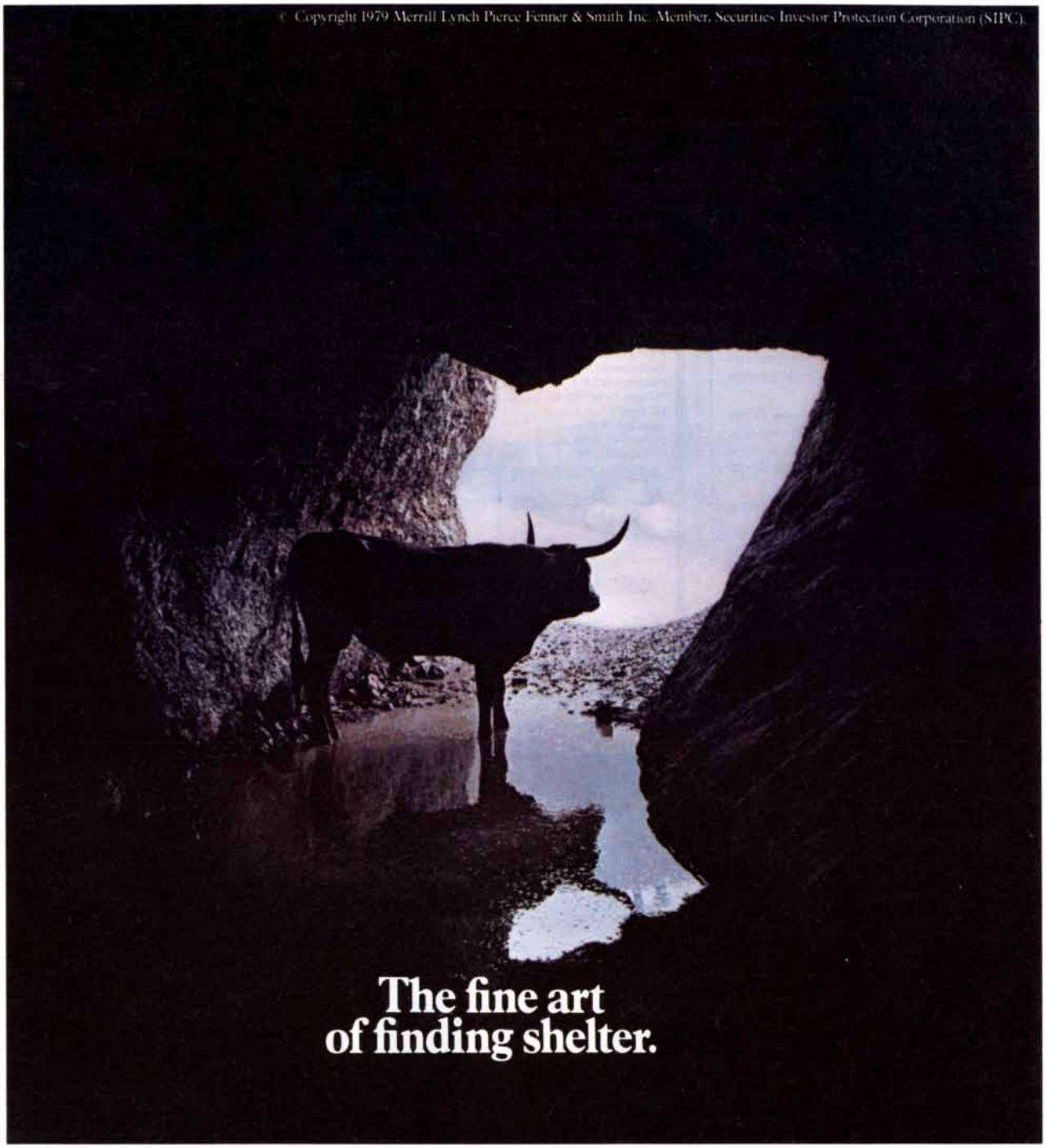
now along the Sacramento, the Rogue, the Columbia. Placer mining and power dams are intolerant of salmon. Across the border with Canada there were fewer people and more time for goals to change; the run remains at about half its old size in the Fraser and the Adams.

This substantial and beautiful volume celebrates the trust now held for the world by the scientific managers and the policymakers of the government of Canada and the province of British Columbia. The book is Canadian: its text, full of detail but never technical, the vivid color photographs (by Marj Trim) that evoke the sea, the land and the creatures of the region, the careful paintings of the salmon in their changing garb and form, the drawings and maps and the making of the book itself. Its story is the fishery and its management, today a complex and precarious enterprise with a wide-flung net of schemes and campaigns. Fishways and hatcheries and protection of the watershed are only the most familiar elements. Across the clear upstream lakes the low-flying DC-6's have all summer been spreading commercial fertilizer to nourish plankton for the little sockeye, as the patient farmers of Canton nourish their farm ponds. The ponds of the sockeye smolt, however, are wild mountain lakes 500 feet deep and 30 miles long. The scheme is working so far, and the sockeye are counted there in the million. When the run was greater, the carcasses of the spawned-out salmon themselves nitrified the lake. A small run begins a vicious circle of decline, one that can perhaps be broken.

Comprehensive, although lacking an index, this book should fascinate young good readers in any classroom or library where the look of river and mountain world is prized, the interaction of living species is held important or the ocean shores of the great Northwest are known. It was meant for the general reader, not at all as a children's book; it stands as a work rich and serious enough to matter to children. The last page offers as afterword the eloquence of Chief Seathl of the Duwamish tribe in Washington, written as a letter to President Pierce ending, "All things are connected. Whatever befalls the earth befalls the sons of the earth."

Biology in General

WILD HABITATS, by Aleta Karstad. Watercolors and pen-and-ink drawings by the author. Charles Scribner's Sons ($12.95). Some travelers ride for days along the rails, looking out at the changing landscape as it slides by. The railroad embankment is itself a narrow strip of particular landscape, much the same as the miles pass. On foot you pace the ties, or trudge alongside, each step a crunch of the gravel, the narrow, unvarying land form stretching far



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into the distance. Here is the domain of weeds, able to grow in the gravel's quick drainage. Often the first occupation of a newly arrived plant immigrant is such an embankment; on the prairies the undisturbed strip offers a refuge to the native grasses, elsewhere long displaced by crops and their followers. The roadbed is high and dry, be it swamp or stream outside the right-of-way, and it supports its own populations. The roadbed gravel often includes some limestone, even far from limestone country. Snails can always be found there, where they can acquire calcium for their shell. Particularly common is one big bright yellow and brown European species, *Cepaea,* its moist body pulled back into its shell, asleep, fastened to some dry surface by the thin membrane it secretes. Are snails, like weed seeds, spread by the trains?

The author, a perceptive young naturalist and scientific illustrator now living in Ottawa, traveled across Canada from coast to coast, covering mountains, prairies, beaches, bog and tundra, the bare rocks of the Canadian shield and a spreading wheat farm, and getting one close look at the Pacific madroña tree in flower. Everywhere she looked, drew, painted and reflected on the natural history of what she saw. Twenty-five habitats, none given more than a few tightly written pages, all embellished and informed by a variety of sketches and watercolors, make up the book. It is a blend of leisurely strolls and careful little catalogues, of quick perception and longer reflection. In a compact volume she has packed a world of knowing experience, enlivened with personal delight and backed by an informed and modern natural history.

CRICKET IN THE GRASS, by Philip Van Soelen. Ink drawings by the author. Sierra Club Books/Charles Scribner's Sons ($9.95). The tawny Sonoma hills are recognizable in the full-page simple drawing, viewed as if from a great height looking to the open sea. Overleaf another drawing brings the reader closer to the grasslands, where a live oak stands. On the following page the oak is close, with a log nearby as well. Next the oak fills the page, then only its burled trunk. Then down in the grass is a big cricket. Draw back and a toad is nearby. Its tongue darts out to snare the cricket. The toad looks satisfied. A garter snake dramatically seizes the toad. At last there is only a lump in the gullet of the snake, which appears to smile. The snake glides off, but wait: a pair of talons fill the picture. The struggle is brief. The hawk flies off with its prey. As the hawk disappears a feather floats down. There is not a word on any page. Four more picture stories, all loosely connected little dramas of the living things in a marsh, a stream, an old log and so on, complete the book, one that even non-

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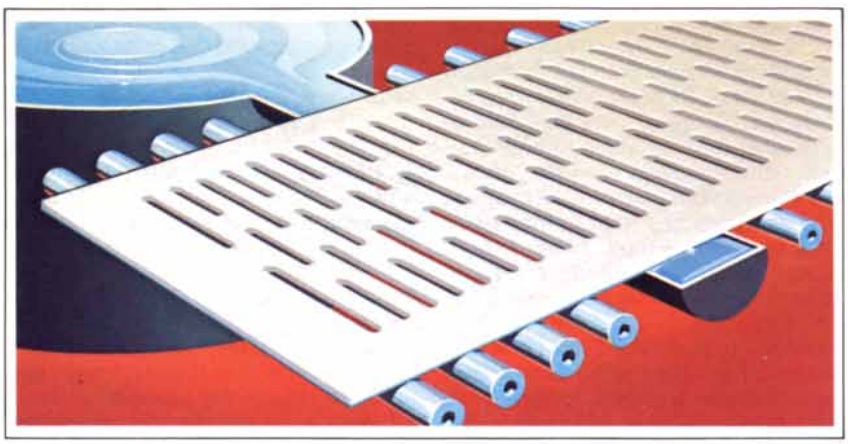

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readers might enjoy. A final text offers a few pages about each of the habitats, with a few lines in simple language about the food and shelter, for example of the cricket. A fisherman floating in his boat just off the salt marsh brings our own species of animal into this unusual work for early readers, open, clear, with a straight look at the facts of predation.

ANIMAL DEFENSES, edited by Charles Osborne. Illustrated with photographs and paintings in color. Time-Life Films, Inc., 100 Eisenhower Drive, Paramus, N.J. 07652 ($8.95). THE HUNTERS, by Philip Whitfield. Illustrated with drawings in black and white by Richard Orr. Simon and Schuster ($14.95). The expectation is that a textbook will be read, the entire thing, page by page. The skill of using a book as a tool, dipping into it, savoring only a part of it at will, is one children need. Happy readers will concede that no really useful book of reference is always so purposefully used. The art of browsing prospers. That art too is worth time in school and out of it. Indeed, browsing is best of all in a book whose structure is less arbitrary and inclusive than that of the alphabet, a book formed on a conception so rich that a single visit cannot exhaust it. Such a book always has surprise built into it, because even an experienced reader cannot quite remember all that is included in its general theme.

Here are two such books, although they are quite different. (They are by chance not unrelated in theme.) *Animal Defenses* is one of the corporate series of the well-known publishers, this one television-tinged, although mainly in the design of the endpapers. It is actually a striking collection of outstandingly well-made and -reproduced color photographs, many of them full pages and a few of them two-page spreads. They are carefully ordered to present by example a straightforward exposition of the animal use of cover, camouflage, overt warning and its simulation in bluff, and something of physical defense and flight. Nearly every page has a couple of paragraphs of text, all of it clear, never technical or very detailed but using the scientific vocabulary. The colors glow: a scarlet-and-black tree frog on a lustrous green leaf, a Jackson's chameleon, jaws agape to show a pinkish mouth, and a defensive circle of determined musk oxen are only three of scores of examples. In some instances this virtuosity of the color halftone misleads. A protected ball of pill millipede appears the same size as a wrapped-up pangolin, although one is the size of a pea and the other is bigger than a basketball. The unwary might well be confused by such shots; the text or the captions ought to help more with scaling information. All in all, however, the book is a first-rate resource.

The Hunters is different in aim and weight. It is also visually impressive, although it has no color photographs at all. (Many of the diagrams have one color in addition to the black.) There are whole-animal illustrations on almost every two-page spread and a wide range of detailed sketches and anatomical drawings besides. These are beautifully textured works of illustration, and they explicate a sophisticated brief text. Some 60 forms, from the swift to the sea otter, from the flea to the piranha, hunters all, are included, with man "the top, top predator." The sea-otter spread, for example, shows the handsome little beast afloat on its back, with a stone on its stomach, banging a big shell held in its paws against the stone to break the shell. Other drawings show the sea otter's dive, its skull and teeth, its manipulative forepaws and webbed hind paws and a graph of its food. About half of the food, gauged by stomach contents, is sea urchin, cracked on the stone anvil.

A brief text tells of the entire family of otters, and of the differences between the coastal and the marine forms. This expert volume is plainly meatier stuff than *Animal Defenses,* although it belongs to the same broad type. These reviewers are dismayed by the absence of references in the book. The author, a London zoologist, is a qualified expert, but the only support he offers for four dozen accounts over a wide range of forms is a final list of a handful of general books and a few specific papers. One or two apropos citations with each description would have given the book a sense of social connectivity and the reader a path to follow beyond it. Who saw the otters using the anvil?

A MYSTERIOUS PRESENCE: MACROPHOTOGRAPHY OF PLANTS. Photographs by Esther Bubley and text by Percy Knauth. Workman Publishing, New York ($9.95). Wonderful columns and capsules dwell in this translucent and highlighted world, winding delicately or crudely clumped, intricately carved or remarkably polished, still yet charged with energy. The title does justice to this loving set of studies of tiny growing plants, most of them seen very early in life, the artful camera yielding a look magnified by an order of magnitude or so. The 15 plants seen include familiar foods, such as squash, peas, potatoes and peanuts, and a couple of flowers. Each study begins with the growing form so small and so young that it is not easy to recognize. Most of the studies continue the shots until the object has grown to a more familiar size and strength, with its delicate infancy or thrustingly eager crudeness in its past. The photographer, who "fell in love with plants," could not destroy her models and planted them in the park or gave them to gardening friends; she worked in a New York apartment. The text is simple but serious botany, treating of endosperms and hypocotyls, little essays able to give us some sense of the meaning and sequence of the structures displayed in the photographs. It is a book of ubiquitous growth and form, a pleasure alike to old-timers and not-yet-readers, a stroll in a world close at hand yet little entered. The book is a bargain, a tour de force with austere appeal to the eye and the mind at any age of wonder. Some of these mysterious presences might disclose themselves to anyone who examined with enough care the fresh vegetables that enter an everyday soup.

Laboratory and Sky

MAGIC THROUGH SCIENCE, by Robert Gardner. Illustrated with photographs and with drawings by Jeff Brown. Doubleday & Company, Inc. ($5.95). THE GREAT SCIENCE MAGIC SHOW, by Ned and Lois Arnold. Illustrated by Tom Huffman and photographs by Meryl Joseph. Franklin Watts, Inc. ($6.90). Natural magic has the most respectable antecedents. In it the magic arises not out of deception but out of the way things are, so presented as to make the most of the wonder and mystery of the world. These two excellent books each offer careful and convincing accounts of many tricks. The how, the why and the way to create theater are presented for young magicians in the grades. These instructions are workable too, not mere say-so transcriptions of pieces from old books. Photographs of the effects accompany many of the descriptions. A short list will help to make the point: A straw can be driven through a potato if you know how; an ice cube can be lifted out of a glass with a piece of string, given a little salt; a flame can appear to burn underwater; a pair of balloons show a surprising failure to equalize pressures. Both books offer dozens more of these little astonishments. The Gardner book extends to a powerful chemical magic, with materials whose supply requires the cooperation of a school laboratory. The Arnolds' chemical requirements can be met in any kitchen. Again, the Gardner optical arsenal is somewhat more demanding. Either book—they are remarkably similar in purpose and tone without strong overlap in detail—is a first-class start toward cheerful and exciting shows in home or classroom, full of fun and the learning of science.

A SPACE STORY, by Karla Kuskin. Illustrated by Marc Simont. Harper & Row, Publishers ($6.95). Sam goes to bed at eight o'clock, but he likes to put it off, first with the call for a glass of water and then with as many questions as his mother will stand for. One clear night he looks out at the starry sky. First he seeks a count of the stars, then he wants to know if people live there and finally he

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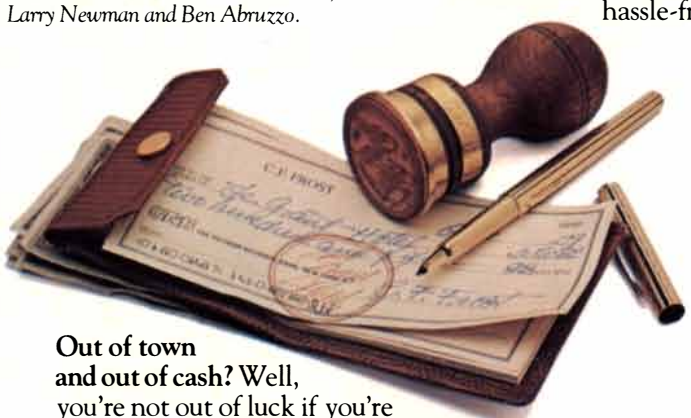

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Why give less than Courvoisier?

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wonders what the people are like. The day is over and his mother "softly shuts the door." We drift off through the deep blue starry sky in page after page, each one a simple but evocative painting, to view the fiery sun, the planets and their satellites, all simply drawn and briefly described. Nowhere yet have we reached where someone like Sam might live: all is too cold or too hot or too fluid or too dark. Beyond Pluto the stars stretch out very far. In the later pages we encounter a familiar-looking window on the starry sky, and on the last page we watch a faraway boy just like Sam, and we hear a mother softly shut the door ... far away. This is a gentle, engaging tale with a haunting circularity and a sound basis of fact.

BUBBLES: A CHILDREN'S MUSEUM ACTIVITY BOOK, by Bernie Zubrowski. Illustrations by Joan Drescher. Little, Brown and Company ($6.95). Floating bubbles as big as a volleyball, curved film sculpture the size of a bedsheet? Of course; there are photographs in evidence, kids and their bubbles. No simple giantism is here either. There are small bubbles made in mass production (with the clever use of a balloon), the bubbles as uniform as building blocks and used to construct froth honeycombs and bubble regiments. There are bubbles in curious frames, even a helical film, bubbles within bubbles, bubbles of many kinds closely watched. This little book takes a fresh view of a wonderful old experimental domain, with the techniques simply explained. Elementary school girls and boys will find plenty in it for thought and action; some work space will be required outside the living room. The book is one of a new series of activity books out of the Children's Museum of Boston.

THE GREAT SUNDIAL CUTOUT BOOK, by Robert Adzema and Mablen Jones. Photographs of the models by Rosmarie Hausherr. Illustrations by the authors. Hawthorn Books, Inc. ($9.95). Two sculptors who pioneer in the complex mediums of our day came to sundials through distinct routes: the one through the problem of public outdoor art and how it would look as time passed, the other through an extrapolation of interest in land forms as a source for powerful work in terra-cotta. Seized as artists can be, they built simulators, cut a skylight in the studio ceiling (the snow fell in!), studied and designed, guided by maquettes in paper that were their path to realization. Their good-size spiral-bound book embodies 16 patterns printed on heavy paperboard, which can be cut and assembled with care to make a variety of workable sundials on a small scale. None is too difficult for a neat paper cutter to construct. The text explains a variety of dials; drawings and photographs assist comprehension. It is no trivial task to grasp how the dials work, but it is a rewarding entry into an art as old as writing and as new as the ingenuity of the designer. A plane-faced dial, a cube dial, an equatorial dial with "the mysterious analemma" (adequately clarified, if not perhaps exhausted) and a simple single-digit dial sample the styles worked out.

THE CRAB NEBULA, by Simon Mitton. Photographs, graphs and diagrams. Charles Scribner's Sons ($14.95). Astronomy today has two parts, one theorist remarked, the study of the Crab Nebula and all the rest. This little book, beautifully illustrated with images in light, radio and X rays, which go beyond the splendid but by now hackneyed examples, treats of the first part of the science. The level is nonmathematical, albeit quite detailed and semiquantitative, that is, with plenty of graphs, physical quantities and arguments about them, and the free employment of exponential notation. The treatment is more or less chronological as knowledge of this object unfolded. Mitton, a Cambridge astronomer and a skillful popularizer, begins with the story of the Chinese observers of A.D. 1054 and all that arose from their records. He tells us how we came to see that the optical Crab Nebula has a dual nature: the massive expanding basket of glowing gassy filaments and the featureless cloud of fast particles within. The two lead to a knowledge of mass and even of distance. One reads of the striking discovery of the fast central pulsar and of its explanation as a spinning, magnetized neutron star, whose spin energy feeds all the nebular radiations, which the slowing spin rate proves. The clock is losing about one part in 3,000 per year.

The author tells of pulsar theory and something of the conjectures about neutron-star matter; he has even interviewed for their stories the two originators of these ideas, Franco Pacini and Thomas Gold, who worked on the same Cornell corridor, although independently. The book is ended by some extension to other supernovas and by the hint that the quasars might in some way be giant analogues of the Crab. Comprehensive without tedious detail, positive without being overcredulous, it is a good example of popular science at a level beyond the introductory, well suited for serious readers in the upper grades and their older friends. Lord Rosse's earliest drawing at the big reflector is shown, looking less like a crab than like a pineapple. The name of the nebula is his, but it is not quite known why he chose it.

Travel and Technology

OCEAN FLYING: A PILOT'S GUIDE, by Louise Sacchi. McGraw-Hill Book Company ($14.95). A witness offers this story of an Atlantic flight: "We were over Ocean Station Charlie. He asked, 'What kind of plane is your BE-36?' Louise said, 'It's a large Bonanza.' 'How many engines?' says he. 'One,' said Louise. 'There are a lot of idiots in the world,' said he, at which point I picked up the mike and said, 'You can say that again.'" The pilot-author of this cool account, full of the realities of ocean flight, has had an extraordinary career aloft. She professionally ferries light aircraft (very often Beeches), the number of engines your choice, out of the U.S. to anywhere at all, having racked up almost 350 ocean crossings in 17 years of action. Her own photographs take you along Atlantic routes, via Greenland's icy mountains or the Azores' coral strands. The Pacific route, via Hawaii to Asia and Australia, is just as well known to her. There you have less choice; the route legs are long, and the Aleutians, which offer an alternative, are almost always fogbound. The chapters begin with a flight chronicle, lighthearted and precise, and continue to the pilot's self-knowledge, the plane, the engine, emergency equipment, the compass, charts, weather, navigation and the main routes. Diplomacy and paperwork are as important for the highly social activity of transoceanic flight as good sense and engineering understanding.

These attributes are plentiful here, in a book as fascinating for the armchair flier or the passive passenger as it is valuable for anyone who would really fly across an ocean. A reader is caught up in these voyages, fully ready to forgive a foible or two in so grand a navigator, prudently below 10,000 feet (unless there is plenty of oxygen and a turbocharged engine). Study the weather hard before you fly, carry at least some water and cheese, remember good sunglasses ("The icecap of Greenland can be quite blinding") and learn how to take subtle advantage of both the civil and the military aids to aviators.

INTO THE DARK: A BEGINNER'S GUIDE TO DEVELOPING AND PRINTING BLACK AND WHITE NEGATIVES, by Edward E. Davis. Atheneum ($9.95). WORKING WITH LIGHT-SENSITIVE MATERIALS, by Geoffrey Hindley. Van Nostrand Reinhold ($7.95). Glowing with the safelight of common sense, *Into the Dark* is a compact and explicit beginner's guide to satisfying photography. It promises three things: cheaper, faster, better. The author delivers. For cheaper, he talks good sense about the bewildering marketplace, with the first third of his text devoted to cameras, film, accessories, shopping in person and by mail and finally picture composition. Surely that speaks to better as well. The rest of the book leads into the dark, as the title promises, beginning with chemicals and illuminating carefully and step by step the darkroom setup, photographic development, contact printing, enlarge-

ment making and growth in achievement. Once one learns the ways to correct exposure this part is not only cheaper and better but also faster. An eager eight-year-old with a parent to help, a club, a group of cooperative upper-grade children or a couple of high school youngsters could carry out this course, given some space and money and time measured in months.

Working with Light-Sensitive Materials goes much deeper; it is serious activity for a group of high school or college students. Not as close to the camera shops, the nicely illustrated text, by an Australian teacher of photography, seeks to establish the skill from the ground up. The focus is on simple home-built cameras, with or without lenses, on the use of printing on paper directly, without a negative, on making photographic emulsion for oneself and on the technique of photographic silk-screen printing in color. These careful but demanding directions will leave conscientious students with the basic control of a real craft.

THE EADS BRIDGE. Photographic Essay by Quinta Scott. Historical Appraisal by Howard S. Miller. University of Missouri Press ($19). Near a shimmering stainless-steel ornament, the Gateway Arch, a steel-arch bridge crosses the wide Mississippi, as first it did in July, 1874. The railroads could then enter St. Louis, although in fact they were slow to make use of the bridge. The builder of the bridge, James B. Eads, was a remarkable man, an engineer and entrepreneur, an ingenious self-taught mechanic who at the same time was eager to take the counsel of his highly trained German émigré engineers and their careful stress calculations. He was determined to use cast steel, a novelty produced by the first Bessemer converters. In the end his bridge was more wrought iron than steel, but there was chrome-alloy steel in crucial members. The closing of the final arch was suspenseful: packing the ribs in 15 tons of ice to shrink them did not work. Finally it was screwed closed, as Eads had actually foreseen, with a special turnbuckle and "a giant wrench." The story is a fresh one, an eye-opener for anyone who thinks construction work is routine and predictable.

The Eads Bridge still stands firm against the currents and the ice and the wind, but it is all but dead. The trains stopped crossing it in 1974, and most of the automobile traffic follows the new interstate. The bridge remains beautiful; the portfolio of photographs here, comprehensive and intimate, reveals an organic structure, main arches made of strong hollow tubes held with great authoritative hexagonal nuts, all elegantly free of decoration. Along the train deck, seen by few but "trainmen and gandy dancers," we are in a remarkable open

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enclosure, both powerful and gently curving. Walt Whitman and Louis Sullivan celebrated the structure. This brilliant joint study opens to the eye and the mind a view of inland America in a time of triumph. It is a worthwhile book for readers of high school age and older.

THE ANNOTATED JULES VERNE: FROM THE EARTH TO THE MOON, DIRECT IN NINETY-SEVEN HOURS AND TWENTY MINUTES, by Jules Verne. The Only Completely Rendered and Annotated Edition, translated and annotated by Walter James Miller. Thomas Y. Crowell, Publishers ($16.95). With 100 period engravings and margins rich with informed literary criticism and explanatory gloss, this is the story of the Gun Club of Baltimore and how its energies were converted from the battlefield to moon voyaging, not in President Kennedy's time but in Jules Verne's imagination—in 1865. The enthusiastic and learned translator (a poet and professor at New York University) shows us a truer Verne than any yet Englished: a satirist, a critic with "broad social as well as scientific vision," misrepresented in the U.S. by a series of tendentious renderings. It was an irresistible book even so, and it is more wonderful now that the Gun Club in all its colorful eccentricity is shadowed by the corporate managers of NASA. This volume carries us only past lift-off; the sequel *Round the Moon,* which follows the voyagers back to a Pacific splashdown, is not included.

Peoples

I AM EYES: NI MACHO, by Leila Ward. Pictures by Nonny Hogrogian. Greenwillow Books, William Morrow & Company, Inc. ($7.95). IN BIKOLE: EIGHT MODERN STORIES OF LIFE IN A WEST AFRICAN VILLAGE, by Tom Gilroy. With drawings by Monica Vachula. Alfred A. Knopf ($5.95). Between them these two books span the continent of Africa and the years of learning to read. In Swahili one can announce waking up with the poetic words "I am eyes." The Ward-Hogrogian book is a genuinely beautiful one for beginners at reading. On the left-hand page one sees a small girl who watches the world very well, sometimes with her friends or with her mother or father, all excited by the wonderful sights of a Kenyan day. On the opposite page we share those sights, in attractive and convincing colorful paintings. Kilimanjaro, giraffes, flamingos, elephants and coral end with "everywhere where I am eyes, I see butterflies." The text is only a line or two on each page, and the whole of the work carries off with distinction that artists' magic to make something that is both evocative of a special people and a special place and yet entirely universal to curious children.

Tom Gilroy has distilled these well-seen everyday dramas from two years spent as a Peace Corps volunteer in a Senegal savanna village a few years ago. The Serrer villagers grew and ate millet for three meals a day, raising a peanut crop to pay for taxes, new shoes and the wrestling matches. The short stories are strong and warm: a small boy, who later dies, loves his dog and a wonderful pair of shoes, the smaller wrestler somehow wins, the young wife reaches the hospital in time. The bitter is there too: Rosalie runs off to the city rather than marry an old man, and the farmers, impoverished by drought, are punished cruelly for failing to pay their taxes. Serrer life, poor but vital, is here, for those who read well and are old enough to appreciate the strong flavors of some village realities.

MOUSE WOMAN AND THE MUDDLEHEADS, by Christie Harris. Drawings by Douglas Tait. Atheneum ($7.95). RITUAL OF THE WIND: NORTH AMERICAN INDIAN CEREMONIES, MUSIC, AND DANCES, by Jamake Highwater. Drawings by Asa Battles. The Viking Press ($18.95). INDIANS, written and illustrated by Edwin Tunis. Revised by Lorraine E. Williams. Thomas Y. Crowell ($12.95). Things were different long ago. The people lived on the beaches and banks, the villages were bright with the carvings of the clan totems of facade and pole, the backs of the houses to the snowcapped mountains. There were not only human beings dwelling on the rich coasts of the Northwest, the Haida and the Tsimshian and the rest, but also powerful and passionate supernatural beings: the narnauks. One of the best-known of the spirit beings was Mouse Woman, who often appeared as a tiny grandmother in a mouse-skin cloak. Mouse Woman liked everything done properly, which was not always easy to manage. To her those who did not do things properly were muddleheads, and often she had to straighten them out. Here are seven tales of muddleheads, some human, some narnauk, and the muddles they got into until Mouse Woman came along. Here are whirlpools and sea monsters, cedar canoes made into gleaming copper and delicious feasts of cloudberry pudding and smoked salmon. The worst muddles are about love and marriage, it seems, and it is a good thing that young people sometimes have a powerful friend's help, be she as tiny as a mouse, to keep everything equal in this often improper world of human beings and narnauks. These are fresh and lively stories, which have waited a long time for a good storyteller to dig them out of the shelves of ethnographic literature once collected by Franz Boas and people even before him.

In *Ritual of the Wind* Jamake Highwater offers a wide but intimate look at the cultures of the Indians of North America seen as a living presence in the land, a ritual life that offers a cosmology, a guide to behavior and a matrix for what in our culture is called art. It is not a simple book, but it is a rewarding one on several levels. It cites text and action for parts of such well-known sacred events as the Sun Dance of the Plains, the Booger Dance-Drama of the Cherokee, the Rain-Power Ceremony at San Juan Pueblo and a Navajo Night Chant. The sources include direct observation and the older ethnographies: both the original drawings and the remarkable photographs add a great deal to the depth of the presentation, a sympathetic essay suggesting an ancient and synthesizing world view. Serious readers in high school and college years can gain much from this work, which includes a valuable discography of American Indian music and a national calendar of ceremonial events. Here and there the author finds comparisons between the forms of Indian ceremony and the work of a few outstanding artists of the modern non-Indian world.

Edwin Tunis was a meticulous and gifted researcher and draftsman who made a career of careful exposition of the look of the past, of its everyday tasks and tools, of its social history rather than its generals and battles. In *Indians,* first published 20 years ago and now revised by an ethnologist, he presents the variety of the native Americans, people of the woodlands and the plains, of the Southeast, the desert, the coastal towns, the North—all more or less as they were before the Europeans came. Some 250 drawings show the people, their possessions and their actions, from a tiny ear of pod corn to a potlatch and a Hopi weaving. So clearly drawn and honestly described are these things that the book is a volume of first resort for readers of grade school age and older in the culture of the American peoples, particularly for concrete impressions of their lives. Tipi and traps, lacrosse stick and arrow points, graves, children and heroes are all here. The text is straightforward. In the bitter war that raged for two centuries along the frontier "abominable things were done by both sides.... It would seem that, of the two opponents, the Indian had the better excuses. He was fighting a desperate fight in which his own country was being taken away from him.... And yet, suppose we—you and I—had just this continent today, rich and untouched. What would we do about it? Sail away and leave the Indians in peace? We would not!" The tragedy of might has not ended.

THE ROOSTER'S HORNS: A CHINESE PUPPET PLAY TO MAKE AND PERFORM, by Ed Young with Hilary Beckett. Illustrated by Ed Young. William Collins + World Publishing Company ($5.95). What is the rooster doing at daybreak? Why, he is shouting to Heaven, "Give me back my horns!" How it

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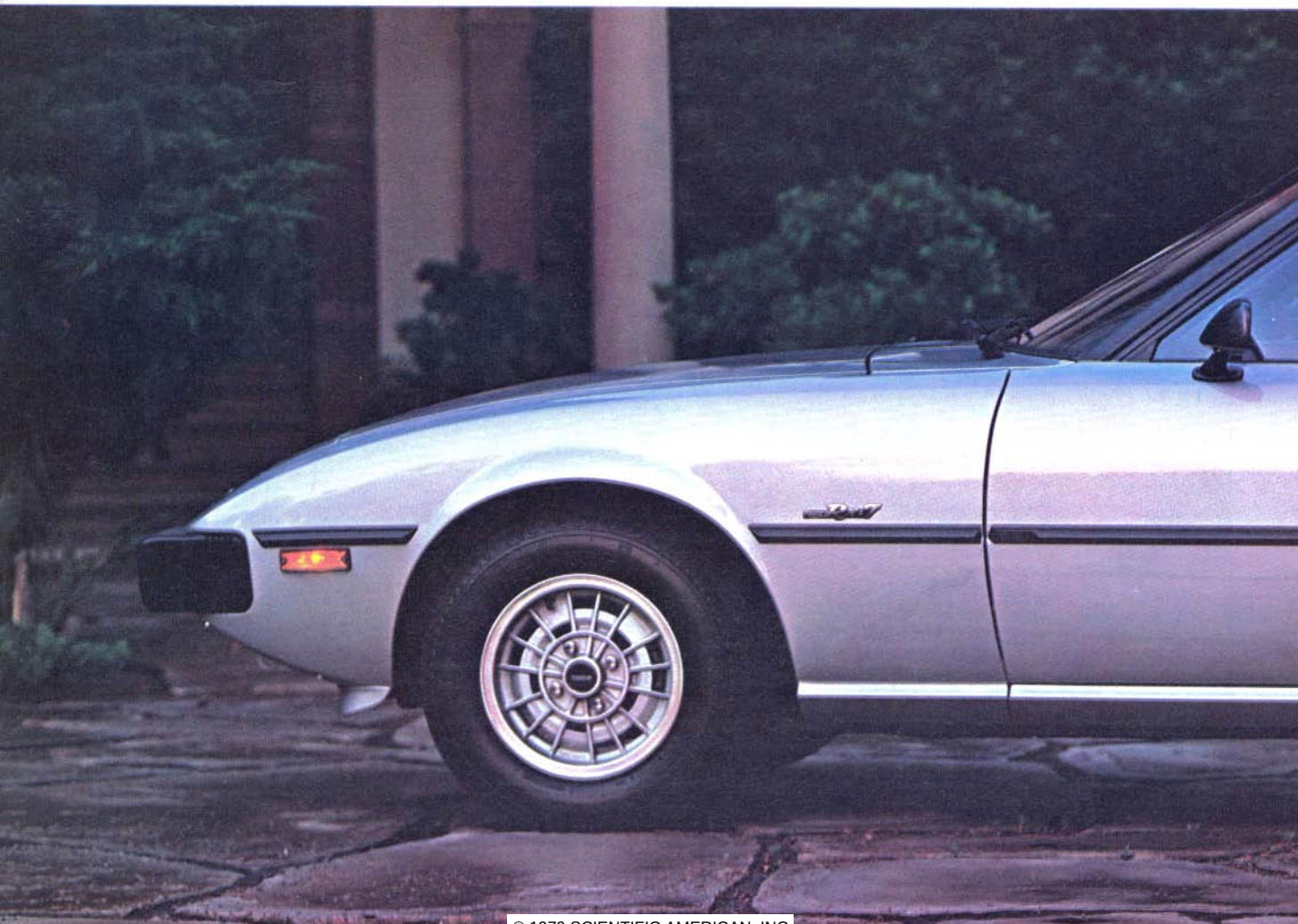

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happened that Rooster lost the magnificent horns that once crowned his head and flanked his bright red comb has been known to Chinese children for a long time. Noble Dragon and tricky Worm cheated him out of them; Dragon never brought them back from the sky. They learn this in China by watching a funny little play done in the wonderful medium of shadow theater. This fetching book tells the story. Its illustrations are richly colored, with patterns for tracing a movable Dragon and a Rooster. It presents full directions, with drawings, for a shadow performance mounted with a lamp, two chairs, a white cloth and a deal of care and planning that is nonetheless well within the reach of a couple of theater-fond kids.

Languages

THE CODE & CIPHER BOOK, by Jane Sarnoff and Reynold Ruffins. Charles Scribner's Sons ($2.95). A paperback reissue of a pleasant little book of a few years back, this lighthearted and well-illustrated work is a sound and simple guide to codes and ciphers. It begins easily enough (the combined Space and Backward ciphers yield SEIKO OCEH TEVA HEWH TESL LETT ONOD for an interesting plaintext) and carries early grade school readers on through shift ciphers, the substitution schemes of Edgar Allan Poe and Arthur Conan Doyle, the Celtic Ogam scheme, the Pigpen drawing cipher, Alberti's code wheel and even a simple cipher based on the telephone dial. A little authentic history is added for spice, and there is a fine two-page sketch of Cockney street life, an introduction to the rhyming slang and the back slang heard within the sound of the Bow bells. It is a book of pleasure and quality; the God forbids will kick and prance when this niagrab koob comes top of Rome.

MICROSOFT BASIC, by Ken Knecht. Dilithium Press, Post Office Box 92, Forest Grove, Ore. 97116 ($9.95). SIXTY CHALLENGING PROBLEMS WITH BASIC SOLUTIONS, by Donald R. Spencer. Illustrations by John R. Beatty. Hayden Book Company, Inc., Rochelle Park, N.J. 07662 ($6.95). BASIC COMPUTER GAMES, microcomputer edition, edited by David H. Ahl. Program conversion by Steve North. Illustrations by George Beker. Workman Publishing ($7.50). Basic is a simple-to-learn high-level computer language related to the Sanskrit of computer tongues, Fortran. It was devised some years ago at Dartmouth for a time-sharing system, but its virtues have given it great currency in the world of today's personal computers: the keyboards with a cathode-ray screen or something similar, not the hand-held calculators.

The tide of this hardware has thrown up plenty of books. These three span the art of learning and using Basic, perhaps less for work than for play. Microsoft, a trademarked name, is a dialect familiar to the most popular home computer (Altair) and is little different from the mother tongue of several of the other widely used machines (Radio Shack and Commodore, for example). *Microsoft Basic* is a straight grammar of the form, a study text in the language. It appears to be workable, although the reviewers are not fluent in the tongue. Its index is a real help and gives it an edge over some of the other grammars offered. Utter the powerful words GOSUB and RUN. If you think you can speak Basic, *Sixty Challenging Problems* is an agreeable form of exercise. It poses the problems, mostly mathematical recreations, and then offers the Basic listings that solve them. *Basic Computer Games* is a kind of reader: in it you read of 101 "Great Games to Play" on your computer. They range from nim and rock-scissors-paper to simulated hockey, checkers and three-dimensional ticktacktoe, plus plenty of combat, space and guessing games. For every game there is a full Basic listing; some of the lists include 300 or 400 instructions. Such is the state of the art today; informed readers will profit from the books, forewarned, of course, of the likely infestation of bugs.

YOU DON'T SAY: HOW PEOPLE COMMUNICATE WITHOUT SPEECH, by Vernon Pizer. Illustrated by Janet McCaffery. G. P. Putnam's Sons ($7.95). In the Canaries they can whistle thought. The talking drums are real enough across much of Africa. Gestures are powerful worldwide, but they are by no means uniform. The upraised thumb will not get you a lift easily in Scotland or Australia; it is an insult. In northern Nigeria a raised fist is not a sign of anger but a friendly greeting. Symbols, glyphs, colors—all are used, some after hard work to build universal understanding. A Swedish surgeon, Dr. Jack Adams-Ray, had to recover from a serious knee injury in a Moscow hospital where he could not communicate with the ward staff. Out of his sense of helplessness he was moved to construct a little booklet, now found in hospitals in many countries. In it cartoons show all kinds of patient-doctor relations. A head is struck by a hammer and pain stars surround it. Point to it and you clearly have a headache. More stars, a bigger hammer, a worse headache. The signs that begin to appear on all our highways are built on a similar idea, not yet perfected but probably better than PED XING. Color codes are familiar, although danger red has its problems. Braille and Ameslan are two elaborate and helpful forms of unspoken language, and even smell communicates deeply. All of this and much more is conveyed in a clear, often surprising and easily read brief book for readers in junior high school.

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Energy-Storage Systems

Energy reservoirs consisting of pumped water, compressed air, batteries and ways of storing heat and "cold" can do much to help coal, nuclear and solar energy replace substantial quantities of oil

by Fritz R. Kalhammer

In his energy address to the nation in July President Carter pledged that the U.S. would never import more oil than it did in 1977: 8.5 million barrels per day. The pledge acknowledged the vital political and economic importance of reducing the country's dependence on foreign oil supplies. A continuation of current patterns of oil consumption in the U.S. could result in a demand of some 30 million barrels per day by the year 2000 and the need to import two-thirds of that amount (since domestic oil production is not likely to ever exceed 10 million barrels per day). The dilemma is central to the U.S. "energy problem," and clearly its solution calls for a shift away from oil to energy resources available domestically.

To understand the technical and economic challenges of such a shift one can begin by considering how petroleum came to be the dominant energy source in the world's economies. In the early years of this century battery-powered electric vehicles were not uncommon, but they were almost entirely displaced by gasoline-powered vehicles because gasoline is the most convenient and inexpensive way to carry around large amounts of energy. In the first half of the century petroleum products and natural gas largely replaced coal as the primary source of space and process heat, both because they burn more cleanly than coal and because they can be stored and transported more easily. Then over the past 30 years many U.S. electric utilities switched from coal to oil and gas because of the lower cost of oil- and gas-fired equipment and its greater flexibility in meeting fluctuating power demands. The challenge is therefore not only to establish alternate supplies of primary energy but also to develop ways of utilizing those supplies with the convenience, efficiency and low cost characteristic of systems based on petroleum. A major factor in meeting that challenge could be a variety of systems for storing energy.

For example, if energy-storage systems based on batteries could be improved sufficiently to make electric propulsion an attractive alternative for 10 million vehicles by the year 2000, the oil savings could amount to .4 million barrels per day. (There are about 125 million cars and light trucks on U.S. roads today.) The development of new energy-storage systems by electric utilities could save .9 million barrels per day by the year 2000, and the widespread installation of storage systems in the residential and commercial sectors could displace oil and gas equivalent to 1.5 million barrels of oil per day. It is clear too, although quantitative estimates are difficult, that the industrial sector also offers significant opportunities for oil savings through heat storage. By expediting the shift away from oil to coal, nuclear and solar energy, energy-storage systems could therefore bring about oil savings of perhaps three million barrels per day by the end of the century. If they were fully implemented over another 10 to 20 years, such systems could result in even larger savings, perhaps as much as 10 million barrels per day. The outcome will depend, however, on how vigorously the U.S. pursues the development and deployment of the energy-storage methods I shall now describe.

I shall discuss opportunities for energy storage in electric-power systems first and then turn to storage applications in transportation and in commercial and residential structures. Finally I shall take up energy storage as it might apply to solar-energy systems, ranging in scale from home-size units to electric-utility power grids.

From their earliest days electric utilities have been confronted with the fundamental problem of meeting fluctuating demands for power at the lowest possible cost consistent with adequate reliability. Traditionally the utilities have responded by setting up combinations of generating plants with different operating and economic characteristics. Typically between 40 and 50 percent of a system's load (the demand "base") is supplied by large coal and nuclear units of the highest efficiency operating on the fuel of lowest cost. Such base-load units are operated continuously for most of the year. The broad daily peak in demand, representing another 30 to 40 percent of the load, is met by "cycling," or intermediate, generating equipment, usually the system's less modern and less efficient fossil-fuel (coal, oil or gas) units, hydroelectric-power units where they are available and gas-turbine units where they are needed. Although the electricity generated by cycling plants costs more than base-load electricity, such plants are the most economical way of generating electricity for part of the time every day, adding up to perhaps 1,500 to 4,000 hours per year. Brief peak demands are met by still older fossil-fuel units and by hydroelectric power, gas- or oil-fired turbines and diesel generators. Such units operate for from a few hundred hours per year to 1,500 hours.

This traditional three-level combination of generating plants has become increasingly less attractive as sharply rising fuel costs penalize the less efficient units. Moreover, coal-fired units now require, or will require, costly pollution-control equipment that represents a technical and economic disincentive to cycling operation. And with the Industrial Fuels Act of 1978 and President Carter's demand that the consumption

of oil be reduced to 50 percent of the consumption of all fuel by 1990 the utilities are under increasing pressure to minimize the operation of oil- and gas-burning equipment. These are clear incentives for utilities to turn to base-load plants as the source of power now generated by cycling and peaking units. The key to moving in this direction is energy storage, which makes it possible to accumulate the output of base-load plants during periods of low demand (nights and weekends) for periods of high demand.

At present there is only one well-established method of energy storage for electric utilities: pumped-hydroelectric storage. The method is of limited applicability both because of the shortage of suitable bodies of water and topographic sites and because of objections from people who perceive such plants as being a major threat to the natural environment. At present less than 2 percent of all U.S. electric energy is obtained from pumped-hydroelectric facilities, and it is doubtful that this small fraction can be much expanded.

One of the several new energy-storage concepts being examined is underground pumped-hydroelectric storage, which would be less limited by topographic and environmental constraints than conventional pumped-hydroelectric systems. In the proposed system a lower reservoir is constructed underground in hard rock, without any connection to a natural body of water. The upper reservoir can also be artificially created and can be much smaller than the one that would be needed for a surface pumped-hydroelectric system of the same energy-storage capacity. The reason is that the distance between the lower reservoir and the upper one can be several thousand feet, compared with less than 1,000 feet for a typical surface pumped-storage system. Energy-storage capacity is directly proportional to the height of the head of water.

The prospects for underground pumped-hydroelectric storage seem good, because practical cavern-excavation and tunneling methods exist for the construction of the lower reservoir and because high-lift pump-turbine technology is essentially in hand (although further improvements are desirable). The chief geological constraint is the need to identify and to predict the characteristics of suitable rock formations. It nonetheless appears that suitable formations exist widely in the northeastern, north-central and western U.S. A preliminary engineering-design study for an underground pumped-hydroelectric facility is being conducted by the Potomac Electric Power Company. The findings, which are expected to be available in 1980, should go far to define the costs, risks, benefits and potential for the technical improvement of this still-untested method.

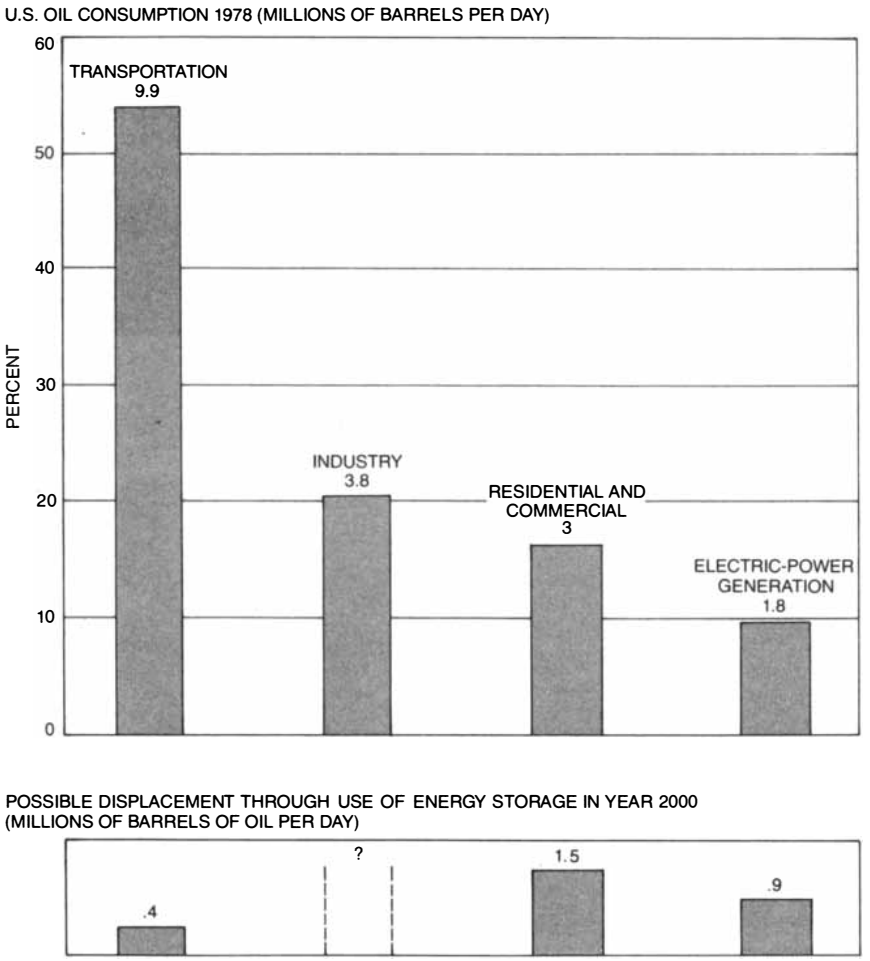
Another conceptually simple way to store energy in a form convenient for power generation is to pump compressed air into an underground reservoir. Compared with pumped-hydroelectric storage, this method has several advantages: a wider choice of geological formations (the storage cavern could be in either hard rock or salt), compactness (the density of the energy stored could be higher) and a smaller minimum size for an economically attractive installation. There is, however, one complica-

PUMPED-STORAGE HYDROELECTRIC PLANT at Ludington on the eastern shore of Lake Michigan is the largest electric-energy storage facility in the world. Off-peak power, available primarily at night and on weekends, is fed to six pump-turbines that raise the water an average of 250 feet from the lower reservoir, Lake Michigan, to the upper reservoir, an artificial lake contained by an earth-fill dam six miles long. At hours of peak electric demand the water in the upper reservoir is discharged through the pump-turbines to Lake Michigan, generating more than 2,000 megawatts at full power, or the equivalent of two large power plants. If the plant were fully discharged, it could generate 15 million kilowatt-hours. Two-thirds of the energy expended in charging the reservoir is recovered. Plant was constructed between 1968 and 1974 at a cost of $300 million, shared by the Consumers Power Company and Detroit Edison Company.

tion: since the air gets hotter when it is compressed, it must be cooled before it is stored in order to prevent fracturing of the rock or creeping of the salt. The stored air must then be reheated by burning a certain amount of fuel as the air is expanded into the turbine that drives the electric generator.

The world's first commercial compressed-air storage installation went into operation recently in Huntorf, near Bremen in West Germany. The plant is connected to the power grid of Nordwestdeutsche Kraftwerke, a German electric utility. During off-peak hours the Huntorf facility draws on the utility's excess generating capacity to compress air to some 1,000 pounds per square inch and store it in two caverns leached out of a salt dome. The combined storage capacity of the caverns is about 300,000 cubic meters (more than 10 million cubic feet). During periods of peak demand the air is expanded, heated by the burning of a certain amount of natural gas and fed through high- and low-pressure turbines that can generate 290,000 kilowatts for about two hours.

At the Huntorf plant each kilowatt-hour of output requires an electric-energy input of .8 kilowatt-hour for air compression and a fuel-energy input of 5,300 British thermal units (B.t.u.) for air reheating. Since the start of commercial operations the system has been charged and discharged several hundred times, generating power somewhat in excess of its design rating. All the major technical objectives of this first-of-a-kind installation have been met. Although the economic performance of the Huntorf installation can be established only in actual service over a period of years, it is clear that a storage facility of this size (less than a million kilowatt-hours) and construction time (less than five years) presents a much smaller financial risk to a utility than even the smallest economically feasible pumped-hydroelectric facility (about 10 million kilowatt-hours).



U.S. OIL CONSUMPTION in 1978 averaged about 18 million barrels per day (MBD), of which slightly more than eight MBD had to be imported. Transportation in all forms (surface, air and marine) was the largest single consumer (*top*). The oil consumed by all four sectors accounted for 47 percent of the nation's total energy demand in 1978. By various stratagems of energy storage a significant fraction of the energy demand now met by oil could over the next 20 years be shifted to coal, nuclear or solar power (*bottom*). An estimated saving of .4 MBD of oil in transportation could be achieved by replacing some 10 to 12 million conventional automobiles with battery-powered ones. Saving of 1.5 MBD of oil in residential and commercial sector assumes that 10 percent of the new structures would be provided with energy-storage systems that would help to shift heating and cooling energy demand to coal, nuclear and solar power. Saving of .9 MBD of oil in electric-power generation assumes construction by the year 2000 of a combination of storage systems (aboveground and underground pumped storage, compressed-air storage and batteries) capable of generating some 70 million kilowatts.

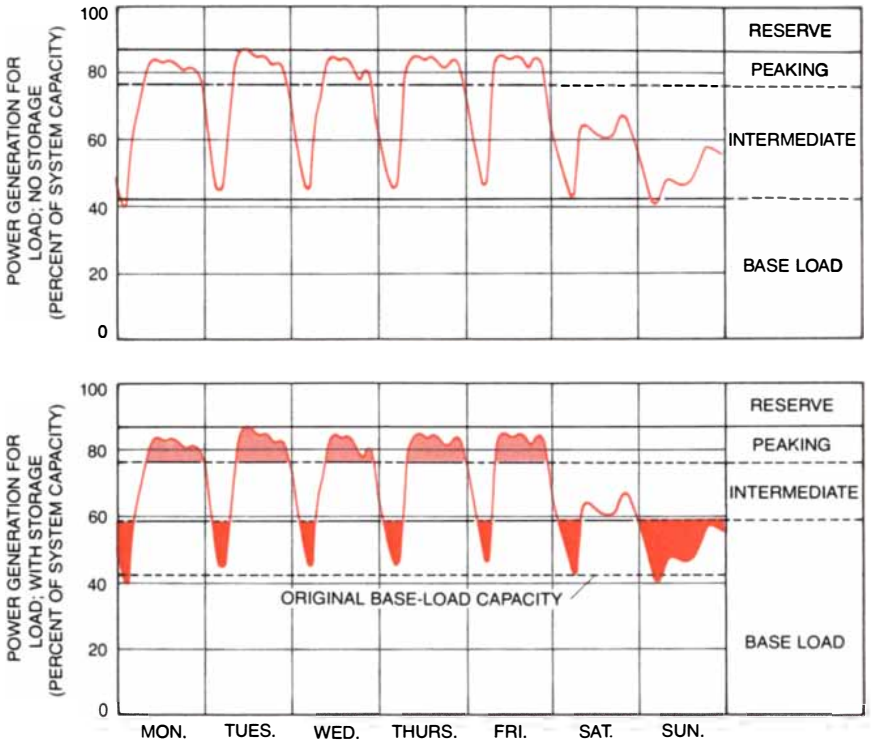
The next step in the development of compressed-air storage technology must be to reduce the quantity of high-quality fuel needed for reheating the air in the expansion phase. One way to get better efficiency will be to recover exhaust heat from the power-generating turbine and use it to preheat the expanding air. This "recuperator" feature is included in current designs for U.S. utilities and should reduce fuel consumption by 25 percent. It should also be feasible to heat the expanding air not with gas or oil but with coal or synthetic fuels derived from it. In addition it may be possible to recycle the heat generated when the air is compressed. Methods for storing the compression heat, which is currently rejected to the atmosphere, are being studied by various engineering groups, including one at the British Central Electricity Generating Board. Such a system might involve placing a bed of ceramic or iron pebbles in the air-flow passage, which would absorb heat from the air on its way to storage and reheat it when it is allowed to expand into the turbines.

It is natural to ask at this point: Instead of passing energy through several conversion stages, why not just store primary heat from a base-load plant's boiler and recover it when it is most needed? Indeed, this concept was put into practice half a century ago at the Berlin-Charlottenburg generating plant, where steel vessels ("Ruth accumulators") were used to store a pressurized mixture of power-plant steam and hot water. During peak hours the stored steam was released to drive a turbine-generator set. This concept of thermal energy storage and others have recently been examined with funding from Federal agencies and the Electric Power Research Institute (EPRI). The conclusion has been that in electric-power systems such schemes are likely to be costlier and less efficient than pumped-hydroelectric or compressed-air energy storage.

The energy-storage system most widely useful to electric utilities could be one based on secondary batteries (batteries that can be recharged). In the early years of this century lead-acid batteries were used in several U.S. cities to supply electric streetcars with direct-current electricity during rush hours. The practice ended with the general adoption of alternating-current power systems. In today's modern power systems battery "storage plants" could be located at various places within an elec-

tric-power grid. In hours of low demand electricity would be converted from high-voltage a.c. into lower-voltage d.c. and stored in the batteries. During peak hours the process would be reversed to carry part of the utility's load.

Battery storage systems could be attractive to utilities on several counts. Their input and output would be entirely electric and could respond rapidly and efficiently to changes in load. The capacity of a storage plant could be established and increased in modular increments, and the batteries could be produced and installed rapidly when they were needed. In recognition of these features U.S. electric utilities have assigned a high priority to battery research and development, first under the Electric Research Council of the Edison Electric Institute and now in the programs of EPRI. Substantial research funds are also being supplied by the Federal Government through the Department of Energy and its national laboratories (notably the Argonne National Laboratory).



WEEKLY LOAD CURVES indicate schematically how utilities would use storage to shift energy from peak to off-peak periods. The upper curve shows how a utility ordinarily meets the fluctuating demand for power by three different classes of generating plants, of which continuously operating base-load plants use the lowest-cost fuel, usually coal or nuclear fuel. The broad daily peaks in demand are met by older and less efficient units, most of which burn oil or gas. The lower curve is an idealized way of showing how energy storage would be used. The low-cost base-load capacity would be increased in order to supply a surplus (*dark color*) that could be accumulated at night and on weekends. Stored energy would then be withdrawn as needed to meet part of the peaks (*light color*), displacing part of oil- and gas-fired generation.

The development programs are focused on several new types of battery that promise both lower initial cost and longer service life than the traditional lead-acid battery. Compared with lead (the negative electrode of the lead-acid battery) and its oxide (the positive electrode) such "active" battery materials as zinc or sodium (for the negative electrode) and chlorine or sulfur (for the positive electrode) are cheaper and need less "inactive" material for support and containment because they have a higher storage capacity per unit weight and volume. Batteries under development are estimated to cost only half as much as the lead-acid battery when they are designed for electric-utility service. Equally important, the components of several of the new batteries should be less susceptible to cumulative physical damage than those of the lead-acid battery (in which the crystal structure and porosity of the negative and positive electrodes are drastically changed in each cycle of charge and discharge).

In the sodium-sulfur battery, for example, the electrodes are liquid and the electrolyte is a special solid ceramic. This radical departure from conventional designs, in which the electrodes are solids and the electrolyte is a liquid, greatly increases prospects for a long service lifetime. Several organizations are currently scaling up from laboratory-size cells to units of demonstration size. For example, the General Electric Company plans to have a 400-cell battery module with a capacity of 100 kilowatt-hours by 1982. The next step may be a prototype battery of 5,000 kilowatt-hours by 1984. Another promising advanced system, the zinc chloride battery, is being developed by Energy Development Associates, a subsidiary of Gulf & Western Industries, Inc. A 50-kilowatt-hour prototype module capable of discharging for five hours at 10 kilowatts has already been demonstrated. In 1981 the company is planning to fabricate a 5,000-kilowatt-hour prototype consisting of 100 such modules.

To test these prototypes and others developed under their funded research-and-development programs the Department of Energy and EPRI are jointly financing the Battery Energy Storage Test Facility (BEST). The Public Service Electric and Gas Company of Newark, N.J., is cosponsoring the facility and will operate it as a national test center beginning next year. Even now the BEST project is stimulating battery development in the U.S. and is bringing into focus the criteria for performance and the requirements for electrical interfacing that future battery energy-storage plants will need to meet before they can become an established part of an electric-utility system.

In order to provide actual operating experience with battery storage coupled to a power grid the Department of Energy is initiating a Storage Battery for Electric Energy Demonstration project (SBEED). Plans call for the completion in 1984 of a facility consisting of a 30,000 kilowatt-hour lead-acid battery coupled to a 10,000-kilowatt a.c.-d.c. converter. The facility will be tied into a small electric-utility system and will be operated by its employees; a lead-acid battery is being used to gain early operating experience with this new method of utility energy storage while minimizing the technical risk. Prospects are good that the main features of battery energy storage can be demonstrated in a way that will create confidence among utilities and commercial interest among the traditional suppliers of utility equipment.

Three other energy-storage concepts that also have been proposed for electric-utility applications merit comment. Hydrogen generated from water by electricity could be stored as a compressed gas or as a metal hydride and reconverted into electricity in a fuel cell. Hydrogen energy-storage systems would have considerable flexibility with respect to the location and operation of the energy-storage plant, but they would be costly, complex and relatively inefficient. Superconducting magnets could store electricity directly and with high efficiency, but the method appears to be inherently costly; to be economic the superconducting installations would need to have an extremely large storage capacity (at least 10 million kilowatt-

hours), and even at that scale their ultimate economic viability is questionable. Flywheels are capable of absorbing and releasing energy quickly, but recent studies indicate that even with advanced designs they will remain too expensive for electric-utility applications. Hence although each of these concepts has some unique advantages, in the foreseeable future none will be able to compete economically with the other storage systems I have been discussing.

Let me turn now to the potential role of storage systems in transportation. In the U.S. vehicles with internal-combustion engines burn about nine million barrels of petroleum-derived fuels every day, three-fourths of it in highway vehicles. The nine million barrels represent close to half of the nation's total consumption of oil. Large oil savings could be realized if vehicles could be economically propelled by electricity (generated from coal or nuclear fuel) stored in batteries aboard the vehicle.

What makes replacement of the combustion-engine vehicle such a formidable task is simply the high density of energy storage that gasoline makes possible. A 22-gallon tank with a volume of three cubic feet can store three million B.t.u. in the form of chemical energy, enough to give the average American automobile a range of between 250 and 400 miles. In that volume lead-acid batteries can store only about six kilowatt-hours (equivalent to 20,500 B.t.u.). The energy-storage problem with electric vehicles is not quite as bad as this comparison suggests: because electricity represents a higher grade of energy than fuel about 40 percent of the energy stored in a battery is available at the driving wheels compared with about 10 percent of the energy stored in fuel. Nevertheless, the typical range of 25 to 50 miles attainable with lead-acid batteries of the maximum acceptable weight (about 2,000 pounds) compares unfavorably with the range of conventional vehicles and is a serious barrier to the broad acceptance of electric vehicles.

The cost of electrochemical energy storage in batteries is another barrier. Once electric vehicles are manufactured in volume, their cost apart from their batteries should be comparable to that of conventional vehicles of similar size. The battery cost will be the difference: the cost of a gasoline tank is inconsequential, but a one-ton lead-acid battery providing a range of 25 to 50 miles on a charge of 30 kilowatt-hours will add at least $1,200 to the cost of the vehicle. Although future batteries may provide higher energy density and hence greater range for a given battery weight or volume, they will probably be more expensive. Therefore the range limitations of future electric vehicles may well be set not by battery weight but by battery costs.

To compensate for their higher initial costs electric vehicles will have to demonstrate that they are cheaper to operate for similar tasks. Their greater efficiency and the continuing escalation of automobile-fuel prices give them the potential for doing so. Future urban electric vehicles should be able to get two miles per kilowatt-hour, or about 50 miles on a dollar's worth of electricity (assuming a typical residential rate of four cents per kilowatt-hour); a conventional vehicle is likely to go only half that distance in urban traffic on a dollar's worth of fuel. The experience of the U.S. Postal Service with its fleet of limited-production electric vehicles shows that under certain conditions the overall economics of initial cost and operation can favor electric vehicles even today.

In the longer run additional economic factors such as low off-peak charging rates, low service and maintenance costs and the anticipated high costs of coal-derived motor fuels for conventional vehicles are likely to favor electric vehicles for many uses. Together with the substantially lower overall efficiency of the route from coal to motor fuel to transportation energy, these considerations suggest that electric vehicles (and perhaps other modes of electrified transportation) could become an important response to the oil-supply problem. This importance is recognized in the Electric and Hybrid Vehicle Act passed by Congress in 1976, and the first electric-vehicle demonstrations called for under the act's $160-million, five-year program are now under way. It is also reflected in the recent announcement by E. M. Estes, president of the General Motors Corporation, that the company intends to produce electric vehicles in the mid-1980's.

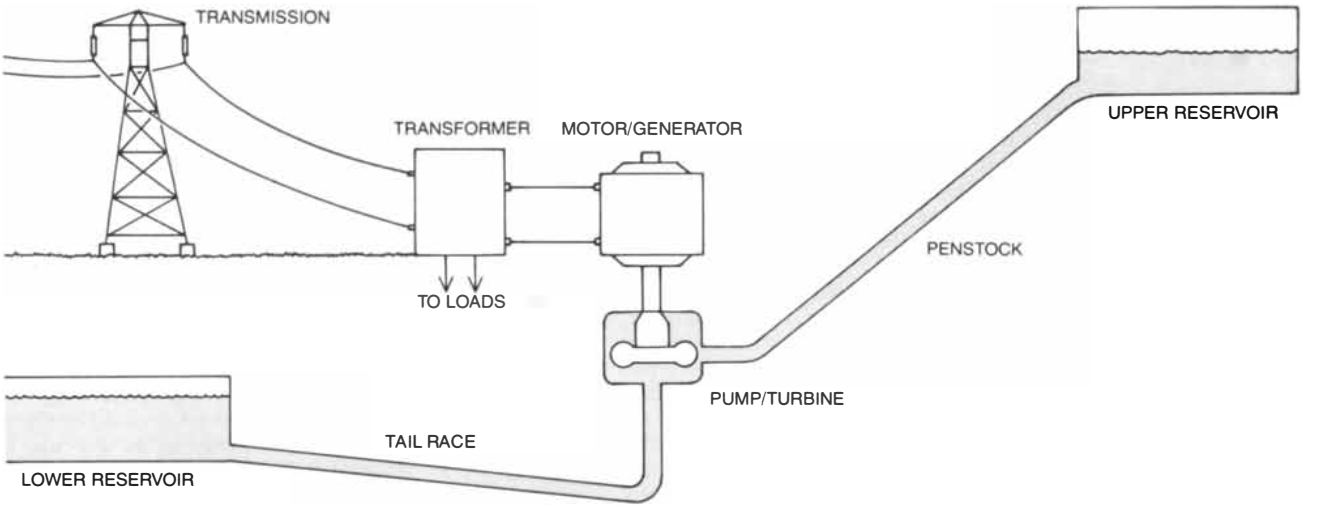
Limited range remains the greatest obstacle to broad acceptance of electric vehicles. This problem is the motivation for intensive battery research-and-development programs supported both privately and by the Government. The General Motors announcement of a zinc–nickel oxide battery (often called the nickel-zinc battery) indicates that progress is being made in these programs. At the same time it is still an open question whether any of the advanced battery systems under development can attain the combination of long life and low cost that would make them widely acceptable. Given this uncertainty, a rational strategy to ease the storage-related range limitation would be to partially recharge batteries during the day whenever the vehicle is not in actual operation. This strategy of *biberonnage* (bottle feeding) would require utilities to make some investment in new facilities, but such outlays are to be expected for any new market. The capital investment, operating costs and logistic complexities would almost certainly be greater for another strategy that is often mentioned: a network of service stations in which a vehicle's empty battery could be quickly exchanged for a fully charged one.

As I have noted, having 10 million electric vehicles on the road by the year 2000 could save .4 million barrels of oil per day. Assuming that the vehicles traveled an average of 10,000 miles per year, the impact of this displacement on the national consumption of electricity would be an increase of 5×10^{10} kilowatt-hours per year (10 million vehicles times 10,000 miles per vehicle times .5 kilowatt-hour per mile), only about 1 percent of the consumption projected for the year 2000. Although this is a small fraction, the impact on regions and individual utilities could be much larger, particularly if it is necessary to charge batteries during hours of peak demand and therefore to reinforce the distribution network.

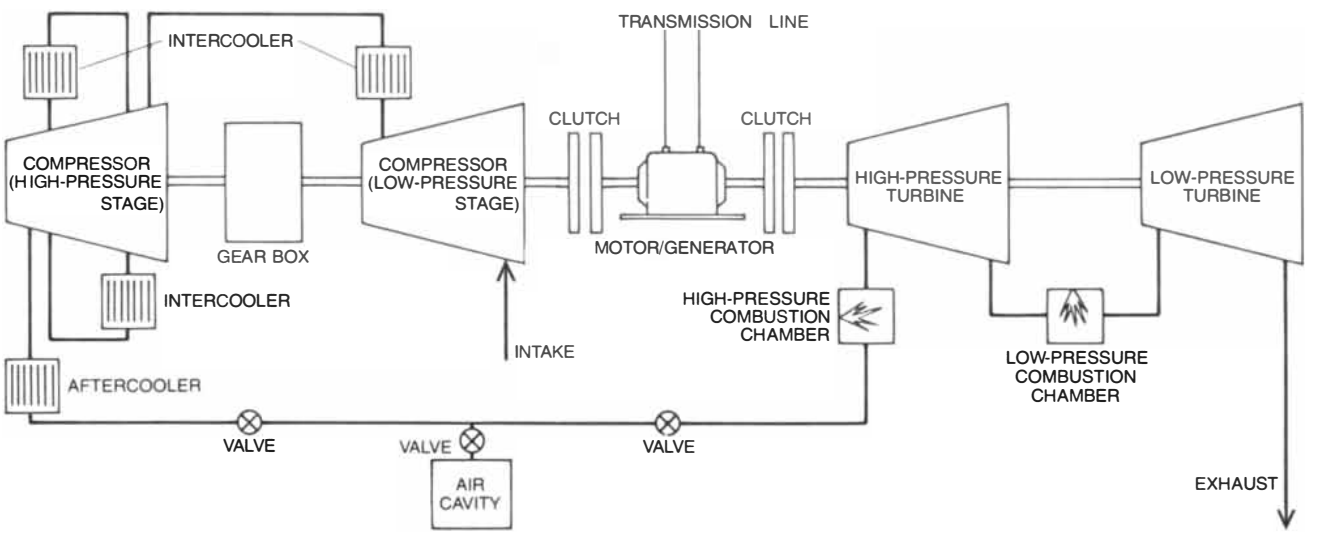
In the longer run, once electric vehicles have become numerous electric utilities will want most of the battery charging to be done in off-peak hours, when coal and nuclear base-load energy is available. In addition to setting preferential rates for off-peak charging, utilities could exercise direct control over equipment for overnight charging and thereby integrate the charging load into the total demand of the power system, with economic benefits for both themselves and the customer.

Important energy uses in which storage systems could bring about a transition to more available and more economic primary sources of energy can be found in the residential, commercial and industrial sectors. These sectors account for about 37 percent of the country's oil consumption and nearly 80 percent of the natural-gas consumption, primarily to provide heat for water, buildings and industrial processes. Shifting much of this demand to coal by burning it at the site of energy consumption would be very difficult because of fuel-handling and pollution problems. These problems can probably be solved by first converting the coal into cleaner-burning gaseous and liquid fuels, but even if the proposed massive programs of coal conversion are begun now, synthetic fuels are not likely to be available in nationally significant quantities much before the year 2000.

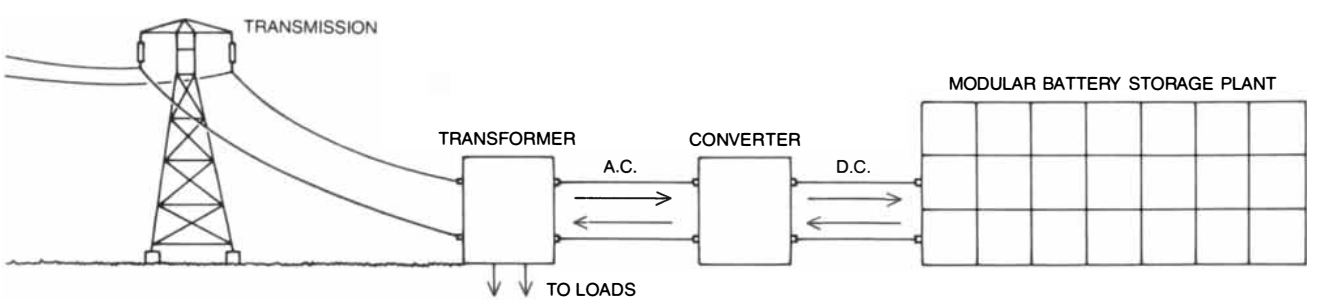
In the meantime the burning of oil and gas to provide heat could be reduced by shifting heating loads to domestic coal and uranium in the form of electricity and by turning to solar energy. If such a strategy is to be effectively implemented, a larger role for energy storage will be important and in some respects even essential. I have discussed how energy storage by electric utilities can contribute to this strategy, and I shall discuss solar energy and its storage



PUMPED-HYDROELECTRIC ENERGY STORAGE is the only large-scale electric-energy storage system whose economic feasibility has so far been demonstrated in the U.S. Surplus base-load generating capacity is used to pump water from a lower reservoir to an upper one in periods of low demand. About 35 such systems with a capacity of more than 25,000 kilowatts are in operation or being constructed in the U.S. Together they represent about 2.5 percent of the nation's total electric-generating capacity. Utilities are considering a variation of pumped storage in which the lower reservoir is a cavern artificially created in rock several thousand feet underground.



COMPRESSED-AIR ENERGY-STORAGE PLANT, the first of its kind, is now operating at Huntorf, near Bremen in West Germany. In periods of low demand (typically over an eight-hour night period) air is compressed and stored at a pressure of about 70 atmospheres in two caverns leached out of a salt dome that have a combined capacity of about 300,000 cubic meters. At times of peak power demand the air is expanded through turbines that can generate 290,000 kilowatts of power for two hours. Coolers remove the heat generated during the compression cycle to keep cavern walls from overheating. Heat so removed is replaced by burning some fuel when air is expanded.



ENERGY STORAGE IN ELECTRIC BATTERIES would have many new advantages if the advanced battery systems that are now under development prove to be successful. Unlike pumped-water and compressed-air storage systems, battery storage plants could be put almost anywhere. Since they could be assembled from mass-produced modular units, they should be economic even in small sizes, and they could be set up quickly at the most advantageous locations within an extended power grid. A battery storage plant with a power rating of, say, 20,000 kilowatts and a capacity of 100,000 to 200,000 kilowatt-hours should not occupy an area of more than half an acre.

in some detail below. There is, however, still another way to employ storage to shift energy demands: the storage of thermal energy close to its end use. In this approach heat or "cold" is generated with off-peak power on the consumer's premises and stored there for consumption during peak demand periods. Since the strategy shifts the storage investment to the consumer, utilities can and must provide financial incentives by offering rates that reflect the lower costs of generating off-peak power.

Through appropriate rates a number of U.S. utilities have induced their customers to employ water heaters as energy-storage devices controlled by timers or by electric signals from the utility. This "load management" strategy has helped utilities to reduce peak demand and to shift some energy to base-load power. The effect would be much greater if space heating were provided from coal and nuclear energy through the storage of heat generated with off-peak power. The practice has been gaining ground in several European countries in recent years. In some parts of West Germany, for example, storage heaters account for nearly a fourth of the total demand for electricity in winter, so that the daily load curve of a utility is almost flat.

The barriers to wider adoption of such storage heating systems in the U.S. are institutional rather than technical or economic. Neither the needed information nor the financing is readily available to encourage investment in such units, and many utilities do not yet offer the appropriate rates. For customers who want to buy storage heating systems, however, a variety of electrically heated storage units are commercially available. They include tanks for pressurized hot water, floor-slab heaters and ceramic-brick units for individual room heaters and central building-heating systems. If such systems were to be installed in 10 million homes by the year 2000, the oil and gas savings could be the equivalent of .5 million barrels of oil per day. The benefits of customer energy storage—the reduction of peak power demand and the shift of demand to off-peak base-load energy—can be maximized if utilities can retain a measure of control over the charging of such units. The control methods currently under investigation include start and stop signals transmitted by radio, signals sent over the wires of the utility's own network and signals sent over telephone lines. Such load management does not normally inconvenience the customer, and it can reduce his electricity bill.

In many regions of the U.S. where on summer days air conditioning represents a large fraction of the daily peak load the storage of "cold" could become very useful. Systems employing electric refrigeration at night to chill water or make ice with which to cool air during the daytime peak are now being tested in homes and commercial buildings in various parts of the country. Experimental installations have shown that the peak power demand for cooling can be reduced as much as 75 percent, which could enable utilities to save substantial amounts of the oil and gas commonly burned in peaking power plants and to defer the need for such plants.

The potential of energy storage in manufacturing processes is harder to evaluate, but there is little doubt that improved and novel methods of storing energy could yield substantial savings in oil and other fuels. In many industrial processes much energy is consumed to heat or melt materials such as steel, aluminum and glass. The efficiency of this "intrinsic" energy storage might be increased by the modification or redesign of such processes, for example by installing better insulation or a system for reflecting infrared radiation back into the hot material. In many cases the thermal energy remaining in the material after the completion of its processing could be recycled for preheating the next batch of material or could be transferred to other steps in the process. In general the storage of thermal energy, either in a medium intrinsic to the process or in a separate thermal storage system, could lead to significant savings of fuel. In some cases it might prove economic to use storage in "cascading" heat downward in a series of temperature steps.

Another potentially significant industrial application for energy storage is in cogeneration, where the high temperatures developed by the burning of fossil fuels for process heating are also utilized to generate electric power. The efficiency advantage conferred by such cogeneration tends to be offset by the fact that the cogenerator's closely coupled production of heat and electricity is rarely matched by the pattern of demand. Thermal energy storage at the cogeneration site, or perhaps electric energy storage on the power grid, could offer possibilities for matching supply and demand with respect to both thermal energy and electric.

BATTERY TYPE	OPERATING TEMPERATURE (DEGREES CELSIUS)	ENERGY DENSITY (WATT-HOURS PER KILOGRAM)	POWER DENSITY (WATTS PER KILOGRAM)	ESTIMATED CYCLE LIFE	ESTIMATED COST (DOLLARS PER KILOWATT-HOUR)	ESTIMATED AVAILABILITY (YEAR) (PROTOTYPES OR EARLY COMMERCIAL MODELS)
LEAD-ACID						
UTILITY DESIGN	AMBIENT	—	—	2,000	80	1984
VEHICLE DESIGN (IMPROVED)	AMBIENT	40	70	>1,000	70	1982
NICKEL-IRON	AMBIENT	55	100	>2,000 (?)	100	1983
NICKEL-ZINC	AMBIENT	75	120	800 (?)	100	1982
ZINC-CHLORINE						
UTILITY DESIGN	30–50	—	—	2,000 (?)	50	1984
VEHICLE DESIGN	30–50	90	90	>1,000 (?)	75	1985
SODIUM-SULFUR						
UTILITY DESIGN	300–350	—	—	>2,000	50	1986
VEHICLE DESIGN	300–350	90	100	>1,000	75	1985
LITHIUM–IRON SULFIDE	400–450	100	>100	1,000 (?)	80	1985

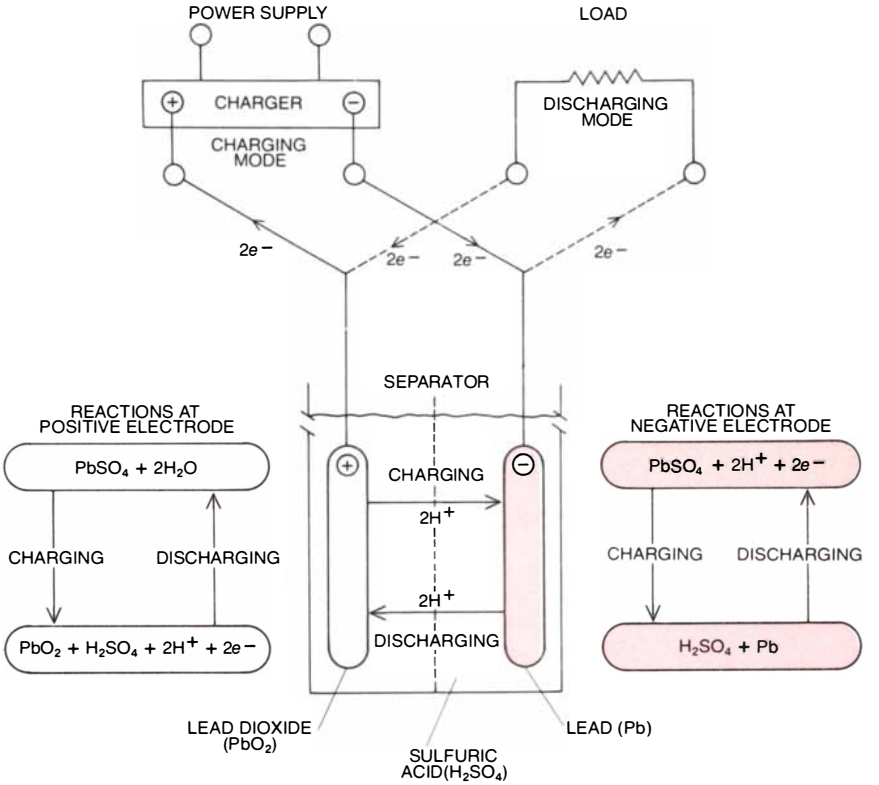
VARIETY OF ADVANCED TYPES OF BATTERIES are currently under development for electric-utility storage systems and electric vehicles because the lead-acid battery probably cannot be improved much further. The table lists the properties of batteries that may prove superior. The most important criterion for storage in electric-power systems is long life: the ability to undergo from 2,000 to 3,000 cycles of charge and discharge over a 10-to-15-year period. For electric vehicles the chief criteria are high energy content and high power for a given weight and volume. (The dashes indicate that these criteria do not apply to electric utilities.) Both the utilities and vehicles will require batteries that are low in cost (preferably less than $50 per kilowatt-hour of storage capacity), safe and efficient.

Once solar energy begins to displace nonrenewable fuels in the U.S. and in the rest of the world, the need for efficient energy-storage systems will become even greater than it is at present. Storage systems will have two broad roles in the utilization of solar energy: to match an intermittent energy supply with a constant or variable energy demand, and to concentrate energy collected in dilute form and thus make it more usable. As long as solar energy supplies only a small fraction of the energy need in a residence, a community or an electric utility, storage may not be essential: the other components of the energy-delivery system (the oil burner, the gas furnace or the utility grid) can fill in when the sun is not shining. As the solar contribution increases, however, so does the need for storage.

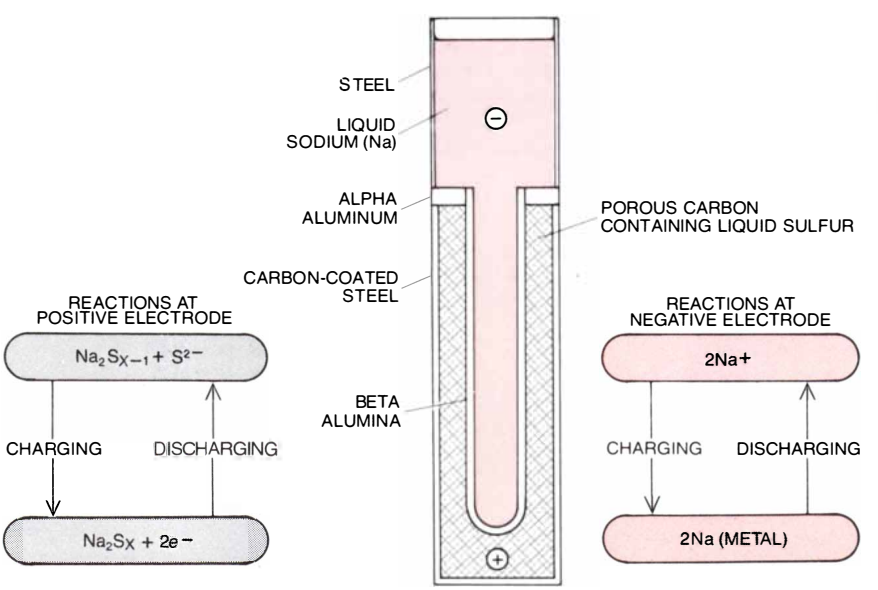
An application for the near future is storage as part of solar water-heating systems. Such storage is important if solar energy is to supply much or most of a household's hot-water requirements. The alternative to storage is to have a backup system including not only a conventional water heater but also the energy system that supplies it with fuel or electricity. It is important to realize that the investment a utility makes in providing the capacity to meet this occasional energy demand can become a major factor in the consumer's total energy cost, often as a "demand charge": a fixed amount that is independent of the quantity of energy actually delivered by the backup water heater. By storing solar-heated water at the site of its use for periods of low solar input the consumer can eliminate or decrease his dependence on external backup systems and reduce the demand charge, often with a net reduction in his total energy cost.

The storage of solar-heated water is technically simple, and systems that accomplish it are available commercially. Hot water is also the preferred storage medium for solar space-heating systems. Because space heating calls for a larger storage reservoir than water heating it is more difficult to physically integrate space-heating storage into a building, particularly an existing one. Per unit of energy delivered, the cost of storage is higher for solar space heating than it is for solar water heating because the space-heating system is not in service for the entire year whereas the water heater is. In principle the utilization of a system for the storage of solar energy could be increased by also employing it for the storage of off-peak electric energy in the form of hot water. Whether this approach or separately optimized solar and off-peak energy-storage systems are better depends not only on the cost of the storage equipment but also on the utility's particular combination of generating equipment and fuel costs.

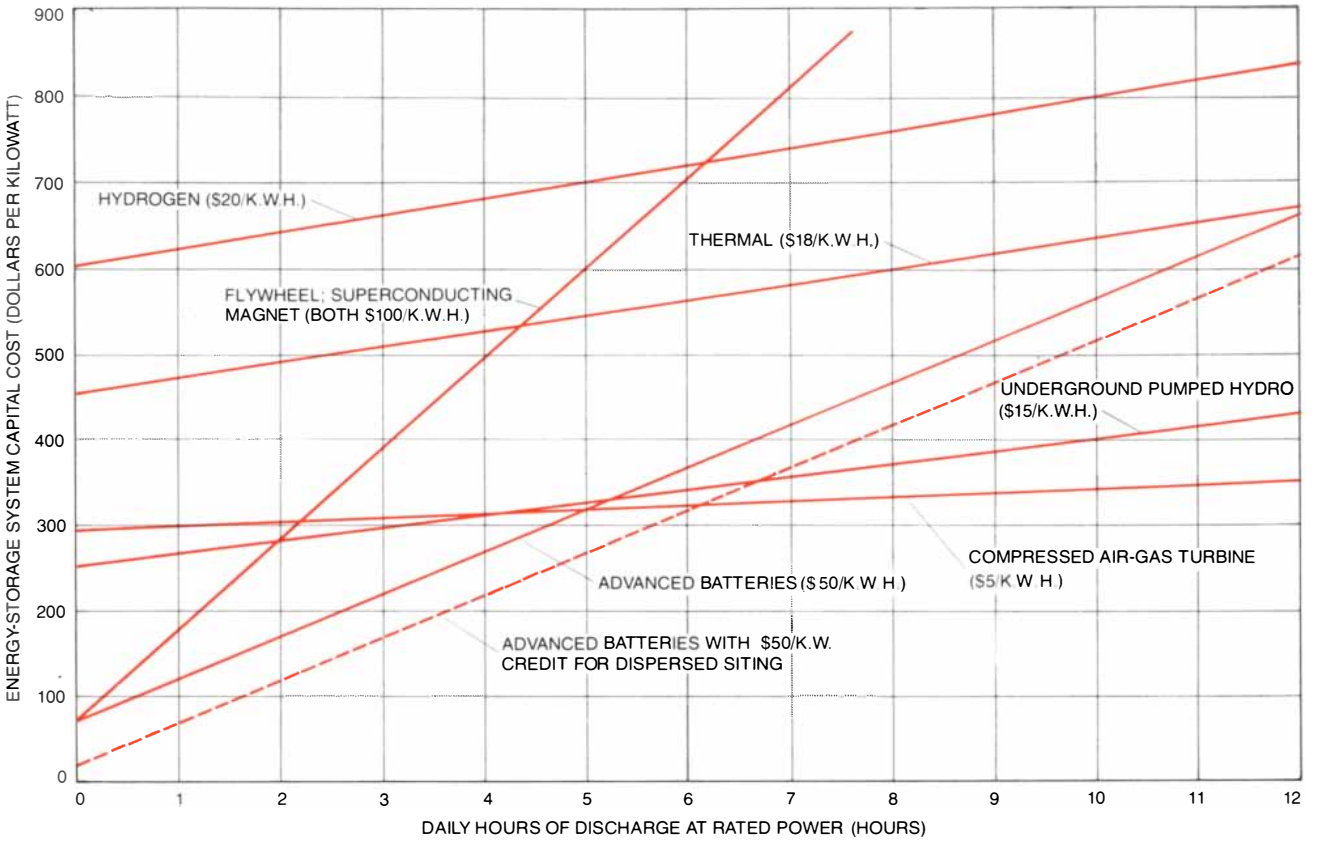
In spite of current uncertainties about



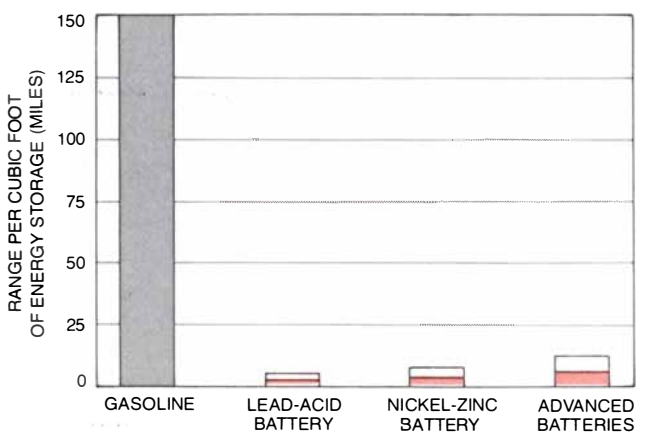
LEAD-ACID STORAGE BATTERY consists of alternate pairs of plates of lead and lead coated with lead dioxide immersed in a dilute solution of sulfuric acid, which serves as an electrolyte. Here only one pair of plates, or electrodes, is shown. During discharge both electrodes become converted into lead sulfate ($PbSO_4$). Charging restores the positive electrode to lead dioxide and the negative electrode to metallic lead. The performance of such a battery deteriorates gradually because of irreversible physical changes in the electrodes; ultimately failure occurs between several hundred and 2,000 cycles, depending on battery design and duty cycle.



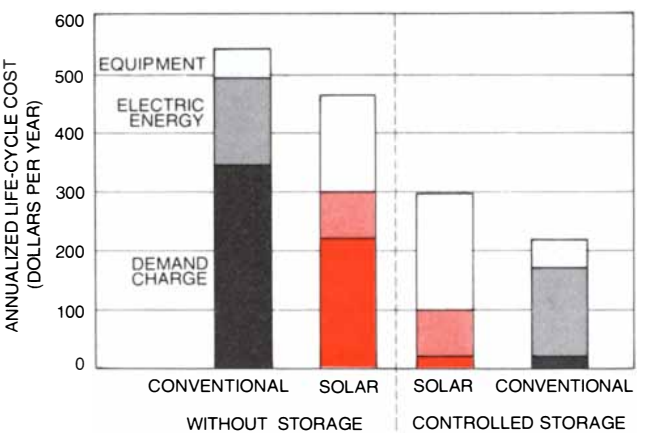
SODIUM-SULFUR CELL is one of several promising new batteries. The cell is operated at from 300 to 350 degrees Celsius, a temperature at which the negative electrode (sodium) and the positive electrode (sulfur) are liquid. Current from the sodium is collected by a steel housing. Sulfur at the positive electrode has a low conductivity and so must be in contact with a porous carbon current collector in contact with a corrosion-resistant steel housing. The positive and negative compartments are separated by an insulating ring of alpha aluminum and the electrolyte, a ceramic tube of beta alumina. At 300 degrees C. the ceramic has an ionic conductivity almost as high as that of a conventional liquid electrolyte at ambient temperature. The ceramic allows only sodium ions to pass, which prevents processes that reduce efficiency and life of the battery. Small cells have been cycled 1,000 times without appreciable degradation.



COSTS OF ENERGY-STORAGE SYSTEMS of interest to electric utilities show a wide variation. The capital cost, usually expressed in dollars per kilowatt of power capacity (*vertical scale*), is the sum of two components: the cost of the conversion subsystem and of the storage subsystem (the "reservoir"). The cost of the storage subsystem is the product of two components: the cost per unit of storage capacity (in dollars per kilowatt-hour) and the maximum time in hours for which a fully charged system can be discharged at the designed power. As is indicated by the labels next to the sloping lines, the cost per unit of capacity appears to be lowest for compressed-air storage (less than $5 per kilowatt-hour) and highest for flywheel storage ($100 per kilowatt-hour). The costs of other systems fall between these figures. The figures given, however, are only approximate and are subject to change with technological advances. As the illustration shows, underground pumped-water storage and compressed-air storage become increasingly attractive when longer discharge at full power is desired; many utilities tend to look for a discharge capability of eight to 10 hours or more. For discharge periods of less than eight hours battery systems have the potential to become the most attractive, provided that low-cost, long-life batteries can be developed; the lower of the two battery curves includes a capital credit of $50 per kilowatt for transmission savings and other benefits associated with dispersed siting and short construction times. Discharge times of less than two hours are not likely to be of practical interest to utilities.



DENSITY OF STORING ENERGY as gasoline gives the conventional automobile a great advantage in range over electric vehicles. An automobile achieving 20 miles to the gallon can go 150 miles on one cubic foot of gasoline, whereas the energy stored in a cubic foot of lead-acid battery would propel an electric vehicle that could be designed today barely four miles. The lower segment of the bars representing the specific range for different batteries is based on a power consumption of one kilowatt-hour per mile. The significance of the development of new batteries for the viability of electric vehicles is apparent. The increment on each of the bars represents the range of improved vehicles that might achieve two miles per kilowatt-hour.



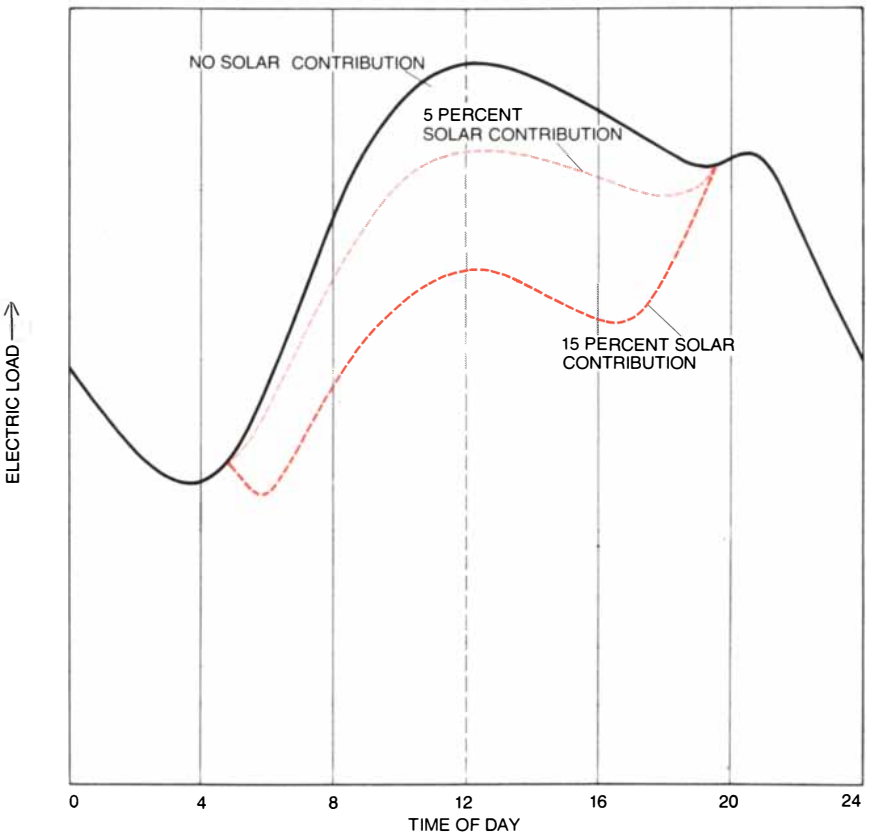
COST OF RESIDENTIAL HOT WATER can be reduced significantly by the addition of a hot-water storage system because storage reduces the utility's need for backup generating capacity for which the consumer must normally pay a "demand charge." The two bars at the left show that the solar-energy input by itself can decrease the backup requirements; in the case on which the bars are based (the service territory of a utility in the eastern U.S.) it could do so to an extent that would more than offset the cost of the equipment. When storage is added to the two systems (*bars at right*), the demand charges become negligible and the conventional system can be cheaper than the solar one provided electricity can be bought at low-cost off-peak rates.

optimum system design and total cost (for capital and operation), the on-site storage of solar heat is likely to pay for itself, particularly if the real costs of oil and gas continue to rise. Moreover, alternatives to hot water as a storage medium may prove to be more economical. For example, solar heat could be transferred by air to a bed of rock under a building or adjacent to it. A still simpler and potentially cheaper approach is to use building materials that can effectively store daytime heat or nighttime "cold," or to integrate into the building surfaces special materials that provide a cost-effective storage function. It is reasonable to speculate that between them these storage methods can help solar energy to capture 10 percent of new residential and commercial consumption of thermal energy over the next 20 years. If it does, the energy savings will be equivalent to some one million barrels of oil per day.

The storage of summer heat for the winter is not beyond the range of possibility, but capital costs must be kept extremely low because the amount of energy delivered per unit of storage capacity in any annual-cycle system is very small. Therefore the only substance that can qualify as the storage medium is water. For example, heat from the sun and from industrial installations could be absorbed and stored seasonally in ponds or small lakes. Another possibility would be to store warm or cool water in natural aquifers. In any of these schemes the high cost of transporting warm or cool water from the reservoir to the user is likely to be a serious economic handicap. Nevertheless, the concept of storing heat in small, specially insulated lakes is being seriously studied in West Germany, and experiments with aquifers for hot- and cold-water storage are under way in the U.S.

In the long run, near the end of the century and beyond, one can expect solar energy to be harnessed to generate increasing amounts of electric power. At first no specific storage capacity will be needed, since solar-electric energy will normally be fed into power grids that will have adequate capabilities for absorbing the fluctuations in the solar input, much as they now balance their electric loads. The situation would change, however, if solar-generated electricity reached a significant fraction of the total power output. At that point the load curve of the system would be likely to develop a pronounced early-evening peak, and energy storage at the system level could help to flatten the peak so that the electricity could be provided by efficient base-load plants. It is clear, then, that installing energy-storage facilities for operation with coal and nuclear base-load plants in the short run will directly aid the introduction of solar-power generation in the longer run.

In contrast to grid-connected solar-electric systems, "stand alone" solar-electric systems, which are currently of interest in developing countries, will require dedicated storage facilities. An example is the 350-kilowatt photovoltaic system that is being designed for two villages in Saudi Arabia. The storage will be provided by lead-acid batteries.



IMPACT OF SOLAR-ENERGY GENERATION on the load curve of a utility is shown schematically for two levels of a solar-energy contribution to the meeting of electric-energy demand; it is assumed that the solar component is fed into the electric grid at all times. If the solar energy could contribute 5 percent of the system's energy supply, it would help to meet the daytime peak and displace some conventional generating capacity. When the solar contribution rises as high as 15 percent, however, the conventional equipment of a utility could experience a sharp evening peak. In that case it might be economic to add one of the electric-utility energy-storage systems to flatten the load on conventional equipment. It is apparent that utilities adding energy-storage systems to systems of generating base-load power from coal or nuclear fuel will be able to more effectively use solar electricity once it is available at an acceptable cost.

From the preceding discussion it should be clear that energy storage could become an important component in the national strategy to reduce dependence on oil and gas through expanded reliance on coal and nuclear energy and through expeditious and economic utilization of solar energy. It also seems clear that energy storage will be playing a significant role in this century. Within the next five years several U.S. utilities will probably announce plans to construct an underground pumped-hydroelectric system or a compressed-air energy-storage system. If the expected progress in battery development is made, battery storage systems could come into service for electric utilities in the late 1980's. Advances in batteries should also accelerate the introduction of electric vehicles for commercial and personal service. The adoption of off-peak and solar-energy storage schemes in residences and commercial buildings will depend more on private initiative than on technological innovation, and it could begin tomorrow; the process could be accelerated by offering utility customers attractive off-peak electric rates and tax incentives for the purchase of solar equipment.

Whether energy storage will have the impact I have suggested here will depend not only on successful technical developments but also on nontechnical factors. Foremost among them are the risks and high costs of developing, commercializing and (for the customer) acquiring new energy technologies. The risk is increased by uncertainties about the future availability and costs of both conventional and new energy sources and about the public policies that affect them. In spite of these uncertainties the potential benefits and technological possibilities appear to be sufficiently great to ensure for energy storage an important role in the energy systems of the future.

Implantable Drug-Delivery Systems

Many therapeutic drugs are most effective when they are delivered into the bloodstream steadily. Such delivery can be accomplished by the surgical implantation of a drug pellet, a reservoir or a pump

by Perry J. Blackshear

Many drugs that are administered for medical reasons work best when the drug is delivered to the bloodstream continuously at a constant rate. A patient taking a drug in intermittent oral doses will often not achieve anything like that result. About the only way to achieve it now is through continuous intravenous infusion, which is normally done in a hospital with an elaborate rig involving bottles of fluid, connecting tubes and cannulas, or intravenous tubing; this is the procedure that goes by the familiar abbreviation "I.V." (for intravenous). Several groups of workers are attempting to perfect new and radically different procedures for delivering a drug by way of a device implanted in the body. Already the strategy serves effectively in such applications as contraception and the chemotherapy of cancer. In the future one can see systems that do such things as release insulin in response to the body's own biochemical feedback loop and so function as a true artificial pancreas, deliver dopamine to the appropriate area of the brain to control Parkinson's disease or infuse immunosuppressive drugs to prevent the rejection of transplanted organs.

As one would expect, an oral dose generally provides a high level of the drug in the blood right after the dose is taken. The drug immediately begins to disappear from the blood, however, at a different rate for each drug in each patient. The rate is usually expressed in terms of the half-life of the drug in the circulation, that is, the time it takes for the concentration of the drug to decrease to half its peak level. If one plots the rise and fall on a graph, a peak-and-valley pattern emerges.

This peak-and-valley effect can give rise to a number of problems. For example, the drug procainamide, which is administered to counteract irregular rhythms of the heart, must be given to most patients every three hours in order to provide blood levels near the therapeutic range; the reason is its brief half-life. Shortly after each dose the concentration of the drug in the blood reaches a level that for some individuals may be toxic. On the other hand, if one skips a dose, as most patients do at night, the blood level of procainamide falls below the therapeutic range, leaving the patient vulnerable to the underlying condition. A continuous infusion of the drug directly into the bloodstream, which would be achieved by an implantable system, avoids the peak-and-valley effect and administers a constant level of a drug to the patient.

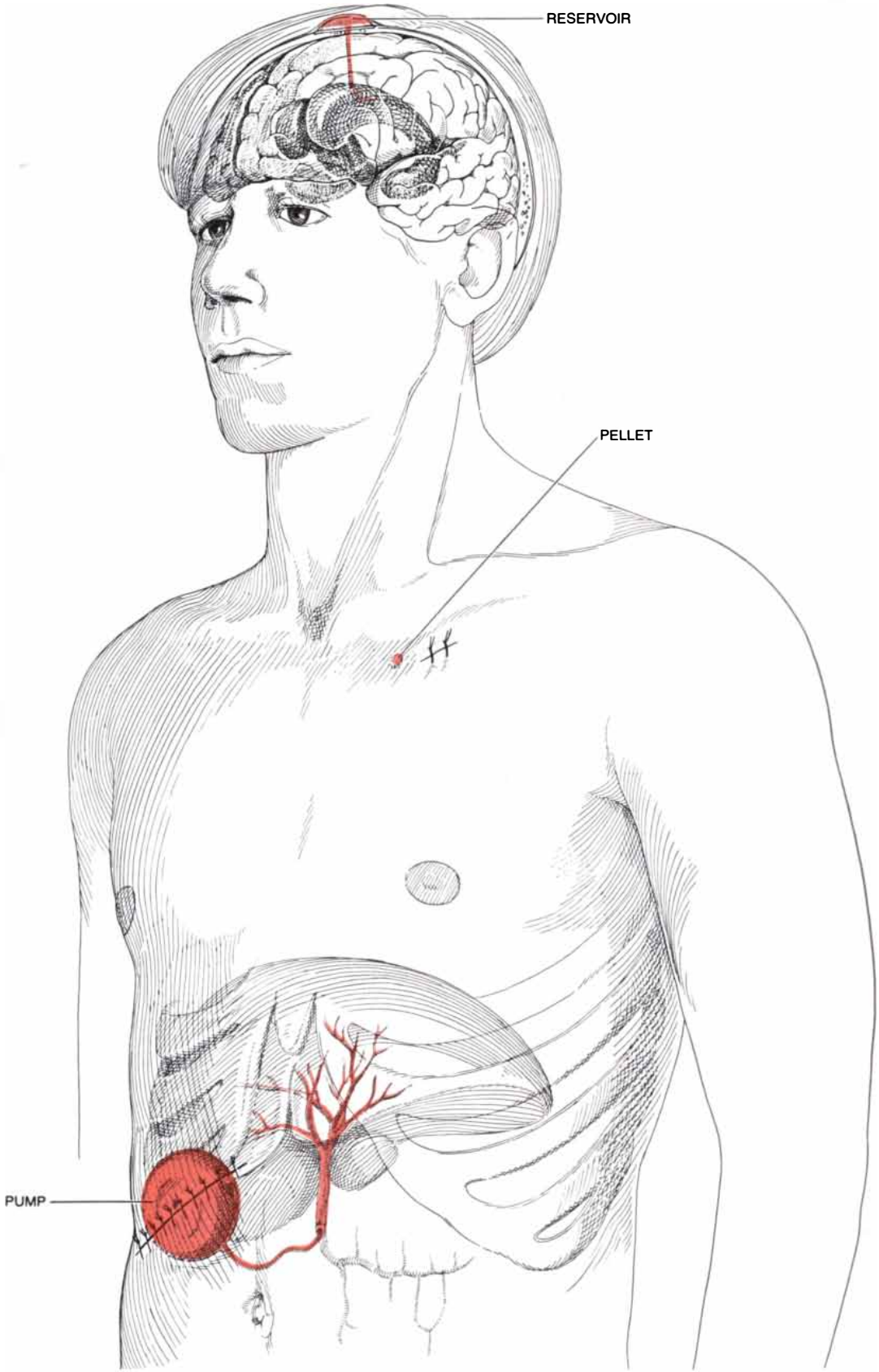
Another reason for developing implantable drug-delivery systems is due to the fact that many drugs must be given by injection because they are inactivated in the gastrointestinal tract. If such a drug also has a short half-life in the circulation, it must be given in frequent uncomfortable injections or by intravenous infusions. Hence the administration of such drugs is limited almost exclusively to hospitalized patients.

Examples of drugs that have a short half-life and must be injected are heparin, the best available agent for preventing the clotting of the blood, and lidocaine, probably the most effective means of suppressing life-threatening disturbances of the heart rhythm. Another substance that must commonly be injected is insulin, the pancreatic hormone that is deficient in diabetes. It has a relatively long half-life when it is given in one of the modern long-acting preparations, and so in many cases it can be administered as infrequently as once a day. Because the levels of insulin in the blood after injection do not closely match the levels achieved with the insulin secreted by the normal pancreas, however, such preparations may cause problems for some diabetics. I shall return to this point below.

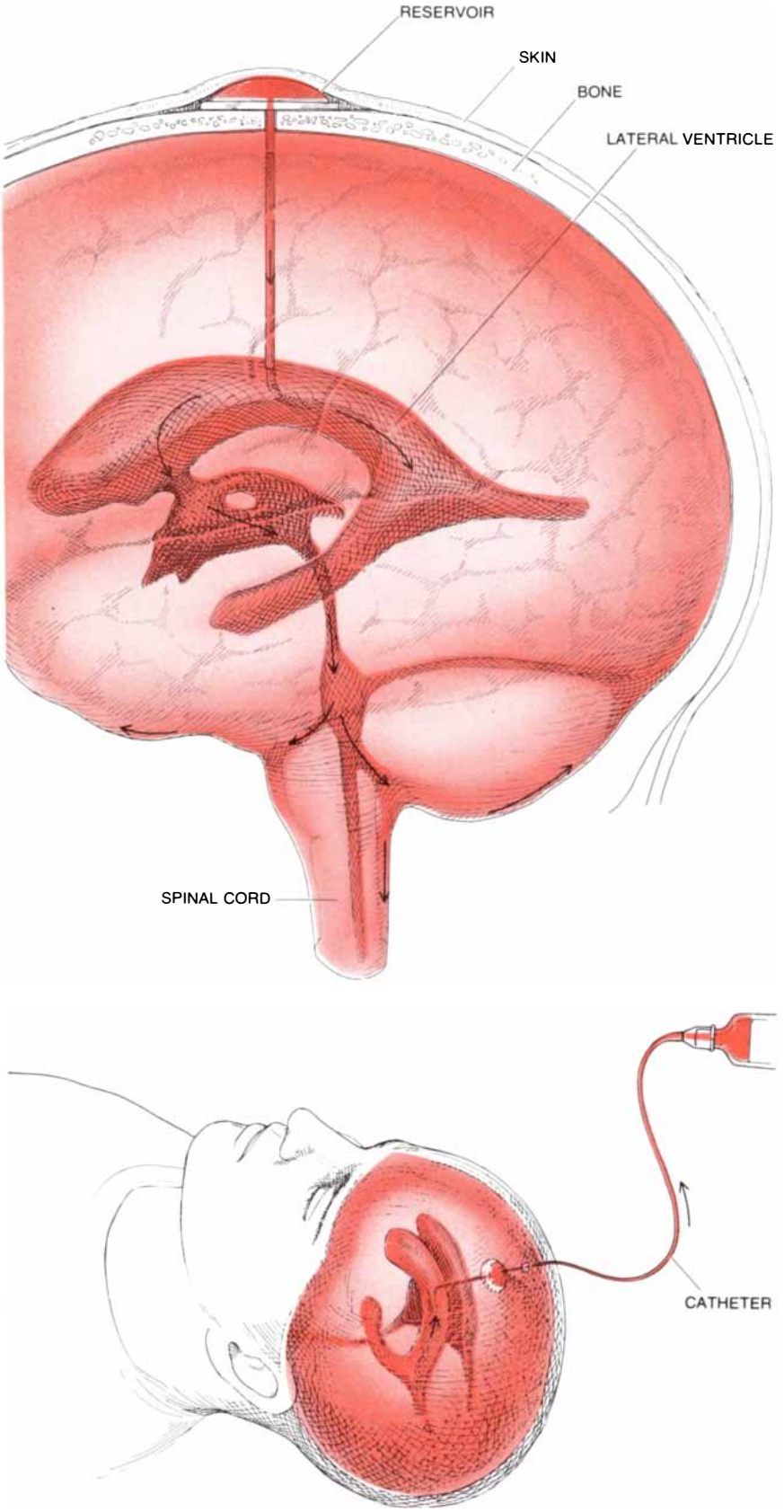
To my knowledge the concept of implantable drug-delivery systems originated with R. Deansley and A. S. Parkes, who in about 1937 presented at the Royal Society of Medicine in London a paper describing the effects of various hormone preparations on the growth of livestock. In one experiment they compressed pure crystalline estrone into small pellets, which they implanted under the skin of brown leghorn capons. Because no blood test for estrogen was available at the time, they assessed the effect of the hormone by shaving areas of the chicken's breast and observing new feathers as they appeared. To their surprise one subcutaneous estrone pellet caused female feathers to grow on the male birds for as long as three months.

In 1938 P. M. F. Bishop of Guy's Hospital in London reported the use of subcutaneous pellets of compressed estrogen in the treatment of a young woman suffering from premature menopause. The effectiveness of the therapy was monitored by the number of hot flashes the woman had per day. Although this technique is hardly as precise as measuring the serum estrogen concentration in picograms per milliliter, which is how such a therapeutic regimen would be monitored today, Bishop and his colleagues concluded that some degree of estrogen replacement continued for as long as five weeks after the implant, as judged by a decrease of 50 percent in the number of hot flashes per day.

The technique of implanting solid pellets of pure hormone quickly evolved to include other steroid hormones. Among them are testosterone for males with a deficiency of the hormone, deoxycorticosterone for the treatment of Addison's disease and estradiol for prostate cancer. The pellets are the simplest kind of implantable drug-delivery device. They release their contents into the subcutaneous tissue mainly through a process of erosion. The rate of release depends primarily on the surface area of the im-



IMPLANTABLE DEVICES are shown in a hypothetical patient (hypothetical because no one person would be likely to have all three devices at the same time). The device implanted under the scalp is the Ommaya reservoir, which has the advantage of giving access to the otherwise largely inaccessible cerebrospinal fluid. The bulbous part close to the scalp can be refilled repeatedly with a hypodermic needle; the drug then drains into a ventricle of the brain. The pellet, which consists of a concentrated drug, is implanted just under the skin. It releases its drug into the subcutaneous tissue mainly through a process of erosion. The implanted pump has a fluorocarbon propellant that maintains a constant pressure on a supply of a drug, so that the pump is able to deliver drug at a constant rate to a vein or an artery.



OMMAYA RESERVOIR is depicted as it would be utilized for the delivery of a drug such as a chemotherapeutic agent (*top*) and as it would serve for the withdrawal of a quantity of cerebrospinal fluid by means of a syringe (*bottom*). In a typical procedure the syringe would be put aside and a second syringe containing a drug would be attached to the catheter. More cerebrospinal fluid would be withdrawn to be mixed with the drug, which would then be injected through the catheter. Finally, fluid in the first syringe would be injected to flush the system.

plant and the solubility of the drug in the body fluids.

Over the past 15 years the concept of implantable drug-delivery systems has reached a somewhat higher level of sophistication. In 1964 Judah Folkman and David M. Long, working at the National Naval Medical Center in Bethesda, Md., described experiments in which compounds of low molecular weight were shown to diffuse out of a small silicone-rubber capsule implanted in the heart muscle of dogs. They also found that the capsule, implanted under the skin, elicited little of the inflammation that often results from the body's defensive mechanisms against foreign substances.

Later studies by these investigators and others demonstrated that several classes of drugs would diffuse out of a silicone-rubber capsule at a fairly constant rate: steroid and thyroid hormones, anesthetic agents and antibiotics. These first studies were limited to fat-soluble compounds of low molecular weight because large molecules such as proteins and polysaccharides will not diffuse through silicone rubber.

By 1972 the development of a different matrix, polyacrylamide, made possible the release of large molecules; the first report of success in this area, involving the protein insulin, was published by B. K. Davis of the Worcester Foundation for Experimental Biology. Further reports by Davis and Folkman extended the technique to several other proteins. The polymers of the time, however, provoked a local inflammatory reaction when they were implanted. More recently Robert Langer and Folkman have demonstrated that the polymers hydroxymethyl methacrylate and ethylene-vinyl acetate copolymer are as effective as polyacrylamide but cause little inflammation.

Usually a polymeric device for delivering a drug is implanted under the skin after a small incision has been made under local anesthesia. Some quite small capsules can be injected under the skin through a large needle. Whatever the combination of drug and polymer, the net drug-delivery effects are much the same. After an initial period of rapid release of the drug, termed the burst effect, the active ingredient is released at a constant rate for prolonged periods of time. Hence after a single subcutaneous implantation of a drug-polymer combination fairly constant levels of the drug can be maintained in the blood.

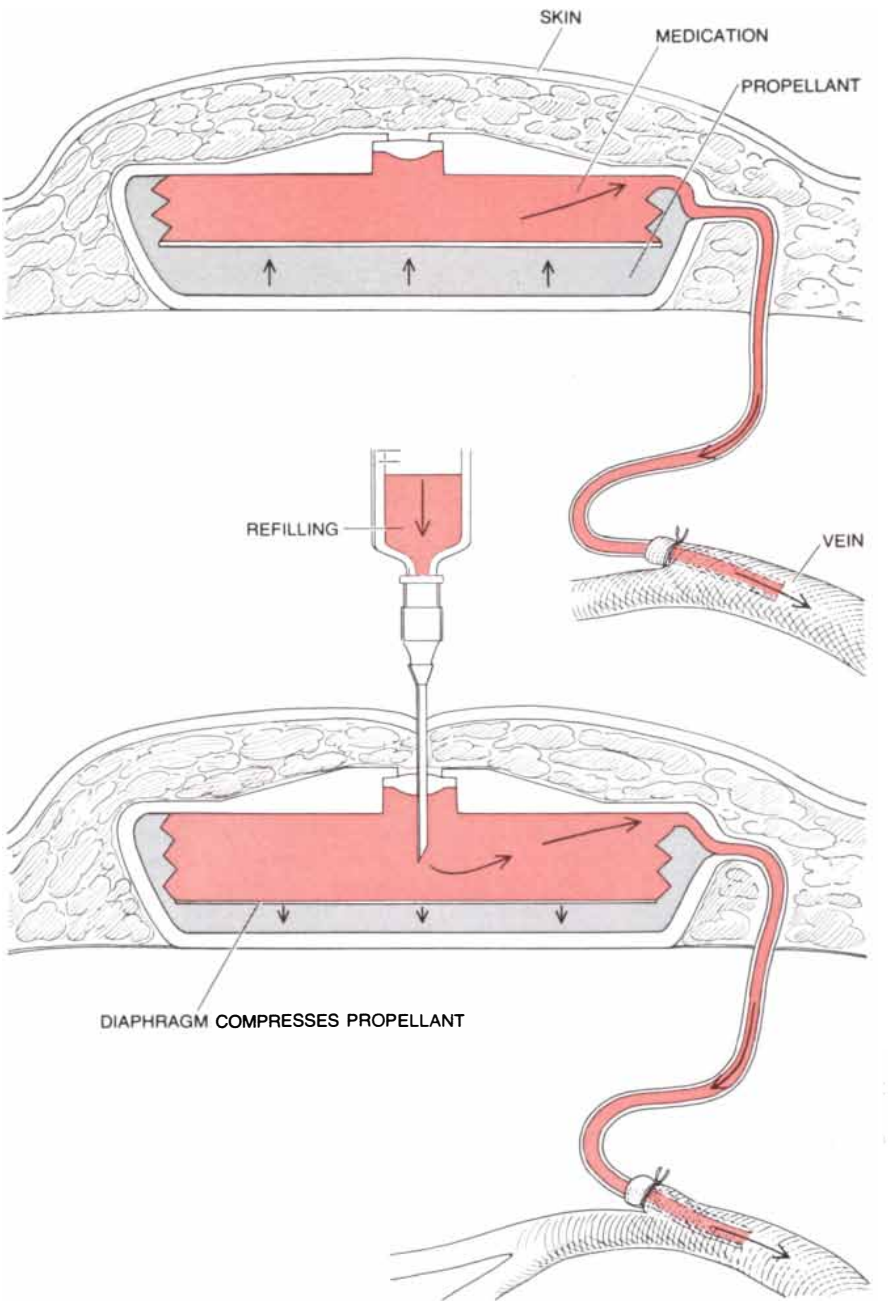
The techniques of implanting capsules containing drugs have now reached the stage of application both in experimental and in clinical settings. Numerous devices have been developed for the diffusion of steroid hormones through silicone rubber. For example, contraceptive devices in the form of sili-

cone-rubber capsules or rings containing progesterone have been implanted subcutaneously or placed in the uterus or the vagina. Hans Marberger of the University of Innsbruck has employed subcutaneous silicone-rubber capsules containing ethinyl estradiol in the treatment of more than 100 patients with prostate cancer. He has also shown that a single capsule of testosterone implanted subcutaneously will release the hormone at a low and fairly constant rate for up to 13 months and that various disorders of male reproductive function caused by a deficiency of testosterone can be treated by this means.

Other devices exploit the principle of controlled drug release from a polymeric matrix without being strictly implantable. The Alza Corporation of Palo Alto, Calif., has developed a number of such devices. They include a wafer of ethylene-vinyl acetate copolymer that releases pilocarpine onto the conjunctiva of the eye in the treatment of glaucoma and a thin membrane containing scopolamine that is placed on the skin, allowing the drug to diffuse through the skin for the treatment of motion sickness and severe nausea resulting from the chemotherapy of cancer. Alza has also developed an intrauterine device that prevents conception through the slow release of a progesterone directly into the uterine cavity.

Many investigators are now applying the principles of controlled release from silicone rubber and other polymers in animal models of a variety of human conditions. Examples include systems for delivering narcotic antagonists such as nalozone in the treatment of opiate addiction, prostaglandins to induce early abortion, various chemotherapeutic agents for the treatment of cancer, insulin for diabetes and heparin in the treatment of abnormal blood clotting.

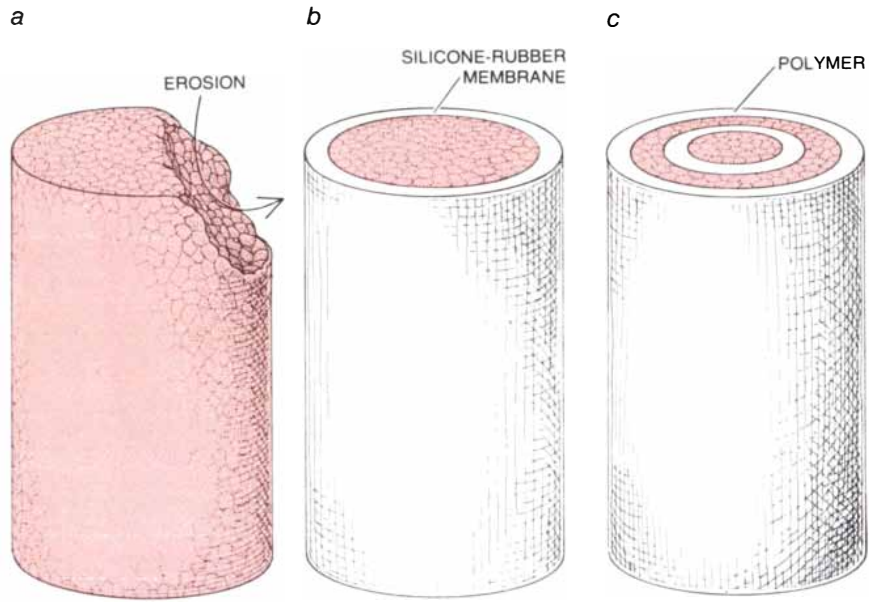
Notwithstanding the advantages of subcutaneous capsules, the delivery of drugs in this way still has many limitations. For one thing, the drug is released into the subcutaneous tissue rather than directly into the bloodstream. Its entry into the circulation is therefore controlled to some degree by the local blood supply, which in turn varies with the amount of fat in the subcutaneous tissue, the activity of the patient and other factors. Moreover, the body sometimes surrounds an implanted object with a dense layer of fibrous tissue, which can impede the diffusion of a drug into the circulation. Another major problem is that the amount of drug delivered cannot be readily adjusted or stopped once the implant is in position. The ability to regulate the dosage is important with powerful drugs such as heparin and insulin, with which overtreatment and undertreatment can be dangerous. Finally, only a few drugs are available in forms sufficiently concentrated to make small, long-term subcutaneous implants practicable.



IMPLANTABLE PUMP, which has the trade name Infusaid, is shown in operation (*top*) and during refilling (*bottom*). The pump consists of a disk made of titanium. Inside it is divided into two chambers by a bellows. The bottom compartment contains a fluorocarbon propellant that at body temperature exerts a constant pressure against the bellows. Above the bellows is the drug, termed the infusate, which is pushed by the propellant into a catheter that is inserted in a vein or an artery. The infusate chamber can be refilled by means of a hypodermic syringe.

To circumvent some of these problems several other types of implantable drug-delivery system have been devised. The first of them to be employed clinically was the Ommaya reservoir, developed in about 1963 by Ayub K. Ommaya of the National Institute of Neurological Diseases and Blindness. This simple device is a small container that is implanted under the skin of the scalp and is connected to a cerebral ventricle by means of a short tube. On the side nearest the skin the reservoir has a self-sealing membrane that can be punctured repeatedly by hypodermic needle; hence the device gives the physician easy and repeated access to the cerebrospinal fluid, the blood-plasma filtrate that bathes the brain and the spinal cord.

The Ommaya reservoir has been useful in the treatment of certain forms of leukemia in which the malignant cells are sequestered in the subarachnoid



IMPLANTABLE PELLETS include the three forms depicted here. The simplest type (*a*) consists of compressed drug or hormone. The material enters the subcutaneous tissue by erosion and goes from there into the bloodstream. In another type of pellet (*b*) the drug or hormone is put in a silicone-rubber capsule, through which it diffuses into the tissue. In the third type (*c*) the drug is contained in a matrix of polymer that degrades within the body, so that it enters the tissue both by diffusion through the outer layer of the polymer and by erosion of the polymer.

space (which is filled with cerebrospinal fluid) and are otherwise protected from chemotherapeutic drugs that do not cross the barrier between the brain and the general circulation of the blood. The reservoir is also useful in chronic forms of fungal meningitis, when high concentrations of antibiotics in the cerebrospinal fluid are needed. The usefulness of the device lies in its ability to provide easy entrance to the otherwise fairly inaccessible subarachnoid space.

The concept of a subcutaneous drug reservoir evolved further in 1970 when Henry Buchwald, Richard L. Varco, Perry L. Blackshear, Jr. (my father), Frank D. Dorman and I at the University of Minnesota School of Medicine designed an implantable infusion pump and began testing it. The purpose of the device was to provide a means of continuously delivering heparin to ambulatory patients with severe clotting problems. Heparin can be given only by injection or infusion, and so it is administered almost exclusively to hospitalized patients. Injections are impractical because they are needed every four to six hours, a function of heparin's short half-life in the circulation; furthermore, recent studies of patients with various clotting problems have shown that the continuous infusion of heparin carries less risk of bleeding complications than periodic injections do.

We first tried to administer heparin by diffusion through silicone-rubber membranes; the attempts failed mainly because of the large size of the heparin molecule. The pump we designed as an improvement on the membranes has remained essentially the same in concept, although its design has been changed several times. It is now being manufactured under the trade name Infusaid by the Metal Bellows Corporation of Sharon, Mass. It consists of a cylindrical disk about the size and shape of an ice-hockey puck. The disk is made of the relatively light metal titanium, so that its empty weight is only 190 grams (6.7 ounces). The titanium is compatible with body tissues.

The inside of the disk is divided into two chambers by a cylindrical titanium bellows, which forms a barrier between the compartments that is collapsible but impermeable. The outer compartment contains a fluorocarbon in a liquid-vapor combination; it serves as the propellant. The inner chamber contains the infusate, the drug to be delivered.

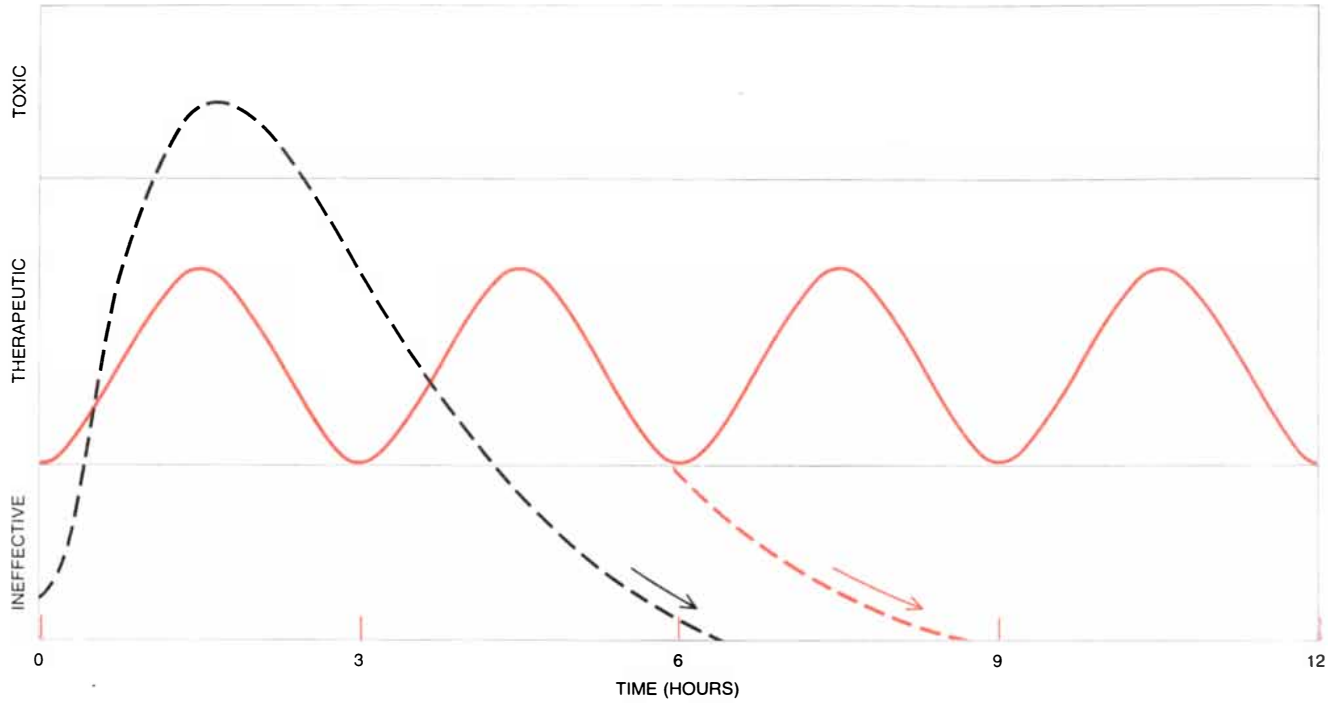
The principle underlying the operation of the pump is the basic physical concept that a liquid in equilibrium with its vapor phase exerts a constant vapor pressure at a given temperature, regardless of its volume. Hence in the relatively constant temperature of the body the fluorocarbon exerts a constant pressure on the infusate and forces it through a series of filters and flow-regulating resistance elements into a vein or an artery. The infusion rate of a particular infusate is therefore constant for any given combination of propellant chemical, flow restrictor and infusate temperature and viscosity.

The amount of active drug delivered can be altered by changing the concentration of the drug in the infusate. The change can be made during the refilling procedure. A different drug or a placebo can be put into the pump in the same way. With an inner-chamber capacity of about 45 milliliters of usable volume and a delivery rate of about one milliliter per day the pump needs to be refilled in most situations about every 45 days.

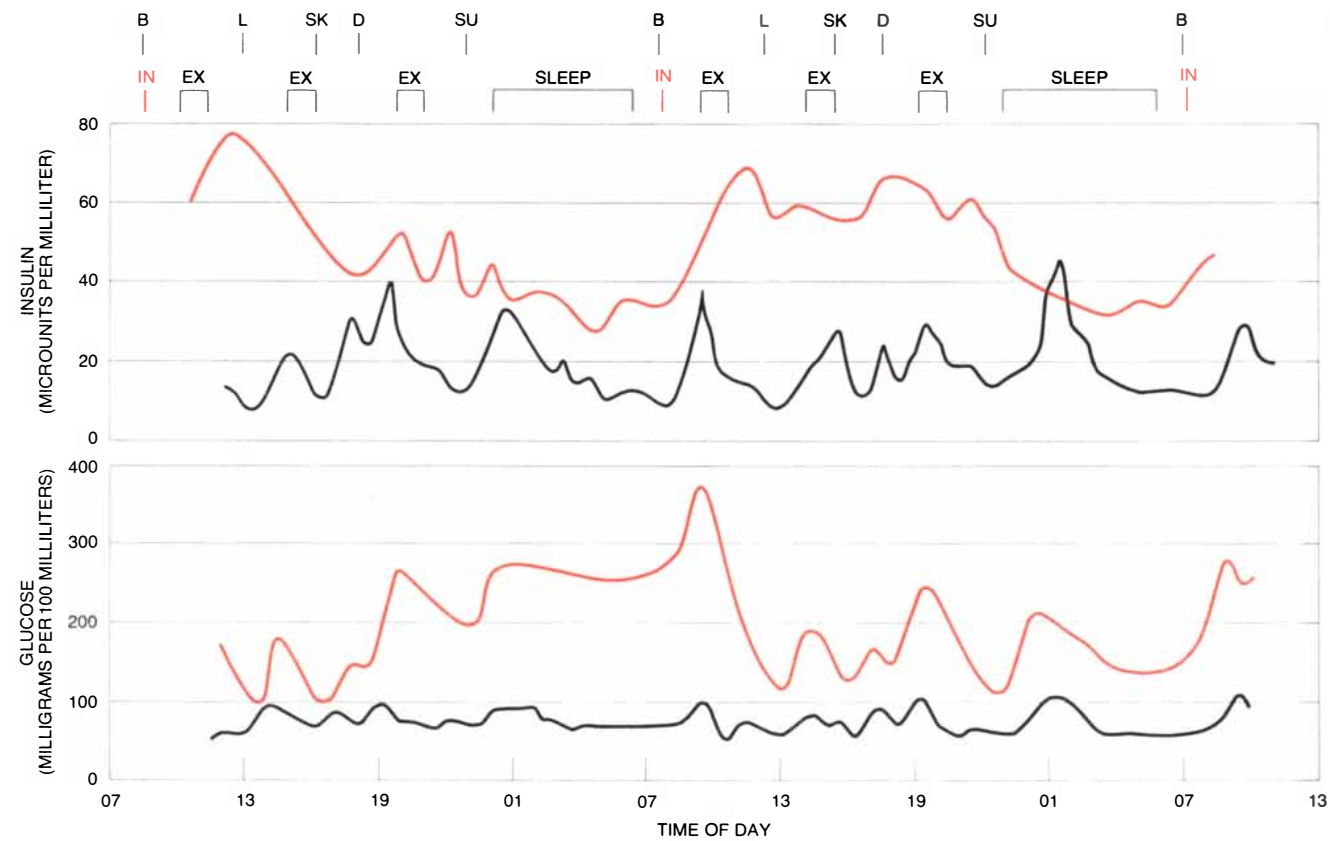
Preliminary studies with dogs demonstrated that the pump could infuse heparin (or sterile water serving as an experimental control) intravenously for more than four years without blockage of the cannula or serious side effects. We then began implanting pumps for the infusion of heparin in a series of human patients with severe clotting problems who had failed to respond to treatment with conventional measures. (My colleagues in these studies were Buchwald, Varco, Thomas D. Rohde and Philip D. Schneider.) Most of the patients had suffered from the recurrent formation of clots in their leg veins, with subsequent migration of clots to the lungs, notwithstanding treatment with the oral anticoagulant sodium warfarin. Many of the patients had had the largest vein in the abdomen (the inferior vena cava) tied off surgically to prevent the movement of clots to the lungs, a procedure that is generally a last resort and that introduces many complications of its own. About a third of the patients were giving themselves heparin from four to six times per day by subcutaneous or even intravenous injection. Heparin, as the most effective anticoagulant drug available, had prevented the recurrent formation of clots in these patients previously, but only at the cost of frequent injections or continuous infusion, a procedure that requires prolonged hospitalization.

When these patients entered the hospital at the University of Minnesota, we first established their intravenous requirement for heparin by means of infusions from a pump outside the body. The pump was then implanted (with local anesthesia) under the skin of the chest wall, a procedure identical with the implantation of a cardiac pacemaker. The delivery cannula was threaded through a tributary vein into the superior vena cava. After being discharged from the hospital a patient was to return every week or two for blood tests and every four to eight weeks for refilling of the pump.

We have now implanted about 20 pumps for the delivery of heparin; some of them have been in place for more than two years. The results of these preliminary trials have been encouraging. Our main objective was to prevent the recurrence of obstructing clots in the lungs and deep in the venous system. In more than 250 patient-months of the infusion of heparin through the pump



PEAK-AND-VALLEY PATTERN of the level of a drug in the blood appears when the concentration resulting from intermittent oral doses is plotted over time. Here the drug is procainamide, which regulates abnormal rhythms of the heart, and the normal dose (*color*) is 375 milligrams every three hours. The concentration of procainamide in the blood serum remains in the therapeutic range unless a dose is missed (*broken colored line*). A dose of 750 milligrams (*black*) rapidly gives rise to a drug concentration that is toxic to some patients.



CONTROL OF DIABETES is difficult with the conventional daily injection of insulin, as is shown in these curves reflecting the concentration of insulin and glucose in the blood of three diabetics (*color*) and three nondiabetics (*black*). Beginning at 7:00 A.M. on the first day their regimen was injection (*IN*), breakfast (*B*), lunch (*L*), exercise (*EX*), snack (*SK*), dinner (*D*), supper (*SU*) and sleep. Higher but unregulated insulin concentrations of diabetics do not prevent wide swings in glucose. Implantable devices could provide steadier levels. A different version of graph was published by G. D. Molnar and others in *Mayo Clinic Proceedings;* it appears with their permission.

only one clinically suggestive episode of thrombosis in a leg vein was encountered, and we saw no lung clots. The pump functioned accurately and reliably, maintaining fairly constant levels of heparin in the blood.

The versatility that distinguishes the pump from passive devices for diffusion was demonstrated during the refilling procedure. At that time the rate of delivery of heparin could be adjusted easily by changing the concentration of the drug in the new solution of infusate. Side effects have been rare. Perhaps the best feature of the pumps is that they enable a patient to go about his daily activities with little more inconvenience than he would have with a cardiac pacemaker. One patient even played a weekly game of volleyball with no ill effects, although this is not an activity we would recommend in the circumstances.

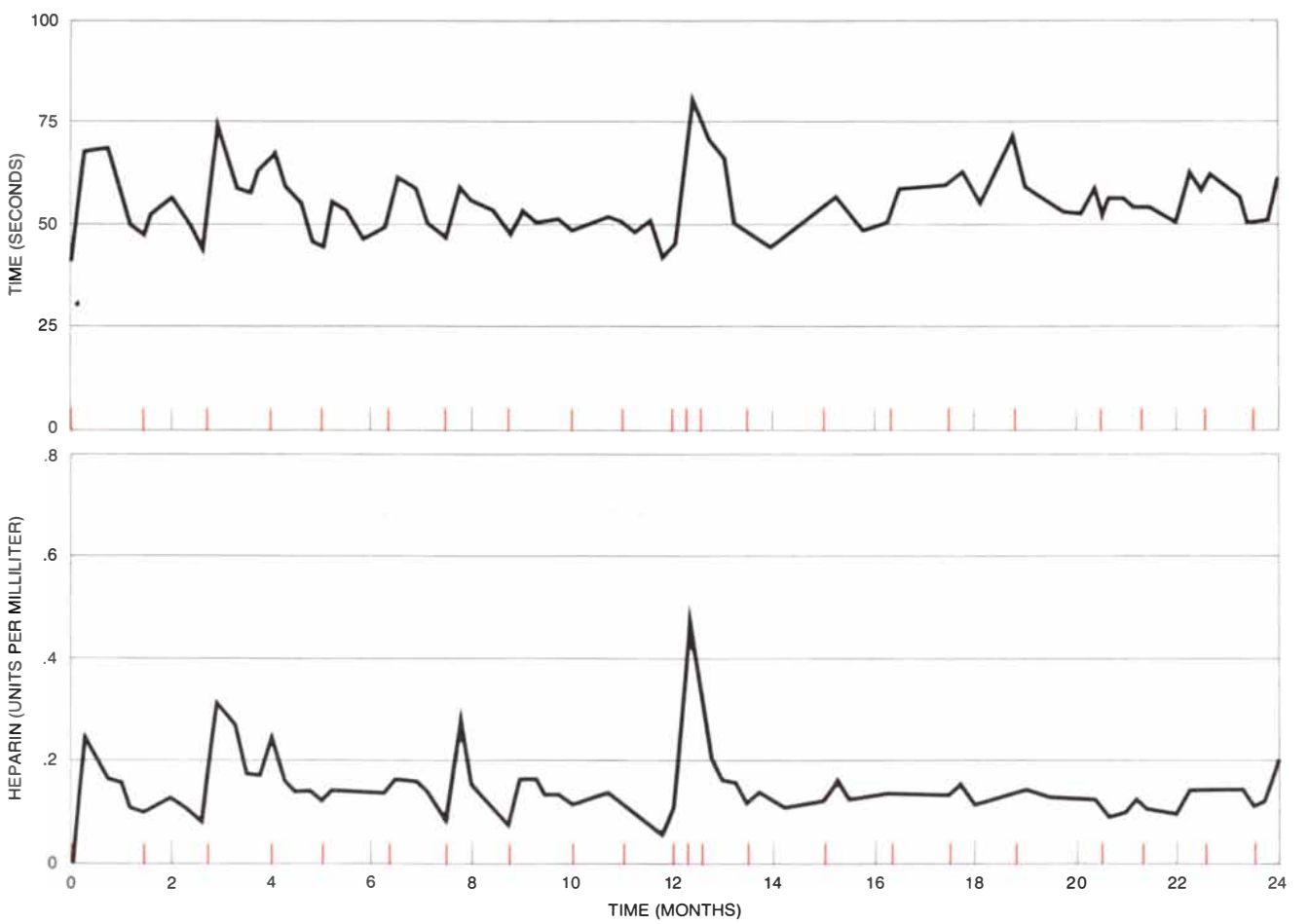
A second clinical application of the pump utilized a main advantage of certain implantable systems, the ability to deliver a drug to a specific target area or organ. We installed the pump to provide an intra-arterial infusion of a chemotherapeutic drug for the treatment of cancers of the liver. These tumors, including not only hepatoma, or primary liver cancer, but also metastatic cancers originating in the bowel or the pancreas, are in most cases rapidly fatal. Chemotherapy has had little effect, notwithstanding its success in the treatment of many other types of cancer.

The liver is unusual in that blood flows to it not only through arteries but also through veins. Most of the organ's normal blood supply is venous, but the blood supply of a liver tumor is almost exclusively arterial. Here was an opening for the delivery of a chemotherapeutic agent by infusion directly into the hepatic artery, which supplies the liver with arterial blood. We knew the pump could be implanted successfully for long periods of time; what was uncertain was whether a cannula in the hepatic artery would remain open when the drug being infused was not an anticoagulant and whether the high pressure and different clotting environment of the arterial system would cause problems.

Studies with dogs indicated that the pump would work. Then our group (Buchwald, Varco, Rohde, Theodor B. Grage, Pericles P. Vassilopoulos and I) implanted pumps in five patients with liver cancer. The pumps were placed under the skin of the abdominal wall and the cannulas were threaded through a branch artery into the hepatic artery. When the incisions had healed, the patients received alternating infusions of 5-fluorodeoxyuridine (the chemotherapeutic agent) and water (to keep the cannula open during a respite when the drug showed signs of reaching toxic levels), each infusion continuing for several weeks.

The pumps worked satisfactorily, and the patients were able to leave the hospital and resume their normal activities. The effects of the drug were less satisfactory. In some patients the symptoms improved and the tumors temporarily stopped growing, but all the patients eventually died or developed more widespread tumors. This result emphasizes the need to test new drugs and different schedules of delivery for this type of cancer.

We hope also to develop an implantable infusion device that would provide a total artificial replacement for the beta cells of the pancreas. These cells normally secrete insulin in a predictable



IMPLANTED PUMP proved to be effective in controlling clotting in a patient with severe clotting problems. The pump delivered a continuous infusion of the anticlotting agent heparin for more than two years. The lower curve reflects the level of heparin in the patient's blood, the upper curve the "plasma-activated partial thromboplastin time," which is a sensitive index of the effects of heparin. The level remains elevated and quite steady throughout the period. The vertical colored marks along the time scale show when pump was refilled.

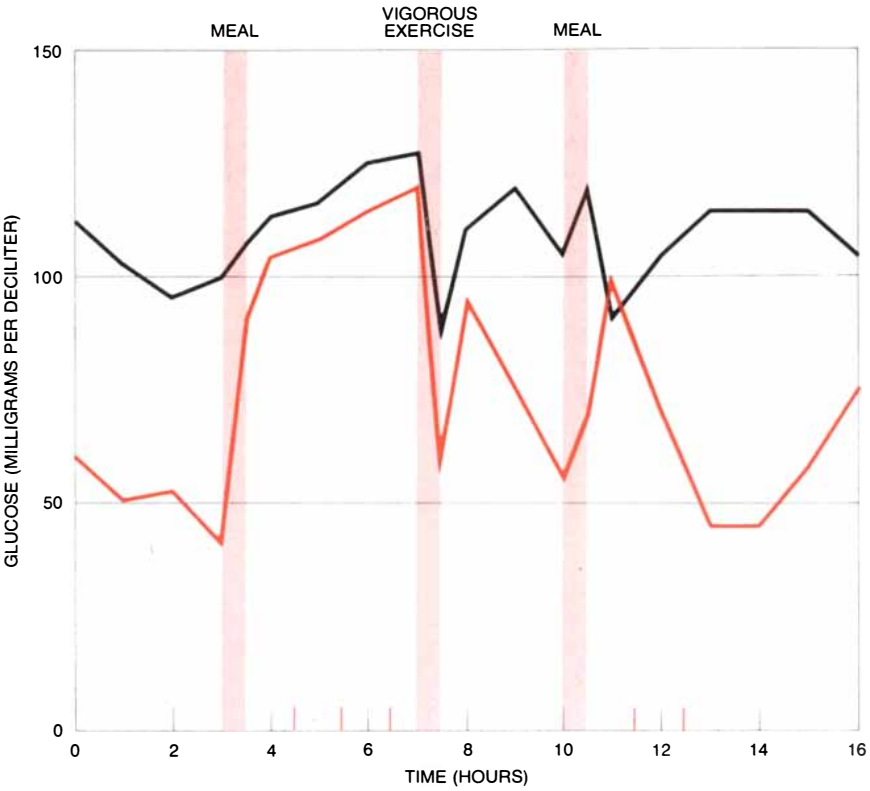
way in response to certain stimuli. The process is absent or deranged in diabetes mellitus. Although the introduction of insulin preparations in the 1920's prevented most patients from dying of acute insulin deficiency, it became apparent in the 1930's that long-term diabetes (even when it was kept under control with insulin) was often associated with a characteristic disease of the blood vessels of the retina, the kidney, the heart, various nerves and other tissues. The collective name for the changes is diabetic vasculopathy; it is common in patients who have had diabetes for 20 years or more and is a major cause of disability and death among them.

Studies with animals have suggested that the symptoms could be delayed or prevented by transplants of the pancreas or parts of it. Such attempts have been limited by the scarcity of suitable human donors and by the side effects of the powerful immunosuppressive drugs needed to prevent the rejection of tissue from an unrelated donor. The best current system, which was described by Anthony M. Albisser and his colleagues at the Hospital for Sick Children in Toronto, achieves almost the same levels of insulin and glucose in the blood as normal physiological mechanisms do. The trouble is that the system needs an apparatus for the continuous sampling of blood, an analyzer to determine the level of glucose in the blood repeatedly and rapidly, a computer to analyze the results and to determine the appropriate insulin dose and an infusion pump to deliver insulin intravenously in a manner approximating the normal delivery by the beta cells of the pancreas.

One can readily see that such a system calls for a roomful of apparatus and is hardly adaptable for implantation. Nevertheless, investigators in several countries are trying to devise miniature versions. The main obstacle at present is the lack of an accurate implantable electrode to sense the concentration of glucose in the blood.

We originally envisioned adapting our infusion pump as the pumping component of a device combining sensor, computer and pump, that is, a true implantable artificial pancreas. In recent years, however, several groups of workers have shown that nearly normal profiles of glucose concentration can be achieved in diabetic patients by infusing insulin at two rates, without feedback control. We have therefore directed our energies to modifying our pump so that it will infuse insulin at the two rates: a low basal rate between meals and a rate between 10 and 20 times higher during and shortly after meals.

To this end we have constructed a magnetic valve that can be actuated and latched in the open position by a magnet placed over it outside the skin. When the valve is opened by this means, a higher rate of flow is obtained until the valve is closed by the external application of the other pole of the magnet. With this system we have been able to maintain almost normal concentrations of glucose in dogs made diabetic by the surgical removal of their pancreas. Although much more information needs to be gathered about this method of delivering insulin and about its effects on metabolic processes, the system may eventually be suitable for human beings with diabetes. In the more distant future a glucose sensor that can be implanted for long periods of time may be developed, perhaps leading to a true artificial pancreas with feedback control of the secretion of insulin.



MODIFIED PUMP delivered insulin at two rates to a diabetic dog and thereby achieved (*color*) levels of glucose in the blood near the normal concentration (*black*). The implanted pump infused a low level of insulin constantly; additional bursts of insulin were delivered after meals by actuating a valve with an external magnet held over the pump. Times of the bursts are shown by the vertical colored lines along the time scale. When the insulin was removed from the pump after 16 hours, the glucose concentration rose rapidly to the level found in diabetics. This illustration is a modified version of a diagram that was published by the author and others in *Diabetes;* it is presented here with permission of the American Diabetes Association.

It will be evident from my description of the implantable drug-delivery systems available today that this branch of pharmacology is still in its embryonic stage. Its possibilities are nonetheless exciting. With devices of the type I have described almost any drug can be released over long periods from a capsule into subcutaneous tissue or other tissues, can be injected repeatedly into the cerebrospinal fluid or can be infused slowly into a vein, an artery or a cavity of the body. Many applications are possible, including (beyond the ones I have described) the infusion of agents such as lidocaine for irregular heart rhythms, perhaps in response to the sensing of an abnormal rhythm by an implanted pacemaker; the infusion of immunosuppressive drugs to prevent the rejection of transplanted organs; the administration of analgesics for chronic severe pain, and the localized infusion of antibiotics and other drugs.

I am most excited by the potential of the devices in the rapidly growing field of neuropharmacology. For example, it is known that in Parkinson's disease dopamine is deficient in some areas of the brain. Delivering dopamine to the appropriate area through an implantable device might be more specific and more effective than the therapy available today. Similarly, with the almost daily discovery of new classes of neurotransmitters and neuropeptides within the brain it seems likely that before too long the biochemical bases of other common neurological and psychiatric disorders will be elucidated. In such disorders specific and localized therapy might well be helpful.

Gene Transplantation and the Analysis of Development

Purified genes microinjected into an amphibian oocyte can be "read" accurately and abundantly. The oocyte may serve as a living test tube for studying the molecular details of gene regulation in development

by E. M. De Robertis and J. B. Gurdon

The likelihood that biologists may soon understand in detail how genes work has been substantially improved by recent advances in isolating particular genes from higher organisms, recombining them with bacterial plasmids, cloning them in large numbers in bacteria and learning the sequence of their component nucleotides. Having the gene and knowing its nucleotide sequence is not enough, however, to reveal how the gene functions, and in particular how it is regulated—turned on and off—in the intricately controlled process of differentiation and specialization that constitutes development.

For that one requires a laboratory preparation in which the gene can go about its work and the substances that regulate its activity can be observed in action. Here we shall describe experiments in which an intact living cell serves as a test tube where genes from other cells, introduced by microinjection, function normally. The experiments have already thrown some new light on development and on how genes work. Perhaps more important in the long run, they suggest a new way the substances that control gene activity can be investigated.

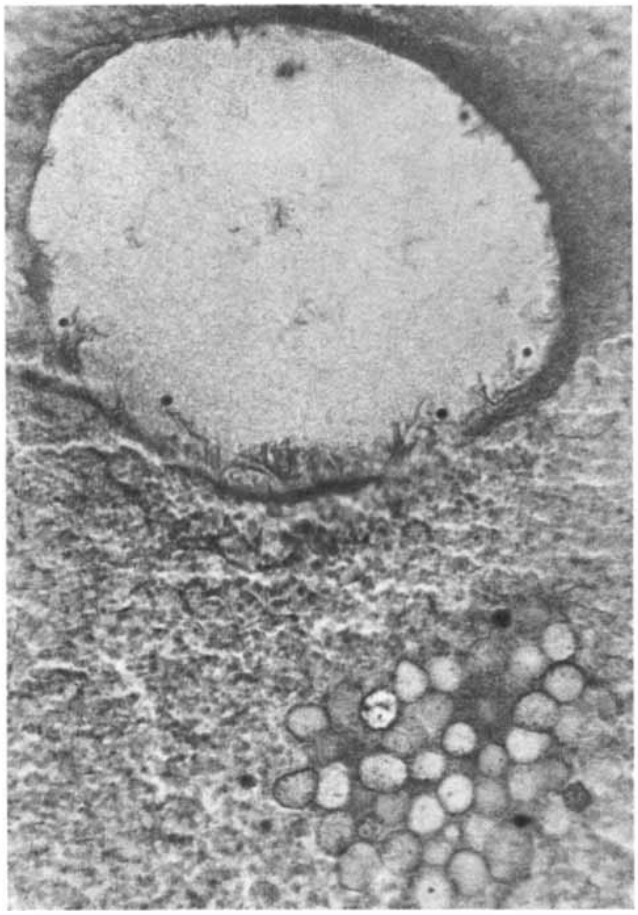
The problem of cell differentiation is to understand how an apparently structureless egg gives rise to a complex embryo with many specialized tissues. At the turn of the century experimental embryologists approached the question by means of micromanipulation, destroying certain embryonic cells with fine needles or transplanting bits of tissue from one embryo to another and noting the effects on early development. These methods are still of great value for learning how cells become organized in space to give rise to particular structures. They do not easily allow direct conclusions to be drawn, however, on the molecular basis of gene control in development. Nor do the usual approaches of biochemical investigation, in which purified molecules are reacted in the test tube. The complex conditions of a normal cellular environment are hard to reproduce in vitro, so that few genes—if any—of eukaryotic organisms (organisms higher than bacteria) are accurately regulated in test tubes. Our objective has therefore been to develop procedures for combining the precision of test-tube experimentation with the natural environment of the living cell by introducing purified large molecules into frog oocytes.

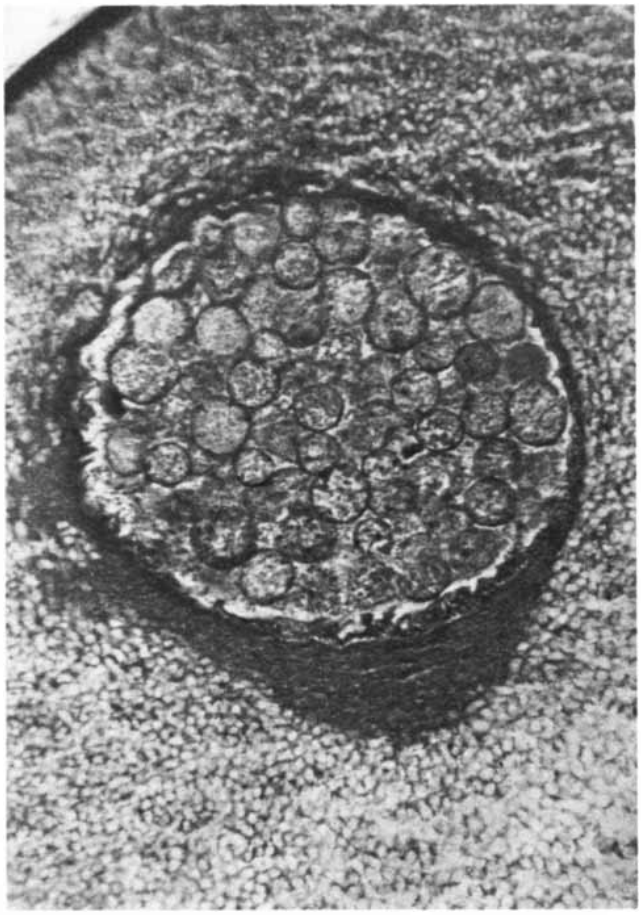
Oocytes are the precursors of egg cells. They grow and accumulate in the mother frog; after hormonal stimulation they mature to become eggs, which are deposited in pond water and then fertilized. Amphibian oocytes are a convenient experimental material because of their large size (1.2 millimeters in diameter), their resistance to manipulation (they can be injected with as much as 5 percent of their volume without adverse effects) and their viability in culture (they can be kept alive and functioning for weeks in a simple saline solution). They are particularly appropriate for developmental studies because they are destined to become eggs and then embryos, and they already contain most of the molecular machinery required for early development. The source of oocytes for most of our experiments is *Xenopus laevis,* a South African frog particularly well suited for laboratory conditions.

Microinjection experiments began in our laboratory some years ago when one of us (Gurdon) undertook to answer a long-standing question in developmental biology: Do the many kinds of specialized cells of an adult organism continue to contain the entire genome (complete set of genes) of the organism in spite of their tremendous differences in form and function? In other words, is cell differentiation accomplished not by the loss of some genes and the retention of others but rather by the differential regulation of the same full set of genes that was present in the fertilized egg? The latter proved to be the case. When a single nucleus (the part of the cell that contains the genes) of a tadpole somatic cell such as an intestinal epithelial cell was transplanted into an egg whose own chromosomes had been destroyed by ultraviolet radiation, the egg divided and eventually gave rise to a normal embryo, which developed into a normal tadpole and then into a frog [see "Transplanted Nuclei and Cell Differentiation," by J. B. Gurdon; SCIENTIFIC AMERICAN, December, 1968]. The experiment showed that genes are not lost in the course of cell differentiation; the specialized intestinal cell possesses all the genes necessary for the complex life cycle of a frog.

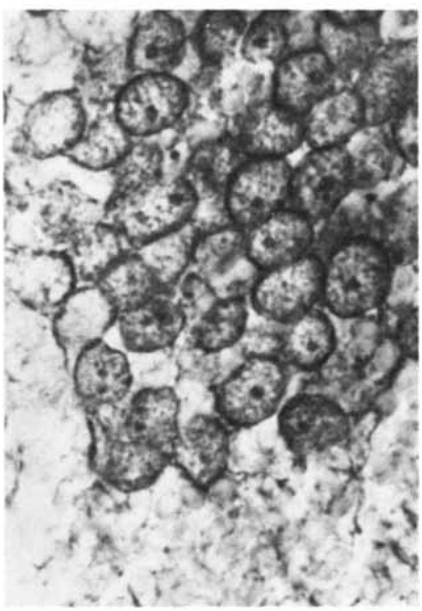
This experiment also showed that the pattern of gene expression normally characteristic of the transplanted nucleus must be reprogrammed, by factors present in the enucleated egg or early embryo, to give rise to new types of cell specialization. For example, the nucleus of a differentiated skin cell in an adult frog that preferentially expresses the gene for the protein keratin can give rise, when it is transplanted, to a swimming tadpole with diverse specialized tissues such as blood, muscle and the lens of the eye, whose cells respectively express preferentially the genes for hemoglobin, muscle proteins and lens crystallin. The first indications of differentiated cell functions only become apparent, however, after an egg has undergone some 10 to 15 rounds of cell division. Hence the experiment does not establish whether gene-regulating substances that reprogram the transplanted nucleus are already present in the oocyte or the unfertilized egg or whether these substances arise later in development.

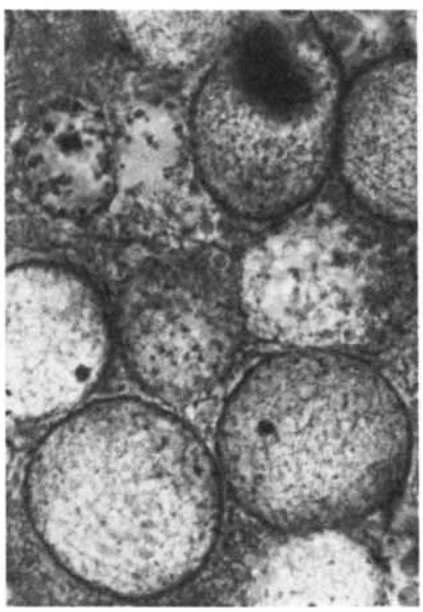
The answer to this question was crucial, because if gene-regulating substances were present in the oocyte or the egg, one could hope eventually to find and study them. Frog oocytes can be cultured without cell division for many

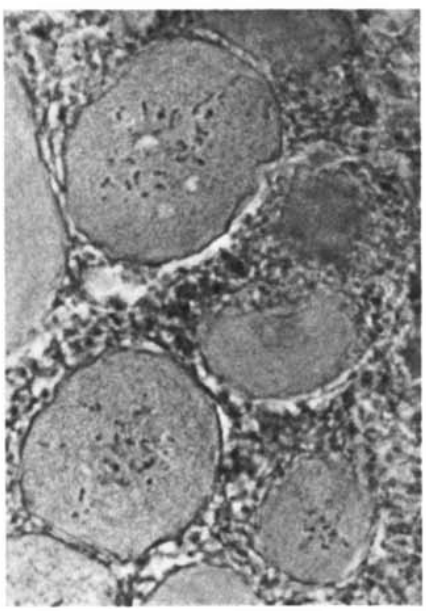




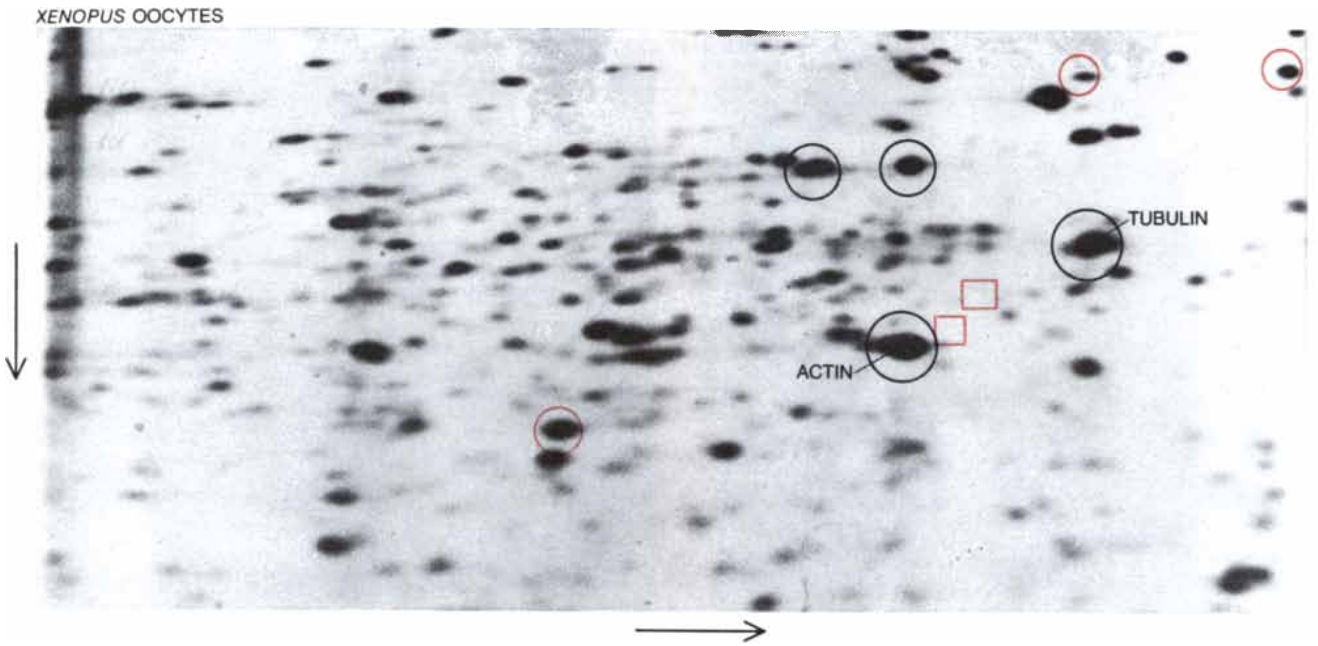
NUCLEI OF HUMAN CELLS survive and function when they are microinjected into the frog oocyte, a precursor of the egg. Nuclei of HeLa cells, a cultured line of human cancer cells, appear in these photomicrographs made by the authors. In the micrograph at the left the nuclei have been injected into the cytoplasm of the oocyte and are visible below the very large oocyte nucleus. In the micrograph at the right the human nuclei have been injected directly into the oocyte nucleus and under the influence of substances in the nucleus have swelled up and are synthesizing RNA at a much increased rate. Success in injecting whole nuclei into the nucleus of the oocyte led to the development of methods for injecting purified molecules of DNA (or genes) into the nucleus, where they too are transcribed into RNA.







MICROINJECTED NUCLEI of HeLa cells are shown in these photomicrographs at three stages. Immediately after injection (*left*) the nuclei look as they do in HeLa cells: the small nuclear organelles called nucleoli are prominent and some of the chromatin (a complex of DNA and protein) is condensed. Three days after injection (*center*) the nuclei have enlarged about tenfold and their chromatin is dispersed. After about two weeks of culturing (*right*) chromosome threads are visible; they resemble to some extent "lampbrush" chromosomes characteristic of oocytes but not of the chromosomes of cultured HeLa cells. Three preparations are enlarged 1,200 diameters.



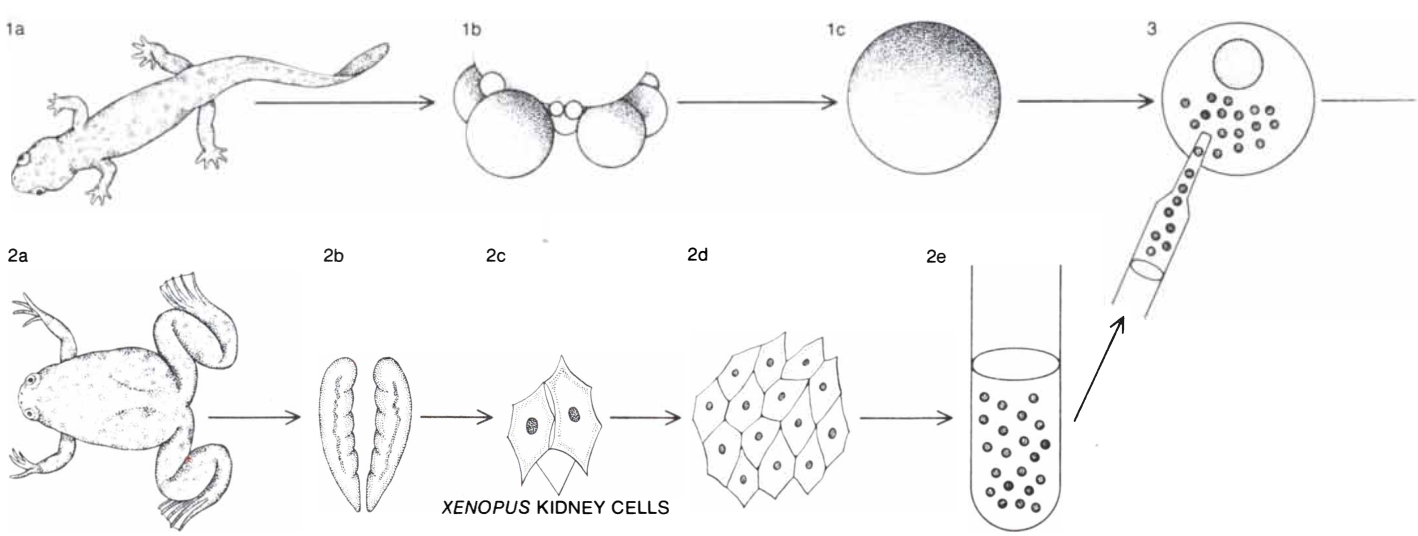
RADIOACTIVELY LABELED PROTEINS manufactured by the oocytes (*left*) and by cultured kidney cells of the frog *Xenopus laevis* (*right*) are compared. The proteins were extracted from the oocytes and the kidney cells and were subjected to electrophoresis in two dimensions, a procedure that separates them first according to their electric charge (*horizontal arrows*) and then according to their molec-

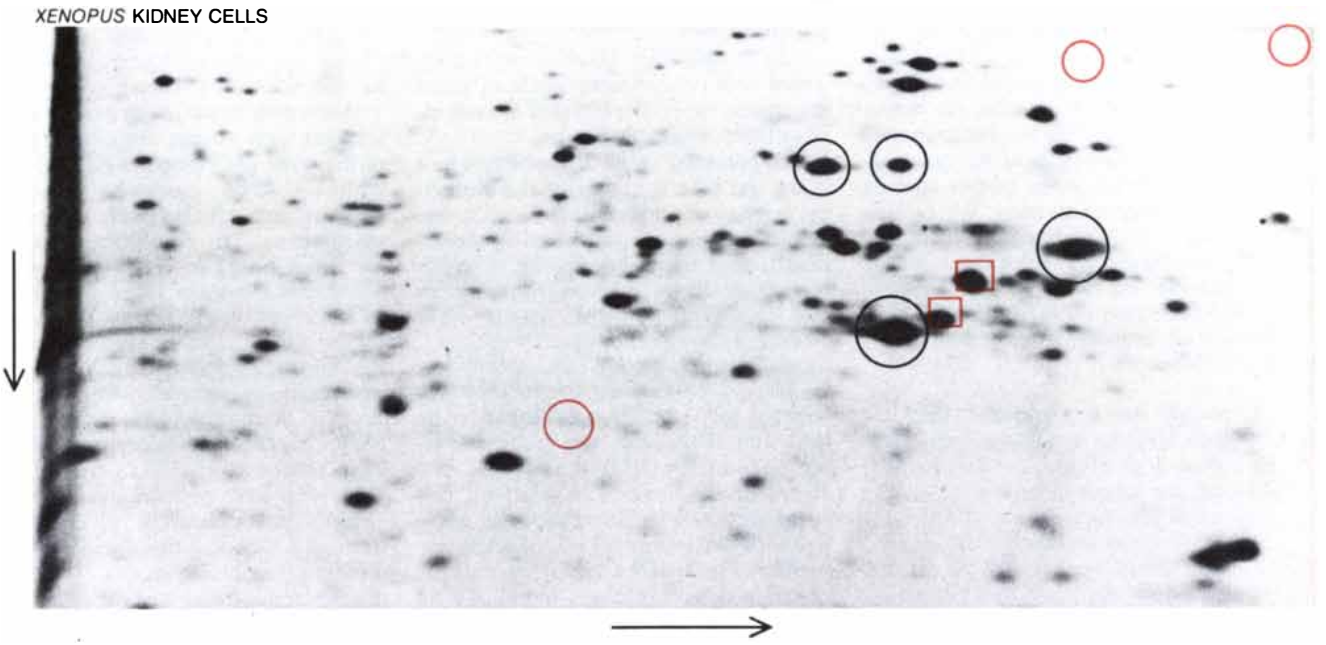
days after the injection of nuclei; eggs, on the other hand, become blastulas consisting of 50,000 cells within a few hours. We therefore designed experiments that would show whether or not the genes of transplanted nuclei were reprogrammed in oocytes.

Somatic-cell nuclei survive after injection into oocytes only if they are isolated by a gentle procedure; nuclei denuded of cytoplasm (the extranuclear material) invariably die after transplantation. We treat a suspension of cells with lysolecithin, a phospholipid that inserts itself into the cell's outer membrane and makes it permeable. In this way we can prepare a suspension of nuclei surrounded by a protective layer of cytoplasm. We inject a large number of such nuclei (about 200) into each oocyte, thereby ensuring that the expression of injected genes will be easily seen against the background expression of the oocyte's own genes.

The transplanted nuclei enlarge by as much as 100 times their original volume in the first three days after injection. Although the nuclei do not divide, they become very active in the synthesis of RNA. (Genes are molecules of DNA, which encodes the genetic information. Three kinds of RNA are transcribed from DNA; each of them participates in some way in the translation of genetic information into proteins and thus into cell form and function. Messenger RNA is the instruction tape encoding the sequence in which amino acid subunits are assembled into protein chains; ribosomal RNA is a constituent of ribosomes, the structures on which the assembly takes place; transfer-RNA molecules fit the correct amino acids into the growing protein chain.) The high level of RNA synthesis characteristic of injected nuclei mimics the normal activity of the oocyte's own nucleus. During this cellular phase (meiotic prophase I) the oocyte DNA does not replicate but is transcribed actively into RNA to prepare for protein synthesis during early development. This high level of gene transcription causes the oocyte chromosomes to assume a characteristic "lampbrush" morphology.

To learn whether or not the oocyte contains gene-regulating substances that can reprogram individual genes, we examined the protein products of the



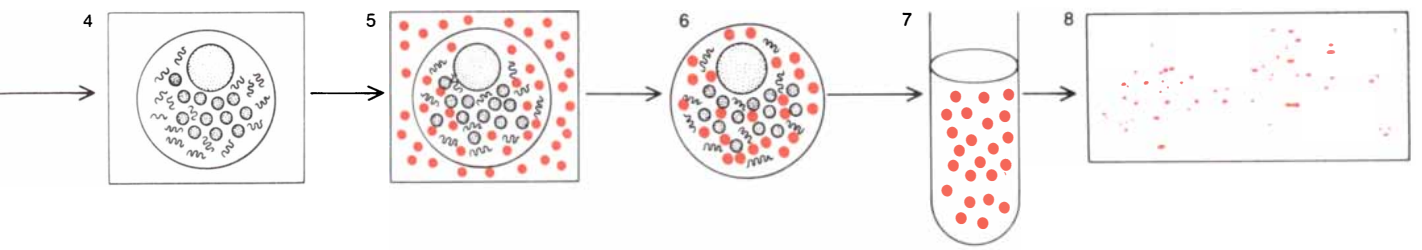


ular weight (*vertical arrows*); the proteins are seen as gray spots on a film exposed to electrophoresis gel. "Housekeeping" proteins (*black circles*) are synthesized by both kinds of cell. "Luxury" proteins are specific to each kind of cell: oocyte-specific proteins are synthesized by oocytes but not by kidney cells (*colored circles*) and kidney-specific proteins by kidney cells but not by oocytes (*colored squares*).

genes in injected nuclei. A sensitive method for identifying particular proteins had been devised by Patrick O'Farrell of the University of Colorado. This method involves two successive separations of the proteins by electrophoresis in a polyacrylamide gel, first according to their electric charge and then, in a direction at a right angle to the first separation, according to their molecular weight. The result is a pattern of spots, made visible by staining or by radioactivity, each of which represents a small protein molecule (a polypeptide) having a particular charge and size. Proteins characteristic of specific tissues are readily distinguishable. When gels showing the proteins synthesized by *Xenopus* oocytes and by *Xenopus* cultured kidney cells are compared, a number of proteins are seen to be synthesized by both types of cell; they are the "housekeeping" proteins that all cells require in order to build their skeletal framework, membranes, ribosomes and organelles. Other proteins are specific to oocytes or to kidney cells; they are the "luxury" proteins, encoded by genes that are expressed only in particular tissues.

The question we asked was: Is there any change in the types of protein-encoding genes expressed by cell nuclei obtained from *Xenopus* kidney cells when those nuclei are injected into an amphibian oocyte? We injected the frog kidney nuclei into the oocytes of the newt *Pleurodeles waltlii,* whose proteins can be distinguished from those of *Xenopus* on two-dimensional gels. The oocytes were cultured for several days, during which time messenger RNA was synthesized and accumulated in the cytoplasm. Then the oocytes were supplied with radioactive amino acids, which were incorporated into proteins encoded by the newly synthesized RNA. The radioactive proteins were subjected to two-dimensional electrophoresis, and when the electrophoretic gel was dried and placed on X-ray film, each protein appeared as a dark spot on the photographic emulsion.

Examination of the exposed and developed films (called autoradiographs) showed that the genes for several *Xenopus* housekeeping proteins were expressed but not the genes for kidney-specific proteins. More important, some proteins were synthesized that are normally characteristic of the frog oocyte.



NUCLEAR-INJECTION EXPERIMENT shows that the oocyte can reprogram kidney-cell genes to conform to an oocyte gene-expression pattern. Oocytes are removed from the newt *Pleurodeles waltlii* (*1a–c*). Cells from *X. laevis* kidney are cultured and their nuclei are extracted (*2a–e*) and injected into a newt oocyte (*3*). The oocyte is cultured for three days (*4*); in that time messenger RNA (*black wavy lines*) accumulates in the cytoplasm. Radioactively labeled amino acids (*small colored dots*) are introduced (*5*) and synthesis of proteins (*6*) proceeds for six hours. The radioactively labeled proteins (*large colored dots*) are extracted (*7*) and separated by electrophoresis. Analysis of an X-ray film exposed by the radioactive proteins (an autoradiograph) indicates that frog housekeeping genes are expressed, that the kidney-specific genes are not expressed and that genes characteristic of the frog oocyte are expressed. Apparently newt oocyte cytoplasm contains some as yet unidentified substances that "turn on" genes that were not previously expressed in the kidney cells.

These oocyte-specific frog proteins had not been synthesized in the kidney nucleus before transplantation; their genes had been activated by the newt oocyte's cytoplasm. In other words, the transplanted nuclei had been reprogrammed by normal components of the newt oocyte to conform to an oocyte-specific pattern of gene expression. We believe (although it is by no means proved) that the gene-regulating substances whose functioning was demonstrated by these experiments may serve to control the activity of chromosomal genes during early development.

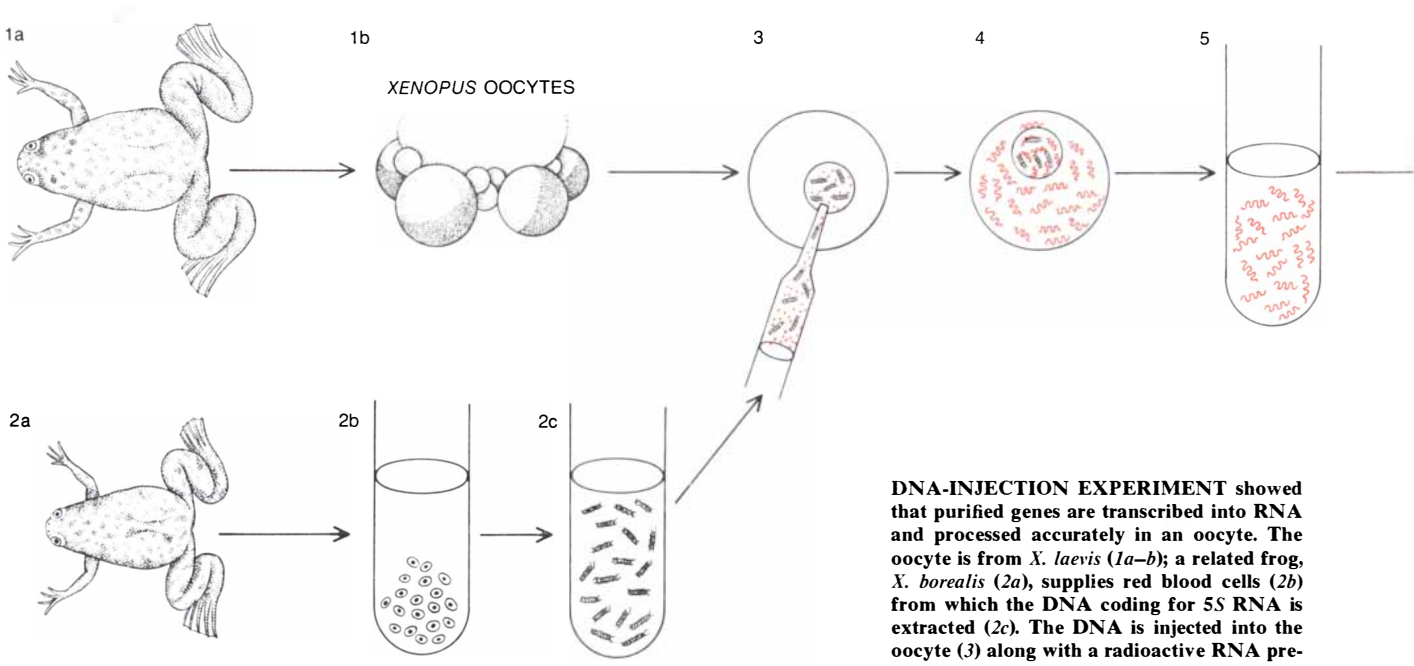
Although the experiments with injected nuclei established the presence in oocytes of gene-controlling substances, the transplantation of nuclei was not a promising method for finding out what those substances are and how they work. A nucleus holds several thousand different genes, many of which are presumably reprogrammed in an oocyte by independent molecular events that cannot readily be sorted out and analyzed. Ideally it would be desirable to study the activation or inactivation of a single type of gene by observing the molecular events that accompany changes in the activity of the gene when it is transplanted into an oocyte. We hoped to learn how to inject into an oocyte many copies of a single gene (as purified DNA) in such a way that the product of the gene would be synthesized correctly and abundantly. Correctness was essential because transcription by a random process or by one not normally characteristic of the oocyte would not reveal anything useful about the normal operation of gene-controlling molecules. Abundance was desirable because it would make the gene product readily detectable in a relatively short time, thereby enabling one to study the early stages in the synthesis and processing of RNA. The experiments we shall now describe have established that at least some kinds of genes are transcribed correctly and abundantly in DNA-injected oocytes.

The potential value of the oocyte as a living test tube for assaying the biological activity of purified nucleic acids was first indicated some years ago by experiments, done in our laboratory, in which messenger RNA from various species was injected into frog oocytes [see "Rabbit Hemoglobin from Frog Eggs," by Charles Lane; SCIENTIFIC AMERICAN, August, 1976]. Purified messenger RNA injected into oocytes was found to be fully functional and extremely stable; the oocytes synthesized proteins very efficiently and are now widely used as a laboratory system for translating messenger RNA into protein. A logical extension of these RNA-translating experiments was to investigate the ability of *Xenopus* oocytes to carry out the step in gene expression that precedes translation: the transcription of microinjected DNA into RNA.

We started by trying to inject DNA into the nucleus of an oocyte, using the same technique that had enabled us to inject the nuclei of kidney cells into that part of the cell. The nucleus is not readily visible within an intact oocyte, but it is always in the same place, and like the oocyte itself it is quite large (.4 millimeter in diameter). An oocyte has a pigmented "animal" hemisphere and a yellow or white yolky "vegetal" hemisphere, and the nucleus is always found below the center of the pigmented half. If the injection needle is directed toward that region, it becomes possible (with some practice) to penetrate the nucleus in more than 50 percent of the attempts. The misses do not matter, because DNA is not transcribed in the cytoplasm. To ensure that at least a certain amount of DNA has been successfully injected into nuclei we work with groups of 10 or more oocytes at a time.

In a typical experiment each oocyte is injected with a large number of copies of the same gene (about a billion) along with an RNA precursor, guanosine triphosphate, labeled with radioactive phosphorus. The oocytes are cultured for a few hours or a few days, during which RNA is transcribed from the injected DNA continuously, accounting for as much as 80 percent of the total RNA synthesis by the oocyte. In our first successful experiments, which were carried out in collaboration with Janet E. Mertz, the DNA we injected was that of simian virus 40 (SV40), a small tumor virus. We were able to show that the viral DNA was transcribed into RNA, some of which was translated into viral proteins, specifically some of the proteins forming the capsid, or outer coat, of the virus. This means at least some of the RNA transcripts were copies of entire viral genes and were correctly processed, exported into the oocyte cytoplasm and recognized by the protein-synthesizing machinery.

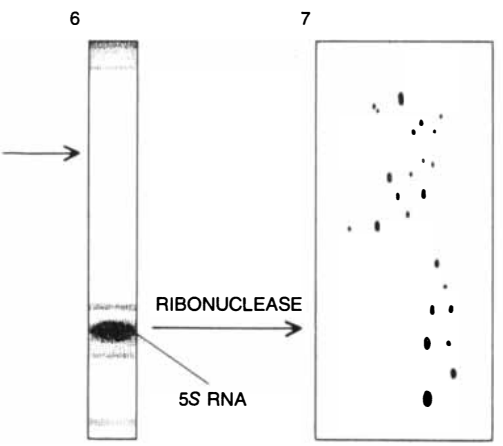
The remarkable accuracy of transcription of injected DNA was demonstrated by experiments, done in collaboration with Donald D. Brown of the Department of Embryology of the Carnegie Institution of Washington, in which the genes that code for 5*S* ribosomal RNA in the frog *Xenopus borealis* were injected into oocytes of *X. laevis*. The 5*S* (for five Svedberg units) RNA is a component of one of the subunits of the ribosome, and in the frog cell the genes coding for it are present in multiple copies (about 20,000 per cell). Oocytes injected with purified 5*S* DNA synthesized large amounts of RNA having the same size and nucleotide composition



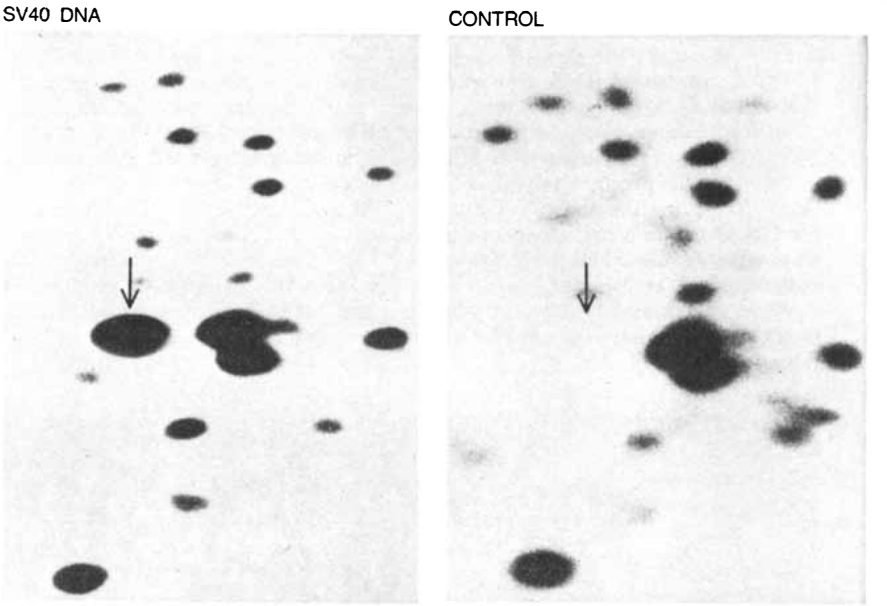
DNA-INJECTION EXPERIMENT showed that purified genes are transcribed into RNA and processed accurately in an oocyte. The oocyte is from *X. laevis* (*1a–b*); a related frog, *X. borealis* (*2a*), supplies red blood cells (*2b*) from which the DNA coding for 5*S* RNA is extracted (*2c*). The DNA is injected into the oocyte (*3*) along with a radioactive RNA pre-

as *X. borealis* 5*S* RNA. The *X. laevis* oocyte's RNA polymerase (the enzyme that synthesizes RNA) was apparently able to recognize the injected DNA's initiation and termination signals, which define the stretch of DNA to be transcribed. The abundance of correct RNA products transcribed immediately from the injected genes showed they resulted from a selective initial reading of the DNA by the polymerase, which had correctly transcribed only the parts of the DNA coding directly for 5*S* RNA. The alternative, which had been difficult to exclude in experiments with normal unmanipulated cells, was that the polymerase reads all of the DNA, including regions that do not code for protein. In this case only the stretches of RNA representing the desired final product would be stable, the other stretches being quickly degraded.

Selectivity of transcription is also demonstrated by the oocyte's choice of the correct type of RNA polymerase. Eukaryotic cells have three different polymerases that transcribe DNA into RNA. Type I transcribes the genes for two larger ribosomal RNA's, 18*S* and 28*S* ribosomal RNA, Type II transcribes protein-coding genes and Type III transcribes the genes for 5*S* ribosomal RNA and transfer RNA. The three types of polymerase can be distinguished by their different sensitivity to inhibition by the fungal toxin alpha-amanitin. (This inhibitory effect is the commonest cause of human poisoning by mushrooms.) RNA polymerase II is inhibited by low levels of alpha-amanitin, polymerase III is inhibited only by high levels and polymerase I is not inhibited at all. We found that microinjected SV40 DNA, which contains only protein-coding genes, was transcribed by polymerase II, whereas the gene for 5*S* RNA was transcribed by polymerase III, even when both DNA's were injected together into the same oocyte.



cursor (*colored dots*). Injected DNA is transcribed (*4*) into radioactive RNA (*colored wavy lines*), which is extracted from cell (*5*). Electrophoresis (*6*) shows that 60 percent of the radioactive RNA is the size of 5*S* RNA. An enzyme, ribonuclease *T*1, breaks 5*S* RNA into sequences whose electrophoresis pattern (*7*) matches that of the *X. borealis* 5*S* RNA.



MICROINJECTION OF VIRAL DNA, that of simian virus 40 (SV40), into oocytes is followed by transcription of the DNA into messenger RNA and translation of the viral RNA into viral proteins. Two-dimensional gel electrophoresis (*left*) shows a protein of the outer coat of the virus, virion protein 1 (*arrow*); the virion protein is not present on a control gel (*right*) displaying proteins synthesized by oocytes injected with a saline solution instead of SV40 DNA.

An important advantage of gene-injection experiments is that they provide information about initial gene products. One way to observe the initial product is to examine the RNA very soon after the radioactive label has been supplied and before any secondary processing can have taken place, as we did in the 5*S*-RNA experiment. Another way is to actually examine the nascent RNA molecules with the electron microscope as they are being synthesized. O. L. Miller, Jr., of the University of Virginia devised an ingenious technique whereby isolated nuclei are gently disrupted and their chromosomal material is centrifuged directly onto an electron-microscope specimen holder. With this method the genes being transcribed are spread out, complete with their attached RNA polymerase molecules and growing RNA chains [see "The Visualization of Genes in Action," by O. L. Miller, Jr.; SCIENTIFIC AMERICAN, March, 1973].

In collaboration with Michael F. Trendelenburg we applied Miller's method to oocytes injected with a gene coding for 40*S* ribosomal RNA, a precursor molecule that is subsequently processed to form the 18*S* and 28*S* RNA's. The 40*S* DNA had been inserted into a bacterial plasmid (a small circular molecule of extrachromosomal bacterial DNA) by recombinant-DNA techniques. With the plasmid as its vehicle the 40*S* DNA was cloned in bacteria, and large amounts of it were injected into oocytes. Our electron micrographs showed the injected ribosomal gene, still incorporated in a plasmid, being accurately transcribed by the oocyte's polymerase molecules. If this method of analysis can be applied to other cloned eukaryotic genes, it should yield new information about initiation and termination sites, the density of polymerases and other details of gene transcription, information that is not now obtainable by other means for genes normally present in a cell in only one copy or a few copies.

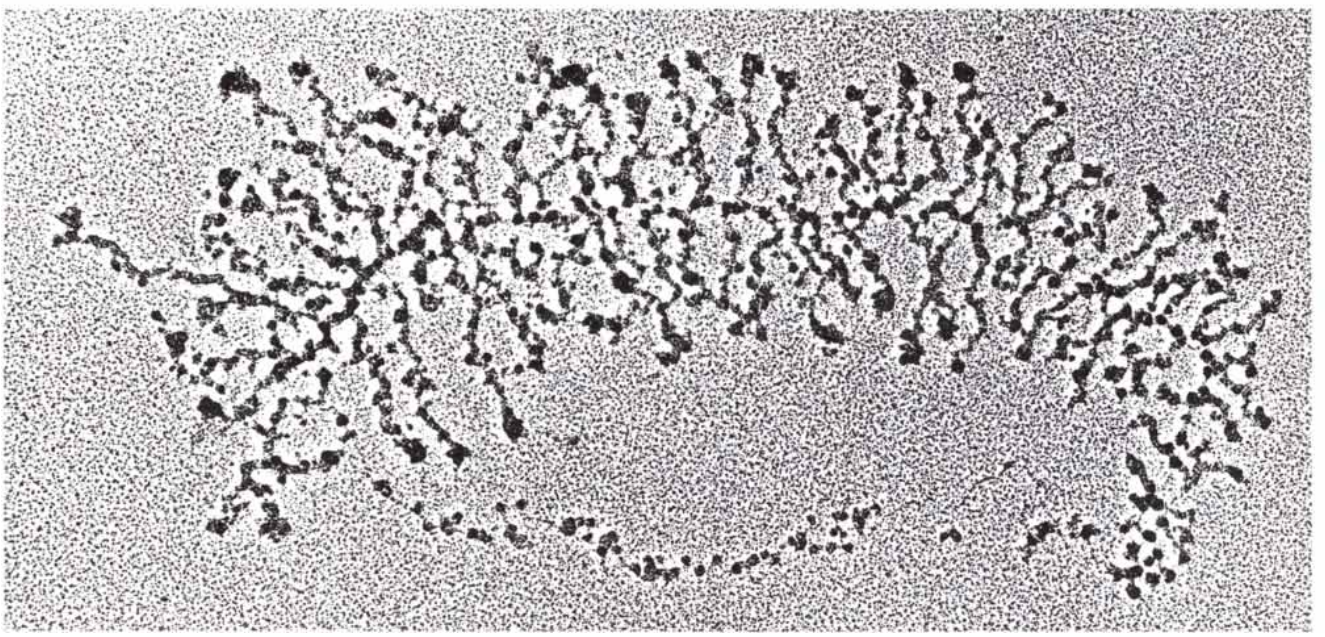
In the case of 5*S* RNA the initial transcript is the final RNA product. In most cases, however, the initial transcript undergoes several kinds of processing in the cell to yield the final product: segments of the initial transcript are removed and some of the nucleotide bases that constitute the strand of RNA are methylated or otherwise modified. Injected oocytes have proved to be an effective system for the analysis of RNA processing. One type of RNA that undergoes considerable processing is transfer RNA. Stuart G. Clarkson and Max L. Birnstiel of the University of Zurich had shown that transfer-RNA genes are transcribed very efficiently when injected into oocytes.

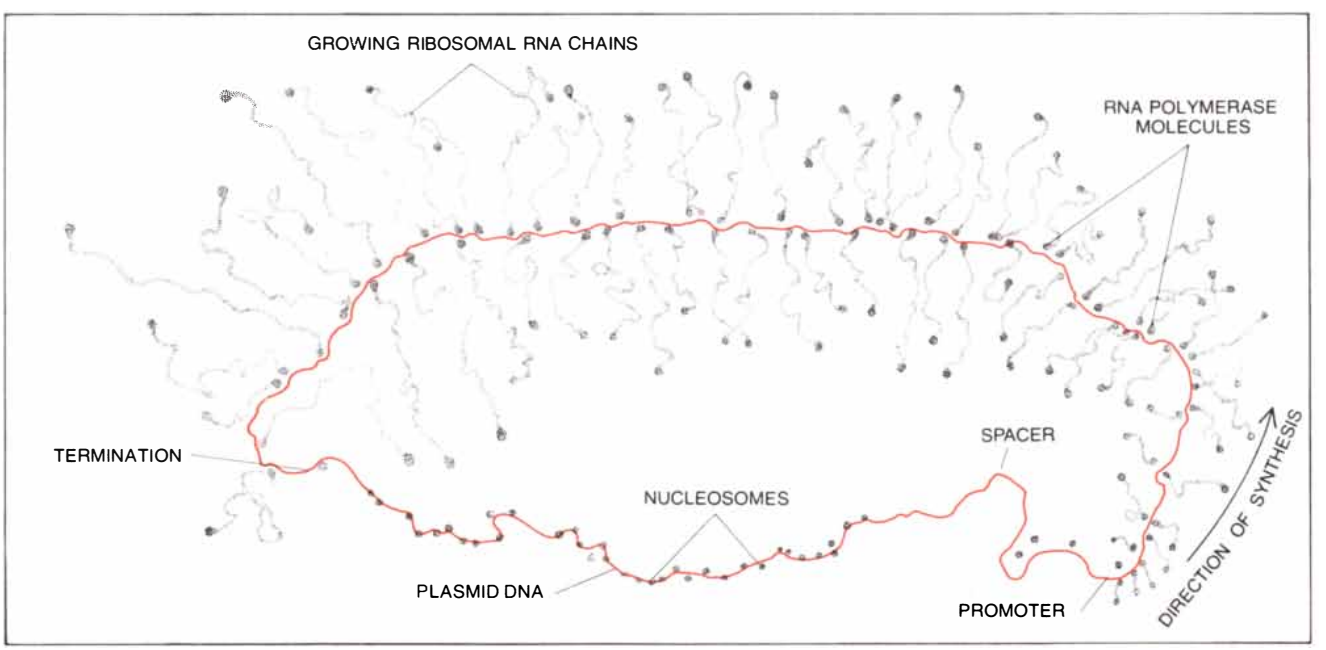
We undertook to examine in detail the processing of the gene that codes in baker's yeast (*Saccharomyces cerevisiae*) for the transfer RNA specific for the amino acid tyrosine. The gene, which had been cloned in a plasmid by Maynard V. Olson of the University of Washington, was of interest because it was known to contain a 14-nucleotide noncoding segment inserted in the nucleotide sequence coding for the transfer-RNA molecule. The presence of noncoding "intervening sequences" in genes came as a surprise to molecular biologists in 1977; such se-

quences have since been found in a wide variety of eukaryotic genes coding for proteins, ribosomal RNA and transfer RNA and in viral genes. Genes that incorporate intervening sequences are transcribed into precursor RNA's longer than the final product; to yield a functional RNA (such as the tyrosine transfer RNA) the internal sequences must be precisely excised and the RNA molecule religated, or "spliced."

When we examined the primary RNA transcript synthesized by the yeast transfer-RNA genes in oocytes, we found that it included not only the 14-nucleotide intervening sequence but also a "leader" sequence of additional nucleotides preceding the transfer RNA itself. The leader had until then gone unnoticed in experiments with yeast cells; it was observable in our experiment because the oocyte method produces a large yield of radioactively labeled transfer RNA and little else, making it possible to examine the initial transcript before it is processed.

A possible function for the leader became apparent when we examined the order in which particular nucleotide-base modifications appeared. Certain nucleotides had already been modified in the RNA precursor carrying the leader; other modifications were not present at that stage and appeared only after the leader was removed. In other words, the precursor RNA with a leader is a substrate for certain nucleotide-modification enzymes and the later form, deprived of the leader, is a substrate for





GENE FOR RIBOSOMAL RNA is seen in action in the electron micrograph at the top, made by Michael F. Trendelenburg in the author's laboratory. The DNA coding for a 40*S* ribosomal precursor molecule had been recombined with a plasmid (a circular molecule of bacterial DNA) and cloned in bacteria. A large number of gene-bearing plasmids were then injected into an oocyte. As the drawing at the bottom shows, the gene (*color*) is being transcribed into RNA. Beginning at the promoter, or initiation, site molecules of RNA polymerase are moving along the gene, each of them at the base of a growing strand of RNA. The plasmid DNA is not being transcribed and is studded with nucleosomes (DNA-protein complexes characteristic of eukaryotic chromosomes but not of bacterial-plasmid DNA). The nucleosomes were presumably formed by interaction of plasmid with oocyte proteins. A nucleosome-free "spacer" region precedes gene.

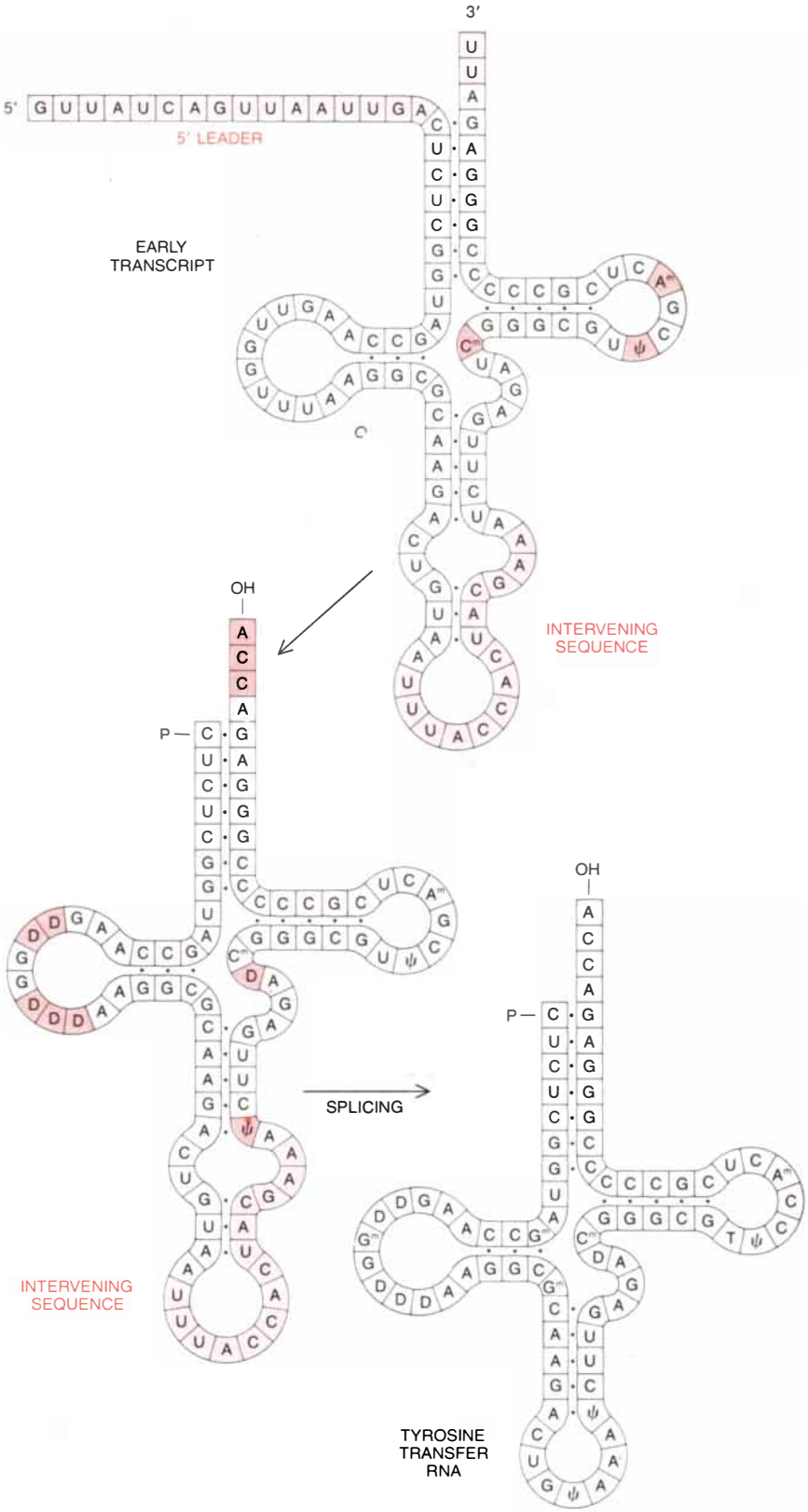
other nucleotide-modification enzymes. The leader sequence apparently serves to order the intricate events of transfer-RNA processing.

The ability of the frog oocyte to correctly excise the intervening sequence and then to religate the molecule of a yeast transfer RNA indicates that the elements of the splicing operation have been conserved throughout a long evolutionary history. Clarkson has recently analyzed the gene for tyrosine transfer RNA in *X. laevis* itself. It too has an intervening sequence, but the sequence is quite different from that of the equivalent gene in yeast. This finding suggests that the splicing enzyme does not recognize the intervening sequence as such; rather it seems to recognize the part of the molecule that will eventually become mature transfer RNA, whose three-dimensional shape tends to be highly conserved in all species, and to excise whatever does not conform to that shape. It is interesting that one can learn such intimate details about the splicing mechanism without having to purify the splicing enzyme itself.

There is evidence that the oocyte can also splice messenger RNA's transcribed from injected SV40 DNA. We pointed out above that oocytes injected with SV40 DNA proceed to synthesize SV40 capsid proteins, and Duri Rüngger of the University of Geneva has shown that the tumor antigens encoded by the virus DNA are also synthesized in oocytes. The processing of SV40 messenger RNA is known to involve various splicing events; in the absence of splicing the correct protein products are not synthesized. In general, therefore, one cell type can correctly splice the transcripts of genes not normally active in that cell type or even in its species. This apparent lack of specificity strongly suggests that splicing is not among the main mechanisms bringing about selective expression of particular genes as cells differentiate.

Combined with DNA cloning, the microinjection of genes into oocytes makes possible a new kind of genetic analysis. In its usual form a genetic experiment begins with the observation of mutant individuals of a species, which in eukaryotic organisms are usually recognized by some abnormality in form. Indeed, the classic era in genetics began in 1910 when Thomas Hunt Morgan found a white-eyed fruit fly in a population of normal red-eyed flies. By collecting a large number of such mutant individuals it is possible to map the location of the mutated gene on a chromosome and eventually to learn the biochemical nature of the alteration.

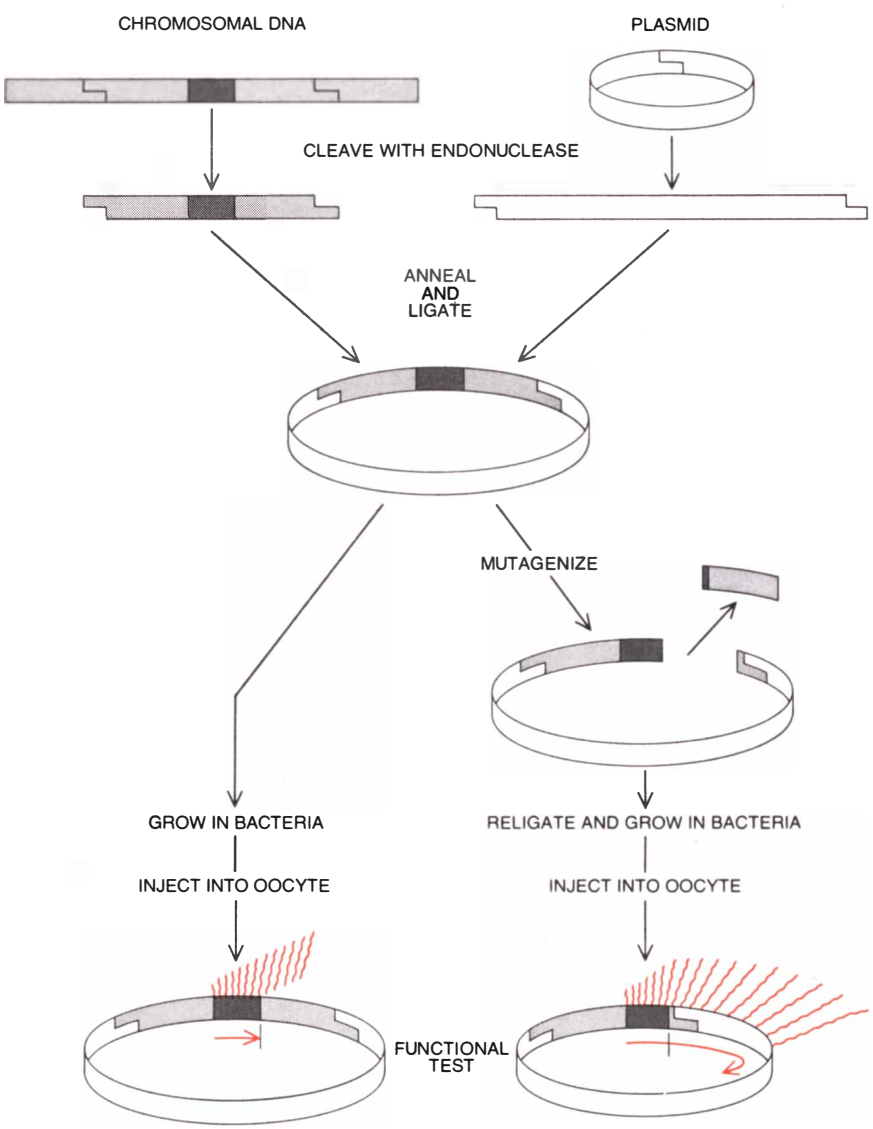
In the in vitro version of genetics that has recently become possible, mutations can be introduced into eukaryotic genes that have been cloned in plasmids. For example, a number of nucleotides can



TRANSFER RNA is processed accurately when the gene for yeast tyrosine transfer RNA is injected into a frog oocyte. The early transcript (*top*) was found to have a previously unobserved "leader" sequence at the 5′ end, a two-nucleotide trailing sequence at the 3′ end and a 14-nucleotide intervening sequence (*light color*). At this stage the molecule has three unusual nucleotides (*dark color*) in addition to the four normal nucleotides *A, G, U* and *C:* two methylated nucleotides (*m*) and a pseudouridylic acid (ψ). Processing removes the leader and modifies the 3′ end, adding the nucleotides *CCA* (*center*). Several more unusual nucleotides also appear, including dihydrouridylic acid (*D*). Apparently the presence or absence of the leader has an effect on timing of particular nucleotide modifications. In splicing step the intervening sequence is excised and chain is religated to yield functional tyrosine transfer-RNA molecule (*bottom*).

be deleted by treating the gene's DNA with restriction endonucleases, enzymes that cleave DNA at well-defined sites, or a particular change can be induced in a single nucleotide with a chemical mutagen. The mutation can be characterized precisely by the new methods for determining DNA sequences. Then the biological effect of the mutation can be tested by injecting the mutated DNA into oocytes and observing its function. One can determine, for example, what region of the DNA contains the promoter (the initiation signal for the RNA polymerase) or whether a particular nucleotide in an RNA precursor is required for correct splicing or other processing events.

This new kind of genetics, in which purified genes are mutated in a chemically defined way and subsequently tested for biological activity, is now well under way in many laboratories around the world. Since we began to work on DNA injection into oocytes some other experimental systems for testing the biological activity of purified, cloned DNA have been developed. For example, a cell-free system incorporating nuclei isolated from oocytes has been shown to transcribe the gene for 5*S* RNA correctly. Fragments of eukaryotic DNA have also been inserted into SV40; susceptible cells are infected with the recombinant virus and the functioning of the eukaryotic DNA is observed. Although these studies are only beginning, it is clear that in vitro experiments will play an important role in molecular biology.



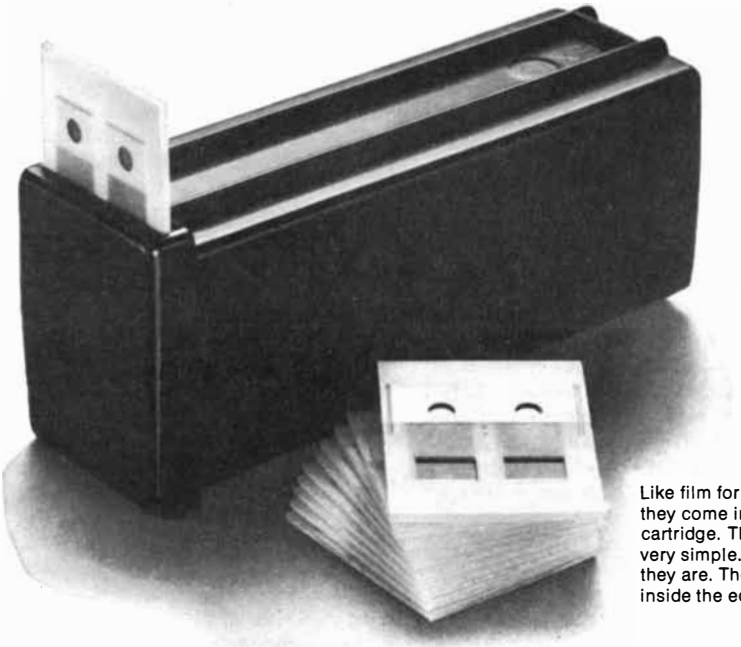
GENE CLONING AND MICROINJECTION can be combined in a new kind of genetic experiment. Chromosomal DNA bearing a gene under study is recombined with a bacterial plasmid by recombinant-DNA techniques: the DNA's are cleaved with an endonuclease (a restriction enzyme) that provides "sticky ends," so that the gene can be inserted into the plasmid. Some of the recombinant plasmids are then mutagenized by deleting a sequence of nucleotides at the end of the gene under study; the precise extent of the deletion can be determined by nucleotide-sequencing methods. The plasmids are cloned in bacteria to provide large amounts of the original gene (*left*) and the mutated gene (*right*), which are injected into oocytes for a functional test. In this case the original gene is transcribed into RNA molecules (*color*) of the proper size. The mutated gene is not: transcription continues beyond the end of gene into plasmid DNA. Presumably deletion eliminated the termination signal recognized by RNA polymerase.

What has this new and sophisticated molecular genetics to do with the development of the frog egg? The nuclear-transplantation experiments described above showed that oocytes contain regulatory substances capable of reprogramming the expression of genes in injected nuclei. These substances could turn out to be important for establishing the initial distinctions among different kinds of cells; to achieve differentiation it would only be necessary for gene-controlling molecules to become unequally distributed among embryonic cells. This idea is not new. In 1934 Morgan wrote: "It is known that the protoplasm of different parts of the embryo is somewhat different. The initial differences in the protoplasmic regions may be supposed to affect the activity of genes. The genes will then in turn affect the protoplasm, which will start a new series of reciprocal reactions. In this way we can picture to ourselves the gradual elaboration and differentiation of the various regions of the embryo."

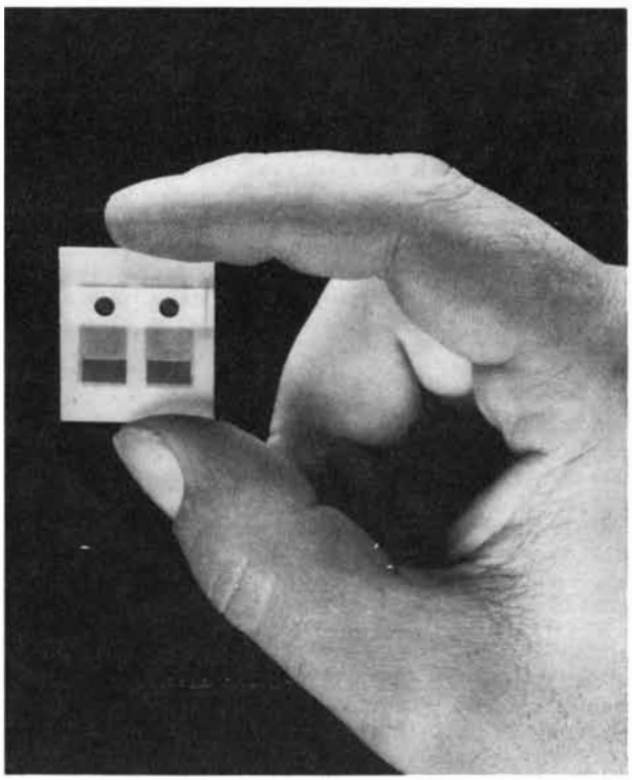
We believe that in order to make progress in the analysis of development it will be necessary to isolate the gene-controlling molecules and to learn, in precise molecular terms, how they regulate genes. There are several ways the injection of oocytes can contribute to this effort. In the immediate future important regions of DNA near the coding segments of genes can be mapped by the mutagenizing and injection procedures described above. Once this stage has been reached for genes switched on or off in development it may be possible to inject such genes into oocytes, to recover the genes while they are still associated with the oocyte's gene-regulating molecules and then to identify the molecules. It may be that the oocyte will lack enough regulatory molecules for switching all the injected genes on or off. In that case the molecules associated with the DNA of chromosomes could be extracted from the cells in which the genes in question are normally present (active or inactive) and could be injected into oocytes along with the purified genes. The oocyte would then act as a test system in which to identify the chromosomal molecules that activate or repress particular genes.

These suggestions look to the future and are necessarily speculative. At this point the primary importance of our work on the microinjection of genes into oocytes is that it provides the first experimental system in which purified, cloned genes are transcribed accurately and extensively. A living cell seems to be able to handle purified molecules more efficiently and more accurately than the biochemist's test tube currently allows.

Phase 2 in a very ambitious program



Like film for a camera they come in this cartridge. They look very simple. In a way they are. They work inside the equipment.



Use once. Two little strips of polyester film base bearing 500 nanometres of evaporated silver. Surface of the silver oxidized to AgCl. Thin layer of cellulose acetate over that. Sandwich the strips between polystyrene covers, with a cross strip of ion-free paper embedded in the top cover. Paper acts as the "salt-bridge" mentioned in books and articles about ion-sensing instruments, which are exquisite examples of craftsmanship. These miniature equivalents stamped out by our production machinery may be a great invention, but they lack individual character that the user must learn over the course of time.

Instrumentation to measure serum electrolytes meters simultaneously into the two round holes 10 μl each of reference fluid and patient serum. Within 30 seconds ions are crossing the paper bridge. A pair of contacts pierce through the rectangular windows to the silver. They pick up the potential difference between the two half-cells. At three minutes it has reached a steady state. Circuitry reads out the chloride concentration.

To measure potassium we coat KCl in gelatin over the AgCl and over that a potassium-selective membrane of polyvinyl chloride containing an aromatic ester dispersion in which is dissolved a compound with a very convenient degree of affinity for K^+. (One learns how nicely such multilayer systems work after 40 years of making lots of very successful color film.) Three minutes after the drops touch, 0.1% of the water has been imbibed, quite enough to establish steady-state potentials at the interfaces. A concentration cell is now operating with the potential at each electrode determined by the K^+ activity in the outer solution. The potential on one side is bucked against the potential from its identical companion strip. If there is any small residual drift, it's the same for both and cancels out.

In this kind of business, accuracy and precision are better stated with numbers than with adjectives. In addition to our own acquisition of pertinent numbers by comparison with the coulometric reference method for Cl^- and the flame photometry reference method for K^+, hospital laboratories small and large are participating in the evaluation process under routine conditions. The same kind of cooperation preceded the introduction of the first phase of Kodak Ektachem clinical chemistry products. That uses multilayer slides that work not potentiometrically but colorimetrically for glucose, blood urea nitrogen, and, just recently, total calcium and total bilirubin.

With reliable numbers easier to come by, will the practice of medicine become mere reaction to sets of numbers? The computer as physician? We don't think so. We certainly hope not.

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SCIENCE AND THE CITIZEN

The Nobel Prizes

The 1979 Nobel prizes in science, which will be formally presented by the King of Sweden at the traditional ceremony in Stockholm on December 10, have honored a smorgasbord of achievements at the frontiers of knowledge: the application of mathematics and computer technology to the invention of a new tool for medical diagnosis; the progress of theories aimed at a unified understanding of the basic forces of nature; the synthesis of an assortment of industrially useful organic compounds; the continuing effort to comprehend and remedy the poverty of nations. Each award, worth about $190,000 this year, will be shared by either two recipients or three.

The prize in physiology or medicine was awarded jointly to Allan M. Cormack of Tufts University and Godfrey Newbold Hounsfield of Electrical and Musical Industries, Ltd. (EMI), for their independent roles in the development of the imaging technique known as computed tomography (CT). In a typical CT-scanning system an X-ray tube is rotated about the long axis of the body of a prone, fully conscious patient. A detector rotating opposite the X-ray tube records the differential absorption of X rays traveling along the various lines projected through the body's tissues. The stored information representing the measured X-ray absorption at a large number of projection angles is then processed by a computer to reconstruct on the screen of a cathode-ray tube a detailed two-dimensional image corresponding to an axial cross section of the body (see "Image Reconstruction from Projections," by Richard Gordon, Gabor T. Herman and Steven A. Johnson; SCIENTIFIC AMERICAN, October, 1975).

Cormack, a native of South Africa, first became interested in the radiological diagnosis and treatment of cancer more than 20 years ago during a six-month stint as a medical physicist at Groote Schuur Hospital in Cape Town. Noting the dearth of knowledge about the relative responses of different parts of the body to radiation, he did some theoretical calculations that led (a few years later) to the publication of a set of mathematical formulas for computing the attenuation of X rays within a two-dimensional cross section of the body based on the known mean values of the absorption of the radiation along a number of straight lines in the cross section. His results, which appeared in a series of reports in *Journal of Applied Physics,* anticipated the subsequent development of the CT-scanning technique. Although Cormack maintains an interest in the field of medical physics (which he regards as a hobby), his main work these days is on the theory of elementary-particle interactions. He has been a member of the faculty at Tufts since 1957.

Hounsfield, an electronics engineer, has been associated with EMI for almost three decades, ever since he joined the British company's research staff in 1951, shortly after he was graduated from the Faraday House Electrical Engineering College in London. His work on the design of computers capable of recognizing printed characters was what led him, beginning in 1967, to become involved in the investigation of new X-ray scanning methods. Unaware of Cormack's earlier contributions, he developed his own method for the reconstruction of tomographic images. The first commercially available CT scanner, built under his direction, was put on the market by EMI in 1973. In recent years Hounsfield has devoted much of his time to perfecting the system and discovering new uses for it.

In recognition of work done at the other, nonapplied end of the research spectrum this year's prize in physics was divided among three theoreticians: Sheldon Lee Glashow and Steven Weinberg of Harvard University and Abdus Salam, who currently serves in the dual capacity of professor at the Imperial College of Science and Technology in London and director of the International Center for Theoretical Physics in Trieste. By remarkable coincidence Glashow and Weinberg are both members of the same graduating class at the Bronx High School of Science (1950) and at Cornell University (1954); their doctorates are respectively from Harvard and Princeton University. Salam, born in Pakistan, did his doctoral work at the University of Cambridge. According to the citation of the Royal Swedish Academy of Sciences the three were chosen "for their contributions to the theory of the unified weak and electromagnetic interaction between elementary particles, including... the prediction of the weak neutral current."

The weak interaction referred to in the citation is the process responsible for, among other things, the radioactive decay of atomic nuclei. The electromagnetic interaction is the manifestation of the force acting between two electrically charged particles; in the modern theory of quantum electrodynamics such interactions are described mathematically in terms of the exchange of an intermediary particle, the photon, which serves as the quantum of the electromagnetic field.

An example of a weak nuclear interaction is the process of radioactive beta decay, whereby a neutron is transformed into a proton, an electron and a neutrino. A weak interaction of this type is thought to be mediated by the exchange of a heavy charged particle that has so far not been detected: the intermediate vector boson. Alternatively the entire process can be considered analogous to the interaction of two electric currents. In the case of beta decay the currents responsible for the weak interaction carry an electric charge; hence they are called charged weak currents.

According to the prevailing theory of the weak interaction, the basic mathematics of which was worked out independently more than a decade ago by Weinberg and Salam, with important contributions by Glashow and others, there is an underlying connection between the weak force and the electromagnetic force (see "Unified Theories of Elementary-Particle Interaction," by Steven Weinberg; SCIENTIFIC AMERICAN, July, 1974). In other words, at a certain level of analysis both the weak interaction and the electromagnetic one can be described by the same set of mathematical formalisms, which in this instance are called gauge theories. One consequence of the Weinberg-Salam gauge theory is the prediction that there is another type of weak interaction in which the interacting particles do not change their charges, as they do in the case of beta decay, but rather maintain the same charges they had before the event, as they do in the case of ordinary electromagnetic interactions. Such a weak interaction would be characterized by the exchange of an uncharged intermediate vector boson or, in the alternative description, by the operation of a neutral weak current. The first observations of weak interactions of this type were made six years ago in particle-scattering experiments done at high-energy accelerator laboratories in Europe and the U.S. (see "The Detection of Neutral Weak Currents," by David B. Cline, Alfred K. Mann and Carlo Rubbia; SCIENTIFIC AMERICAN, December, 1974).

All three winners of this year's physics prize have been active in recent attempts to forge an even more ambitious unified field theory that would encompass the strong nuclear force, the force responsible for holding the nucleus together. Such a "grand unification," if it can be accomplished, would be based on the concepts of the new theory of quantum chromodynamics, which accounts for the interactions of the class of strongly interacting elementary particles called hadrons in terms of the even more basic constituents of matter called quarks, some 15 varieties of which have already been postulated, distinguished from one another by a set of whimsically named properties (see "Quarks with Color and

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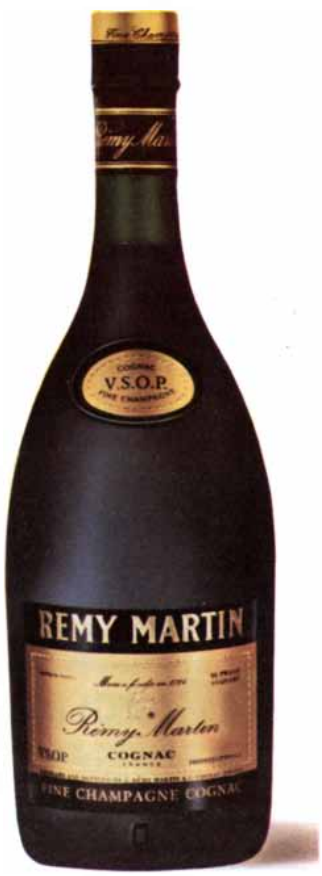

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Flavor," by Sheldon Lee Glashow; SCIENTIFIC AMERICAN, October, 1975).

The prize in chemistry was given to Herbert C. Brown of Purdue University and Georg Wittig of the University of Heidelberg "for their development of the use of boron- and phosphorus-containing compounds, respectively, into important reagents in organic synthesis." Brown, who was born in England but has spent most of his life in the U.S. (receiving his Ph.D. from the University of Chicago in 1938), was cited specifically for his synthesis of sodium borohydride ($NaBH_4$), which has become the "reagent of choice" in chemical processes involving the reduction of carbonyl compounds (metal compounds incorporating the CO group). The Nobel-prize selection committee also noted his work on the modification of the boro-hydrides into reagents for highly selective chemical transformations and his introduction of an entirely new class of compounds, the organoboranes, obtained by reacting diborane (B_2H_6) with olefins (a class of unsaturated hydrocarbons having the general formula C_nH_{2n}). "Thanks to the work of Brown and his co-workers," the committee stated, "the organoboranes have become the most versatile reagents ever created in organic chemistry. They can be used for reductions, rearrangements and additions, and have opened up a range of new possibilities for linking carbon atoms."

Wittig, who at age 82 is professor emeritus at Heidelberg, was honored for his work both in chemical synthesis and in the study of reaction mechanisms. His most important achievement, according to the selection committee, was "the discovery of the rearrangement reaction that bears his name. In the Wittig reaction an organic phosphorus compound with a formal double bond between phosphorus and carbon is reacted with a carbonyl compound. The oxygen of the carbonyl compound is exchanged for carbon, the product being an olefin. This method of making olefins has opened up new possibilities, not the least of which is the synthesis of biologically active substances containing carbon-to-carbon double bonds. For example, vitamin A is synthesized industrially using the Wittig reaction."

The Alfred Nobel Memorial Prize in Economic Sciences, instituted in 1968 by the Bank of Sweden as an addendum to the original prize categories set up by Nobel's will, went to Sir Arthur Lewis of Princeton and Theodore W. Schultz of the University of Chicago, two economists noted for their work on the problems of underdeveloped countries. In naming them the Royal Swedish Academy cited in particular "the importance they attach to facts and empirical research" as well as their shared interest in "the course and the form of development in various eras in different countries," adding that "both are deeply concerned about the need and poverty in the world and engaged in finding ways out of underdevelopment."

Lewis, who was born on the island of St. Lucia in the British West Indies, was knighted by Queen Elizabeth II in 1963 for his service as vice chancellor of the University of the West Indies. Soon afterward he joined the faculty at Princeton, where he now holds the position of James Madison Professor of Political Economy. Formerly he taught at the University of London (where he received his Ph.D. in 1940) and the University of Manchester.

The author of 11 books, Lewis is best known for *The Theory of Economic Development,* published in 1954, a volume regarded as a classic in the field. In this work and others he describes the process of development in terms of two theoretical models. The first model, as summarized in the Nobel-prize citation, "is based on the dual nature of a developing economy. There is an agricultural sector functioning on traditional lines and primarily based on self-support, which engages the labors of the greater part of the population, and a modern market-oriented sector, primarily engaged in industrial production. The driving force in the economy stems from the latter sector, which expands with the support of unlimited supplies of labor, by migration from the agricultural sector, and workers accept the low wages corresponding to the living standards and conventions in an underdeveloped agriculture. The profits in the modern sector... create the growing savings that finance the capital formation for expansion." Lewis' second model explains how under certain conditions the terms of trade between underdeveloped and developed countries are determined by the much lower agricultural productivity in the poorer countries.

Schultz, who is now Charles L. Hutchinson Distinguished Service Professor, emeritus, in the department of economics at Chicago, has also focused in his work on the key role of agricultural productivity in economic development. According to his citation "the main characteristic of Schultz's studies... is that he does not treat agricultural economy in isolation but as an integral part of the entire economy." Among his other distinctions, he "was the first to systematize the analysis of how investments in education can affect productivity in agriculture as well as in the economy as a whole.... Schultz and his students have shown that for a long time there has been a considerably higher yield on 'human capital' than on physical capital in the American economy, and that this tension has resulted in a much faster expansion of educational investments than of other investments."

Schultz, who was born on a farm in South Dakota and went on to earn his

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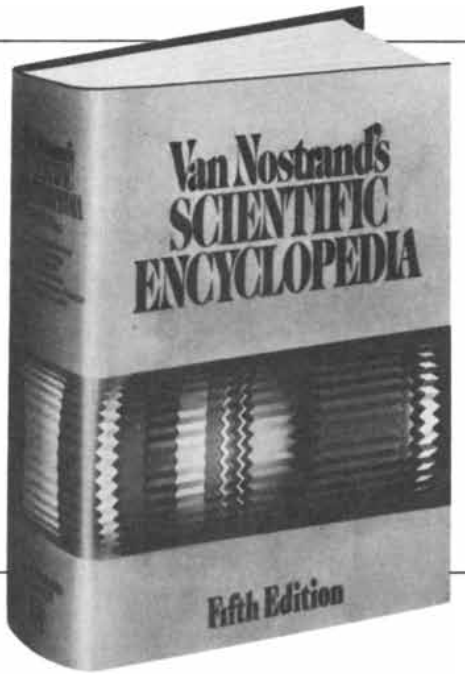

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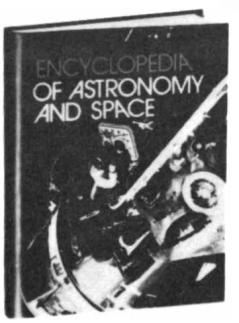

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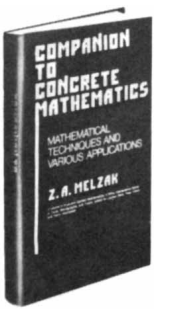

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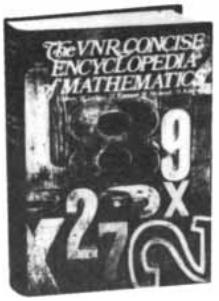

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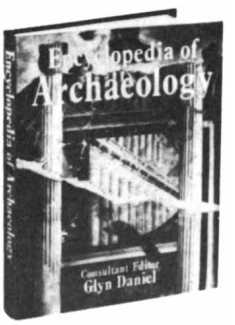

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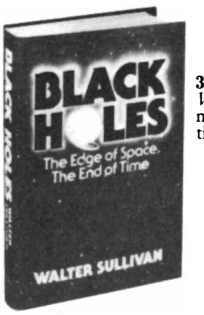

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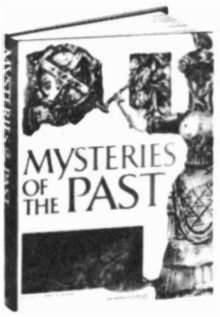

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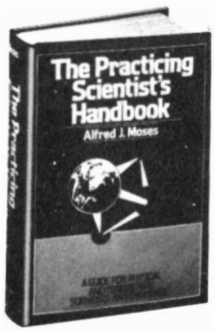

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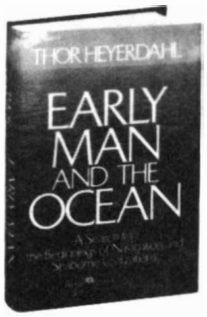

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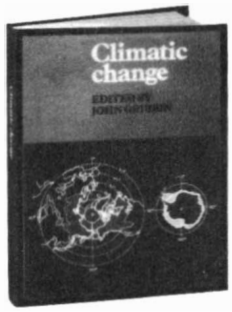

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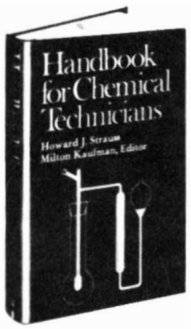

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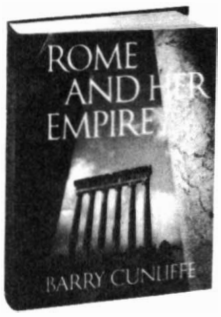

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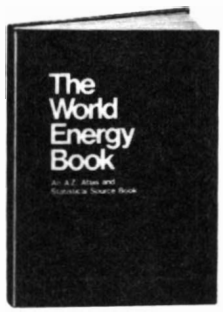

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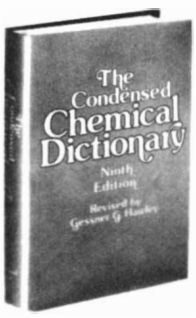

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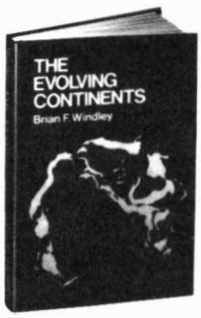

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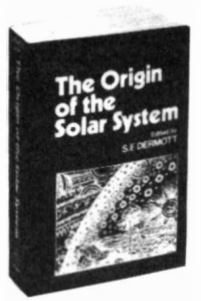

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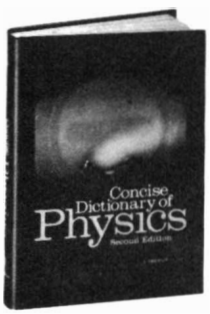

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Ph.D. from the University of Wisconsin, was singled out for special praise by the Nobel-prize selection committee for having always "shown great wisdom as an economist with a striking ability to define development factors that the model-building economists are inclined to neglect."

Count Off

Next March 28 each of the 86 million housing units in the U.S. is scheduled to receive in the mail a questionnaire embodying the 1980 census. Most households will get the "short form," consisting of seven questions about the occupants and 12 about the dwelling; one household in six (one in two in places with a population of less than 2,500) will get the "long form," which has those 19 questions plus 26 more about the people in the dwelling and 20 more about the dwelling unit. The Bureau of the Census has put much effort into the framing of the questions. It also is making a special effort to count everyone, partly because many public and private users rely on the findings and partly because of concern in the bureau about the undercount in the 1970 census, which has been estimated at 2.5 percent (about four million people).

Many of the questions on the forthcoming forms differ little or not at all from the questions that were asked in 1970. The new questions reflect recent trends the Bureau of the Census wants to quantify. For example, among the questions for occupants is one about whether the respondent is a "partner" or "roommate" of the person in whose name the dwelling unit is owned or rented; the question was added to obtain statistics on the growing number of people who live together without being married. The number of possible answers about race has risen from nine in 1970 to 15 in 1980; the expansion is the result of growing ethnic awareness. New questions are added to ascertain the number of part-time workers and the extent of unemployment in 1979. A question about income, which appears only on the long form, is more broadly couched than the 1970 version, which asked about "earnings." The housing questions ask for the first time about condominiums, reflect the rise in housing costs by inquiring about property value up to $200,000 or more (the highest value mentioned in 1970 was $50,000 or more) and monthly rent of $500 or more (compared with $300 or more in 1970).

The bureau's effort to improve its coverage in 1980 is along two lines. One is special publicity to make people more aware of the census; to explain how census data are used so that people will be motivated to respond, and to stress that replies are confidential in the sense that no information about a specific person or a specific dwelling unit is made known outside the census bureau. The program pays particular attention to minority groups, which were disproportionately represented in the undercount of 1970. The second line of approach is to improve census-taking procedures in order to reduce the possibility that people will be missed in the count. One technique focuses on people who are away from their usual residence on April 1 (the official census day); they will be asked to give their usual address and to complete a census questionnaire. A second technique is the "casual count," designed to enumerate people who do not have a residence in the usual sense; it involves visits by census enumerators to places such as mission houses and all-night motion-picture theaters.

The 1980 census will be the first to rely almost entirely on the mail. About 90 percent of the households will be asked to mail in their questionnaires. The other 10 percent, which are mainly in sparsely settled areas, will be asked to keep the questionnaire until a census taker picks it up.

The census is expected to come up with a count of about 222 million people and 79 million households. In 1970 the figures were respectively 203.2 million people and 64 million households. (A household is an occupied housing unit; the number of households is lower than the number of housing units because of vacancies.) The census is also expected to reveal that the number of husbandless women heading families has risen almost 50 percent since 1970 to more than eight million; that the traditional family household of father, mother and one child or more is at its lowest percentage ever (fewer than a third of the households), and that the number of unmarried couples sharing a household has more than doubled since 1970.

Data from the census will serve for many purposes other than the constitutional one of providing the basis for the apportionment of seats in the House of Representatives. Many states now apportion seats in their legislatures on the basis of the census. More than 100 Federal programs distribute money on the basis of population figures, and Government agencies also rely on census statistics for the long-range planning of such facilities as highways, schools and sewer systems. It is in the private sector, however, that the use of census data has been growing the fastest. Many companies draw on the statistics in marketing products, planning the location of new facilities and recruiting workers.

Amplified Genes

One of the major drugs for the treatment of cancer is methotrexate, an analogue of folic acid that disrupts cellular metabolism by inhibiting the enzyme dihydrofolate reductase (DHFR), which participates in the synthesis of proteins and nucleic acids. Rapidly dividing cells, including cancer cells, are preferentially killed by methotrexate. Unfortunately cancer cells can become resistant to the drug by manufacturing extra molecules of the enzyme faster than the drug can inhibit them. Robert T. Schimke and his colleagues at Stanford University have examined the mechanism by which such drug resistance develops in cultured mammalian cells. They propose that the properties of methotrexate resistance have much in common with the process by which bacteria become resistant to antibiotics.

Schimke and his colleagues found that the dramatic increase in the number of DHFR molecules in methotrexate-resistant cells is due to the amplification, or multiplication, of the gene coding for the enzyme. When cultured animal cells are grown in the presence of low concentrations of methotrexate, cells are selected with low degrees of gene amplification. On subsequent stepwise increments in methotrexate, cells are selected with progressively increasing gene number: as many as 1,000 copies of the DHFR gene per cell. Surprisingly, the length of the amplified DNA segment is nearly a million nucleotides, far greater than that required to code for the amino acid sequence of the enzyme. In fact, the copied segment is about 20 times longer than the DHFR gene, even though that gene has a number of very long noncoding sequences that are excised at the RNA level before the protein product is made.

It is proposed that in animal cells genes are duplicated on rare and random occasions. The process would facilitate evolution and might be mediated by a number of mechanisms: unequal crossing-over between paired chromosomes, disproportionate copying of the gene during DNA replication or the uptake of DNA segments from dead cells. According to Schimke, in the absence of selection pressure such duplications are usually unstable and disappear. In the presence of methotrexate, however, the occasional cells with duplicated DHFR genes are favored because they are more resistant to the drug. Further amplification can be achieved by subjecting the cells to conditions of more stringent selection (higher concentrations of methotrexate), thereby favoring those cells that have larger numbers of gene copies. After a number of generations the cells with the optimal number of DHFR genes to allow growth at the given concentration of methotrexate will become dominant in the population. The reason is that the cells with too few copies will be killed by the drug, whereas the cells with an excessive number of copies will be at a growth disadvantage because of their longer generation times.

Schimke and his colleagues find certain analogies between drug resistance due to gene amplification in mammalian

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cells and certain forms of antibiotic resistance in bacteria. For example, resistance to penicillin results from an increase in the amount of the enzyme penicillinase. In some cases this increase results from duplications of chromosomal DNA segments coding for the enzyme. The genes for penicillinase may also be carried on plasmids: small rings of DNA separate from the bacterial chromosome. Similarly, many methotrexate-resistant mammalian cells appear to carry their extra copies of the DHFR gene on nonchromosomal elements known as "minute chromosomes." Indeed, some cells with a highly elevated number of genes have as many as 300 minute chromosomes. Whether these elements can be exchanged between cultured cells as plasmids are exchanged between bacteria in the development of antibiotic resistance is currently being studied.

In cells that carry their extra DHFR genes on minute chromosomes resistance to methotrexate is often lost when the cells are grown for several generations without the drug. Other cell lines, however, have their copies of the DHFR gene present in a chromosome. This system appears to ensure the stability of the drug-resistance trait over many generations. Schimke proposes that the amplifications arise initially in the chromosome. If they are unstable, they are eventually excised from the chromosome to form the minute chromosomes. The stabilization of the drug-resistance trait may involve integration of the minute-chromosome elements into the other chromosomes, along with further changes that prevent the excision of the amplified chromosome segments.

The Poisoning of Isaac Newton

In 1692 Isaac Newton suffered from severe insomnia, poor digestion, amnesia, depression and delusions of persecution. For the next two years he had little contact with people except for a few old friends to whom he occasionally wrote irrational letters. In a letter to John Locke he tried to account for his melancholic withdrawal: "The last winter by sleeping too often by my fire I got an ill habit of sleeping & a distemper wch this summer has been epidemical put me further out of order, so that when I wrote to you I had not slept an hour a night for a fortnight together & for 5 nights together not a wink."

Historians have not been successful in finding the cause of Newton's distemper. In the *Nouvelle Biographie Générale* of 1863 an anonymous author proposed that the death of Newton's mother triggered his breakdown. This hypothesis is implausible: his mother had died some 13 years earlier. Other biographers have attributed Newton's illness to the physical and mental stress that must have accompanied the intense and prolonged labor of writing *Principia Mathematica*. This hypothesis too is unconvincing: he had completed the *Principia* almost five years before the onset of his illness. Still others have suggested that the traumatic loss by fire of his chemical laboratory and valuable manuscripts unhinged his mind. Once again the dates do not support the hypothesis: the fire was years before his illness.

Now two investigations published in *Notes and Records of the Royal Society of London* suggest that Newton's breakdown had a chemical cause. Laila W. Johnson and Myron L. Wolbarsht of the Duke University Eye Center and P. E. Spargo of the University of Cape Town and C. A. Pounds of the Central Research Establishment in Aldermaston have independently proposed that Newton's illness was chiefly the result of poisoning by the metals he used in his chemical and optical experiments. Over the years before his breakdown Newton did many experiments in alchemy with a wide variety of metals, including lead, arsenic, antimony and mercury. Most of the experiments involved heating the metals in large open vessels, in furnaces and over candles, undoubtedly exposing him continually to toxic vapors. Moreover, the symptoms of his illness are those of metallic poisoning.

Newton also had the early chemist's penchant for tasting the products of his experiments. On 108 separate occasions he recorded in his notebooks that he had tasted materials, whose flavors he described as ranging from "tastless" to "sweetish" and "saltish" to "strong stiptick vitriolique tast." And he not only inhaled and ingested toxic materials but also handled and rubbed them. Accordingly lead, arsenic, antimony and mercury and compounds of them probably entered his body through his skin. Another source of toxic material may have been the dark red paint, with cinnabar (mercury sulfide) as its chief pigment, that had been freshly applied to the walls of his room in London at about the time of his breakdown.

To test the hypothesis that Newton suffered from metallic poisoning Spargo and Pounds analyzed (by the ultrasensitive modern techniques of neutron-activation analysis and atomic absorption spectrophotometry) four surviving samples of Newton's hair. All four samples showed unusually high concentrations of lead, antimony and mercury. Although it cannot be known with certainty that all the samples are authentic, two of them provided by the current Earl of Portsmouth have a strong claim to being so. The daughter of Newton's niece Catherine Barton married John Conduitt, whose daughter, also named Catherine, married John Wallop, the first Earl of Portsmouth. The two locks of hair, along with other Newton relics and manuscripts, have been passed down from generation to generation in the Portsmouth family.

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Programming Languages

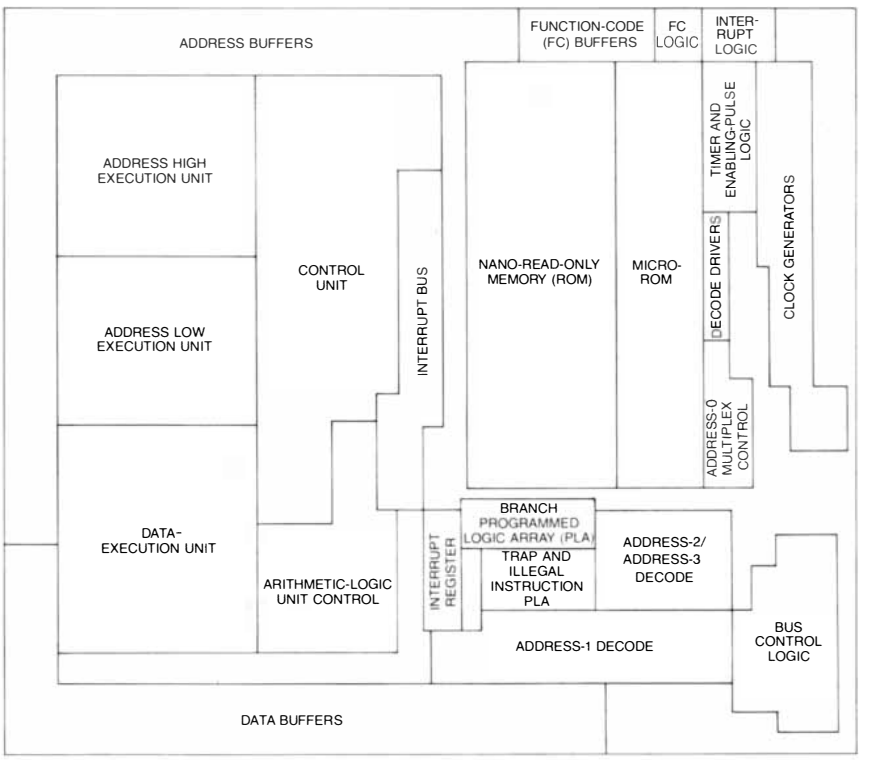
The nature of information processing has been transformed over the past 25 years by high-level programming languages, which provide a variety of mechanisms for encoding complex problems to be solved by computer

by Jerome A. Feldman

To support the continually increasing information-processing demands of modern society it is necessary to write and maintain an enormous number of computer programs: the lists of instructions a computer follows in carrying out its computations. Indeed, the main factor currently limiting the wider application of computer technology is a lag in the production of software, or programs, a situation that is due mainly to a shortage of experienced programmers. How do programmers tell a computer what to do? Today most programs are written in symbolic languages with names such as Fortran, Cobol and Lisp. These are the high-level programming languages, designed to facilitate the formulation of computing problems and to communicate the formulations to the computer. Over the past 25 years the development of these sophisticated languages for specifying computations has changed the nature of computing.

A computer program is a statement in some well-defined language of an algorithm: a step-by-step procedure for solving a problem that terminates after a finite number of steps. Before the first programming languages were introduced solutions to computational problems, whether to be implemented by hand calculation or mechanical, had to be formulated either in mathematical language or in ordinary "natural" language. The trouble with relying on mathematical expressions to encode an algorithm is that although they are precise, they are not expressive: they can encode only a limited range of problems. A natural language, on the other hand, can express a wide range of concepts, but their meaning will be imprecise. (An example that is familiar to many is the difficulty of computing income taxes from the algorithms given in tax forms.) Programming languages offer an unprecedented combination of expressive power and precision. Like mathematical languages they consist of a small number of words with exact meanings, and like natural languages they provide rich conceptual tools for describing relations, actions and processes. As a result programming languages can describe highly complex situations in such a way that their implications can be calculated.

In the U.S. alone there are currently more than 150 programming languages employed for such diverse purposes as business and government data processing, scientific computation, business planning, simulation and modeling, process control and artificial intelligence. Many languages deal with either the manipulation of numbers for scientific and engineering calculations, the manipulation of files for record keeping or some combination of the two. Here I shall review some of the general principles on which the design of programming languages is based. I shall emphasize not the differences in notation or terminology among programming languages but the different capacities for computation offered by some of the most widely used languages. As I shall discuss, a great deal of effort is currently being devoted to designing programming languages that provide more reliable programs at the cost of less human effort. In order to understand the impact these high-level languages have had on the art of computer programming, how-



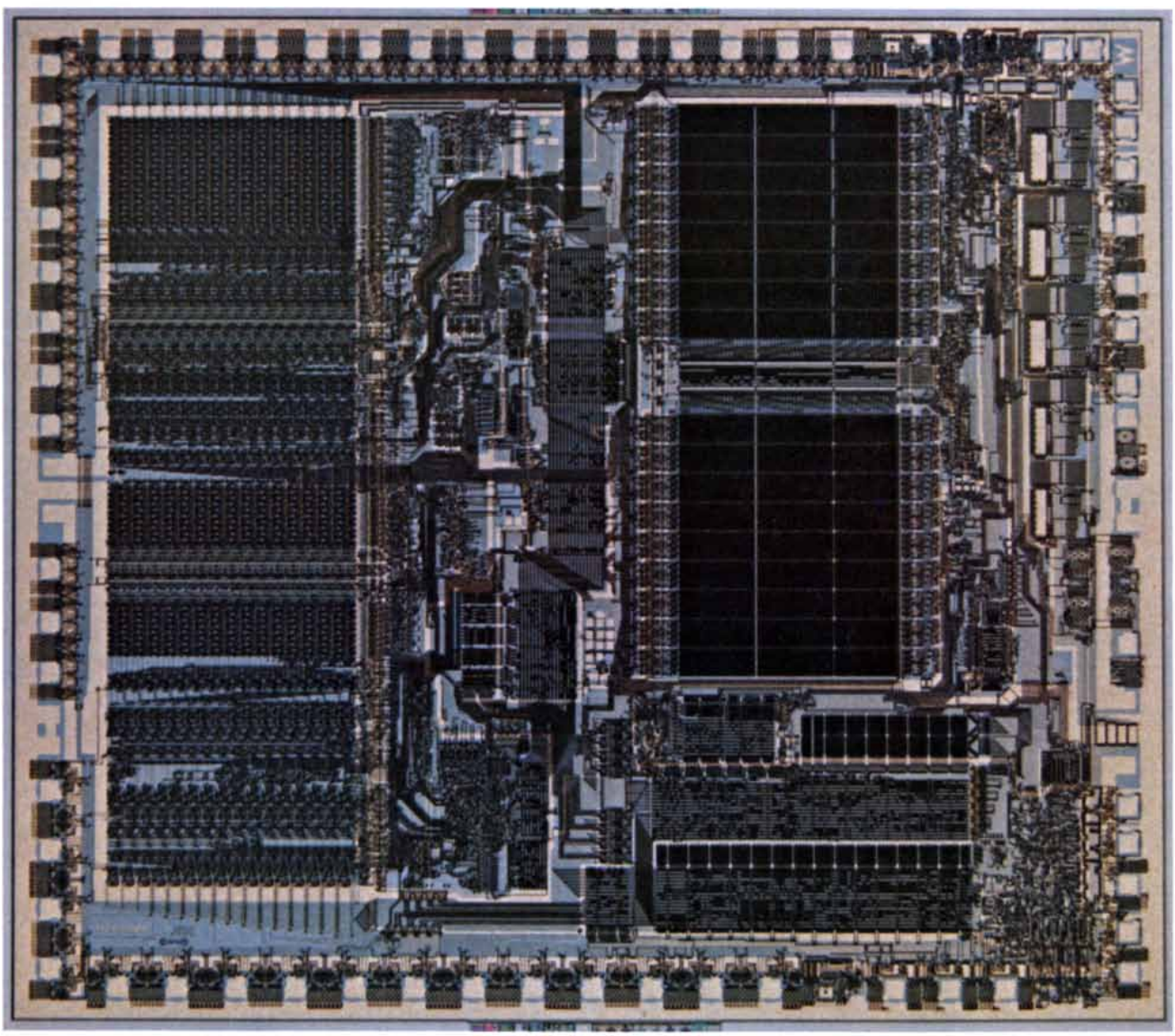
MICROPROCESSOR CHIP made by Motorola Inc., one of a new generation of chips that incorporate special features for implementing high-level programming languages, is shown in the micrograph on the opposite page. A functional map of the microprocessor is shown above. A microprocessor performs the same processing functions as a larger computer, and so it is organized into areas for storing and retrieving strings of binary digits (0's and 1's) representing data and instructions (address high execution unit, address low execution unit) and for performing arithmetical and logical operations (arithmetic-logic unit control, data execution unit). There

ever, it is first necessary to touch briefly on the way a computer system operates.

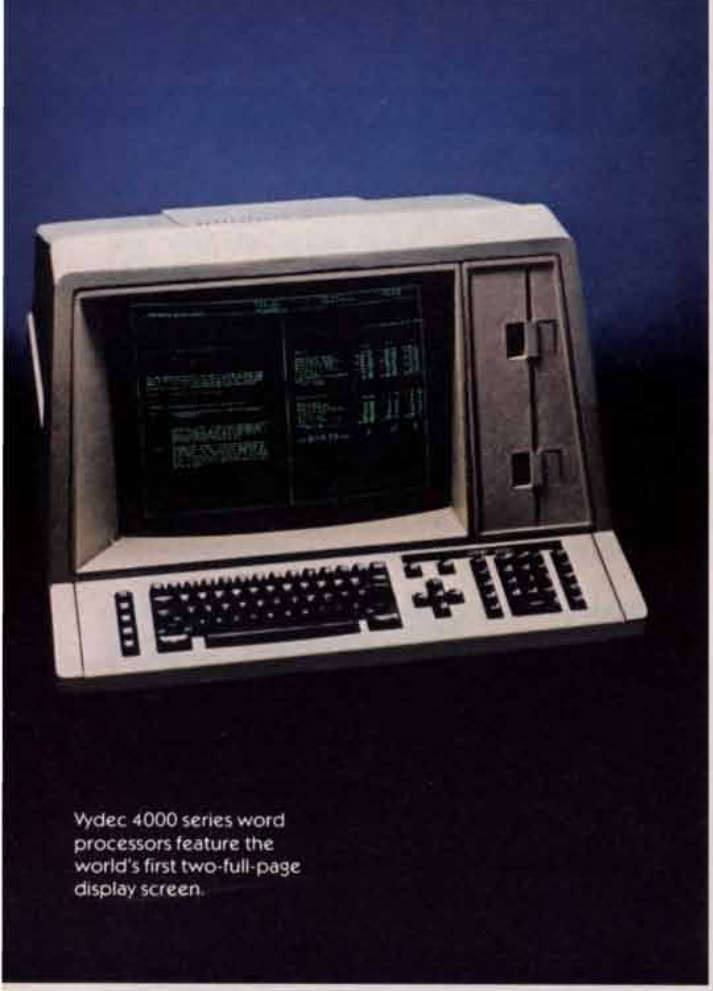
Hardware and Software

The hardware of a computer system consists essentially of input devices for entering information into the computer, output devices for displaying and printing results, a memory unit for storing information and a collection of circuits for performing certain basic computations with the stored information. In the computer, information is represented as strings of binary digits (0's and 1's) that are stored in the large array of gates, or electronic switches, that make up the memory. What makes computers conceptually different from other machines is the fact that these binary strings can be interpreted as instructions as well as data. In other words, the computer controls its own course of action. The built-in functions of the computer not only include the standard arithmetical and logical operations for combining and comparing stored data but also control functions that determine the sequence in which the stored instructions are executed. The software of the computer system serves to build these "hard-wired" arithmetical, logical and control operations into the kinds of complex procedures needed to implement the solutions to computing problems.

The earliest computer programs were written in a rudimentary system of notation called machine language. In machine language each basic machine operation is represented by the numerical code that invokes it in the computer, and each memory location is represented by its numerical address. Fairly quickly, however, the numerical codes of machine language were replaced by the mnemonic codes of a slightly higher-level language called assembly language. A separate program called an assembler was employed to transcribe assembly-language instructions such as FETCH 173 (meaning copy the contents of memory location 173 into the accumulator, or register, where the computations are done), MPY 156 (meaning multiply the contents of the accumulator by the contents of location 156) and STORE 391 (meaning copy the contents of the accumulator into location 391) into the machine codes that



are additional units for carrying out control operations that determine the order in which the statements of stored programs are executed (control unit, programmed logic array units) and for providing interfaces with the large-scale memory and the input and output devices that complete the hardware of the computer system (buffers, decoders and so on). The statements of a high-level programming language are intended to facilitate the user's formulation of computing problems and must be translated by a complex program called a compiler into instructions that are directly executable by the computer. The instructions are (in this chip) themselves further broken down into parts according to fixed microprograms stored in the read-only memories (micro-ROM and nano-ROM). Organization of the chip contains several features to support high-level programming languages, including codes for frequent computations and flexible addressing.



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LANGUAGE	YEAR	ORIGIN OF NAME	MAIN USE
Algol	1960	Algorithmic language	Scientific
APL	1962	A programming language	Scientific, modeling
Basic	1965	Beginner's all-purpose symbolic instruction code	Education
Cobol	1959	Common business-oriented language	Business
Fortran	1954	Formula translator	Scientific
Lisp	1956	List processor	Artificial intelligence
Pascal	1971	Blaise Pascal	Education, systems
PL/I	1964	Programming language I	Business, scientific

MOST WIDELY USED PROGRAMMING LANGUAGES are listed with the year they were first introduced, the origin of their name and their principal applications. Programs written in these expressive but precise languages are made up of complex statements that refer to memory locations by symbolic names called variables rather than by numerical addresses. Each program statement in such a high-level language is equivalent to several machine-code instructions. Programming languages can differ in types of data they are equipped to handle, operations they can perform on data and control functions they provide for structuring programs.

could be executed directly by the computer. (In modern computers there are several arithmetical registers, and the registers to be employed in a particular operation must be specified as part of the instruction that invokes the operation.)

Machine-language and assembly-language programs are detailed and repetitious, dealing with the physical operation of devices such as printers as well as with the intricacies of allocating space in memory, moving data from one location to another and invoking basic operations. As one might expect, writing such programs is a long and painstaking process. The job of programming was transformed when in 1954 programmers at computing facilities in Europe and the U.S. began working with programming languages that would be recognizable today.

In the higher-level programming languages the instructions are fairly complex statements, each equivalent to several machine-language instructions, and they refer to memory locations by names (called variables). The task of transforming the programs written in these languages into machine-executable form is accomplished by a program called a compiler. Unlike an assembler, a compiler does not simply transcribe a program; it also analyzes and reworks it. It performs such complex tasks as reordering operations, choosing internal representations for data, eliminating redundant operations and setting aside extra memory locations (not explicitly called for in the program) to hold intermediate results, in order to generate an effective and efficient machine-language procedure. (A compiler can be designed to emphasize, among other things, speed of computation, efficient utilization of memory or some combination of the two in the machine-language program it generates.) As a compiler translates a program it stores the machine-language translation in the memory of the computer, and when the compilation is finished, it initiates the execution of the machine-language version. Compilers are difficult to write, but once a compiler for a particular language has been generated for a particular computer, any program written to the exact specifications of that language can be run on that computer.

Although it was (and still is) convenient to continue writing some special procedures in assembly language, this new approach eliminated so much of the detail and drudgery of programming that the early compilers were called automatic programming systems. Freeing the programmer from concern with binary strings, memory addresses and primitive operations, they shifted the emphasis in programming from the details of the computer hardware to the computing problem to be solved. As a result the designers of the new higher-level programming languages could address a different aspect of programming, namely providing tools for the difficult task of expressing algorithms in sufficient detail for them to be executed automatically by a machine.

Specifying Algorithms

Before the advent of electronic digital computers most algorithms for solving computational problems (including those of traditional mathematics) were written with the assumption that they would be carried out by a human being, who would make whatever decisions were needed during the course of the computation. Even the earliest electronic computers were so fast, however, that it was impractical to have a human being monitor their computations. Instead the complete specification of the computation had to be contained in the memory and wiring of the machine. In other words, the statement of the algorithm—the computer program—had to include appropriate actions for any situation that might arise. Most people have a great deal of trouble foreseeing all the possible pitfalls in a complex situation. In fact, completely specifying algorithms continues to be the major difficulty in computer programming. Since the introduction of the first compilers most high-level programming languages have been designed with the object of making it easier to express algorithms fully while still generating efficient machine-language procedures. An example may serve to make the problems of communicating algorithms to computers more meaningful.

Consider the task of programming a computer to solve a problem in elementary algebra: finding the two roots, or solutions, of the quadratic equation $AX^2 + BX + C = 0$, where A, B and C are real numbers. The general solution to this problem is provided by the familiar formula

$$X = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A}.$$

In other words, the roots of any quadratic equation can be computed by simply plugging the values of A, B and C into the formula. (One of the two quadratic roots is obtained by interpreting the sign $\pm$ as a plus sign and the other by interpreting it as a minus sign.)

For human beings this formula serves as a sufficiently precise algorithm for computing quadratic roots. Suppose, however, that the computation is to be carried out by a computer. Would simply putting the formula on punched cards or typing it on the keyboard of a terminal give the computer enough information to be able to take in values of A, B and C and return a pair of values for X? More precisely, what constitutes a proper program for implementing the algorithm by computer? Any such program will have to allow for the values of A, B, C and X to vary so that the roots of not just one but any quadratic equation can be computed. In other words, A, B, C and X will be the variables of the program, each one representing a different location in the computer memory. For the purposes of discussion assume that the computer "speaks" the programming language Fortran. (The name is from "formula translator.") In other words, the computer is equipped with a Fortran compiler. Fortran, which now exists in several different versions, was the first well-defined programming language, and it is still the language most widely used for mathematical calculation. (Because the words in a programming language have fixed meanings and therefore cannot evolve to meet changing needs the way a natural language can, it is often necessary to define new versions of programming languages. Each new version, however, is designed

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Consultant: That's why I'm here. Now, about the sand. Are the rest of your dishes clean?

Woman: They're fine. My husband's a Mexican food freak. Even pans with baked-on refried beans get clean. But where did the sand come from?

Consultant: What does the sand look like?

Woman: Like...sand. In a puddle of water that didn't drain out of the teacup.

Consultant: If you're seeing "sand," it could be your dishwasher detergent hasn't dissolved. Do you have a cup with some "sand" in it now?

Woman: Right here by the phone.

Consultant: Does the "sand" look like detergent?

Woman: You mean this is detergent?!?

Consultant: Look closer.

Woman: It does look like detergent. So why didn't it dissolve?

Consultant: Check your water temperature. At your dishwasher, it should be at least 140°. If it's okay, then I suggest you buy a fresh box of detergent. Dishwasher detergent sometimes has a very short shelf life and doesn't dissolve completely when it's old. And make sure you load your teacups properly, so all the water drains out.

Woman: Wow. You really helped. Sorry I bothered you, but at least I didn't have to call a repairman. Thanks for your time.

Consultant: Glad I could help.

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to be compatible with its predecessors, and so the different versions generally have much in common.)

In trying to construct a Fortran program for implementing the formula for computing quadratic roots, the first problems that present themselves are typographical. Input is read one character at a time by the computer, which in most cases does not recognize the position of a character on a line or symbols other than those found on the keyboard of a standard typewriter. Hence the superscript 2 (in B^2), the long horizontal line that denotes division and the square root symbol $\sqrt{\ }$ must be put into different form before the formula can be submitted to the computer. One way to do this is to rewrite the formula as follows: $X = (-B \pm \text{SQRT}(B^{**}2 - 4AC))/(2A)$.

In order to represent computer instructions as linear strings of symbols all the widely used programming languages depend on similar encoding devices, in particular parentheses, special symbols such as ** for exponentiation and some function names such as SQRT for square root. Computers do not generally come equipped with hardware for performing special functions such as taking square roots. Every programming language comes equipped, however, with a library of carefully written programs for executing such functions, which can be stored in computer memory. Compilers have access to the libraries, so that as they translate programs into machine language they can insert the appropriate function programs.

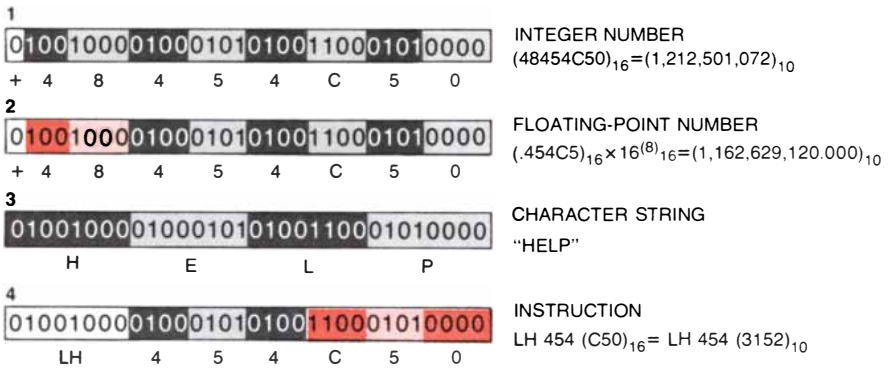
In the rewritten formula $X = (-B \pm \text{SQRT}(B^{**}2 - 4AC))/(2A)$ there is a less obvious typographical problem with the variables *X*, *A*, *B* and *C*. Remember that in programming languages a variable is not an item of data but a label for a location in the memory of the computer. The value of a variable at any moment is the information currently stored there. (The content of a variable can change during the course of a computation.) The problem with the formula is that the standard mathematical practice has been followed for showing the multiplication of variables: placing them side by side without any multiplication symbol between them.

Most programming languages do not accept this convention, because it severely limits the number of different variables that can be employed within a particular program. For example, if the quadratic-roots program included a variable *AC* as well as the variables *A* and *C*, then the computer would not be able to assign a unique value to the expression *4AC*. Problems of this kind rarely arise in human communication, because human beings can depend on the context of an ambiguous statement to help determine its intended meaning. Computers, however, rely on explicit directions, and so most programming languages provide a symbol for indicating multiplication, typically the single asterisk that is utilized in Fortran: $X = (-B \pm \text{SQRT}(B^{**}2 - 4^{*}A^{*}C))/(2^{*}A)$.

The next problem is how to encode the symbol $\pm$, which is employed in the formula as mathematical shorthand to indicate that two different computations are needed to determine the two values of *X*. The general treatment of multiple actions is beyond the scope of current programming languages, and so it is necessary to specify both computations as part of the computer program: $X = (-B + \text{SQRT}(B^{**}2 - 4^{*}A^{*}C))/(2^{*}A)$ and also $X = (-B - \text{SQRT}(B^{**}2 - 4^{*}A^{*}C))/(2^{*}A)$. In other words, during the running of the quadratic-roots program the variable *X*, or the memory location associated with it, would be assigned two different values. Taking all these factors into account, a simple Fortran program for computing quadratic roots could be constructed as follows:

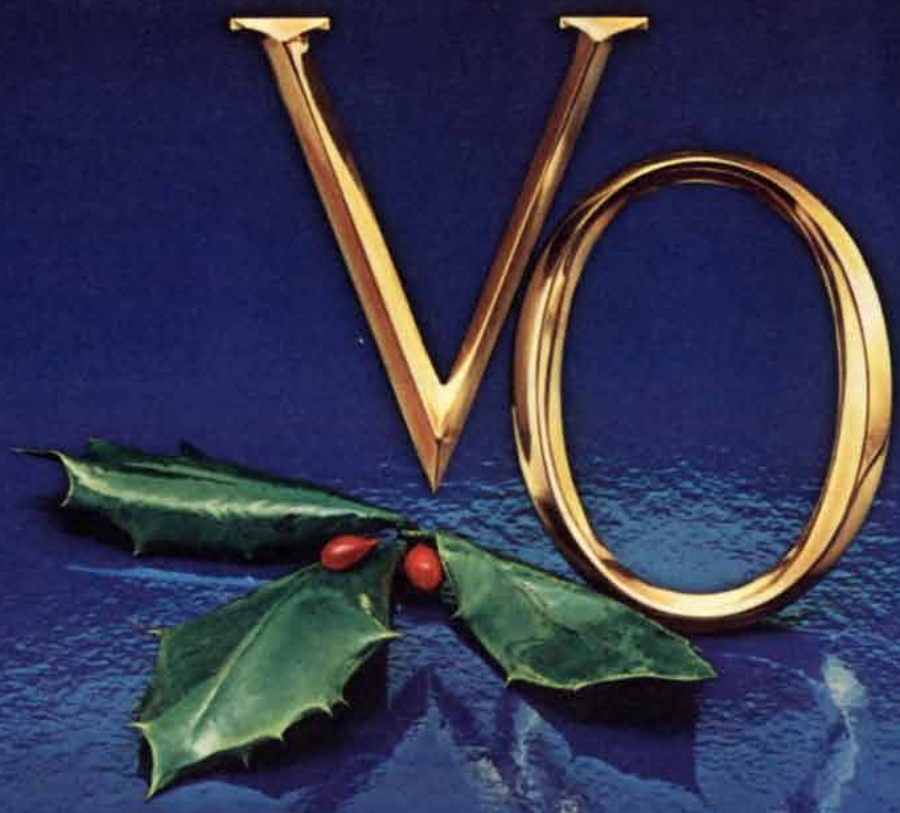
```
READ A, B, C
R = SQRT (B**2 - 4*A*C)
X = (-B + R)/(2*A)
PRINT X
X = (-B - R)/(2*A)
PRINT X
```

This program demonstrates several additional properties of the syntax of programming languages. To begin with, in addition to special built-in functions such as SQRT all programming languages include operations for assigning values to variables and for printing out the values of variables. For example, the statement READ *A, B, C* serves to fill three locations in memory with whatever values for those variables are sup-



STRING OF BITS, or binary digits, can be interpreted in several different ways within a single computer program. For example, most modern computers allocate a single 32-bit word for each location in memory, and in a standard International Business Machines computer there are four different interpretations of the word shown here. First, because each four-bit binary sequence within a word can represent the numerical values 0 through 15, it is generally convenient to store numbers in computer memory in hexadecimal, or base-16, notation, so that each four-bit sequence represents a single digit of a hexadecimal number. (In hexadecimal notation the letters *A, B,... F* serve as digits denoting the numbers 10, 11,... 15.) When the 32-bit word is interpreted as an integer, or fixed, hexadecimal number (*1*), the first bit (*white*) is taken to represent its sign and the next three bits are taken to represent its first digit. Therefore as data of this integer type the word represents the base-16 number +48454C50, which equals the base-10 number +1,212,501,072. Second, although a binary word of fixed length can represent only numbers within a fixed range, that range can be extended (*2*) by allocating, say, one bit of the word to represent a sign (*white*), seven bits to represent an exponent (*dark and light color*) and 24 bits to represent a mantissa, or fractional part (*dark and light gray*), of a hexadecimal number in exponential form. When the word is interpreted as such a floating-point, or real, number, the sign bit determines whether the entire number is negative or positive. In this case, in order to avoid allocating another bit to represent the sign of the exponent, the exponent has been expressed in "excess 40" notation, in which its value is assumed by the computer hardware to be (hexadecimal) 40 less than the number represented by the seven-bit exponent string. Therefore because the exponent portion of the binary word shown holds the hexadecimal number 48, the hexadecimal value of the exponent is 8. As a floating-point number the entire word (translated into base 10) is then interpreted as 1,162,629,120.000. Third, in most computers character data are encoded by means of an eight-bit alphabet: *A* = 01000000 (or 40), *B* = 01000001 (or 41) and so on. (The first 39 characters in the alphabet represent symbols such as punctuation marks and brackets.) Hence the binary word can also be interpreted (*3*) as the character string HELP. Finally, the word can be interpreted (*4*) as a machine instruction in which the first eight bits (*white*) represent a command and the remaining bits hold the memory location (*dark and light color*) and registers (*dark and light gray*) to which the instruction applies. (In a computer arithmetic is done on an array of numbered registers, or accumulators.) In this case the instruction (translated into base 10) is LH 454 3152, which directs the computer to load, or copy, half of a word of data into register 4 from the memory location whose address is the sum of 3152 plus the contents of registers 4 and 5. Machine instructions that are directly executable by the computer imply certain interpretations for the raw binary data to which they refer, but high-level programming languages include a number of additional constructs designed to prevent the confusion of different data types. In particular, type of data to be associated with a given variable, or memory location, can be specified by means of nonexecutable statements called declarations. Once a variable has been declared to be of a certain type the compiler checks extensively to verify that only data of the correct type are placed in variable.

The Standard of Giving.



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plied on an input device. Similarly, the statement PRINT *X*, which appears twice in the program, serves to return the two quadratic roots on an output device. (In most modern computers input is read into and output is displayed on a keyboard-and-cathode-ray-tube unit.) As this program demonstrates, it is sometimes convenient to introduce extra variables for internal use in a computer program, variables whose values are not read into the computer or printed out although they are computed and stored in the course of the computation. In this program the introduction of the variable *R* reduces the number of operations required in the computation.

An Improved Program

Although there are some versions of Fortran in which this program would return quadratic roots, the program is still far from being an adequate rendering of the original formula. One problem that remains is that the function SQRT will not operate properly if the value to which it is to be applied (in this instance $B^{**}2 - 4^{*}A^{*}C$) is negative. The problem can be solved by inserting into the program still another extra variable, $DISC = B^{**}2 - 4^{*}A^{*}C$, and checking to see whether *DISC* is less than zero before invoking the square-root function $R = \text{SQRT}(DISC)$. Taking issues such as these into account, a more complete program for computing quadratic roots can now be designed:

```
      READ A, B, C
      DISC = B**2 - 4*A*C
      IF (DISC) 30, 10, 20
10    X = -B/(2*A)
      PRINT X
      GOTO 100
20    R = SQRT (DISC)
      X = (-B + R)/(2*A)
      PRINT X
      X = (-B - R)/(2*A)
      PRINT X
      GOTO 100
C     COMPUTE COMPLEX ROOTS
30    R = SQRT (-DISC)
      . . .
100   STOP
      END
```

The most significant difference between this program and the preceding one is the presence of the Fortran control statements using IF and GOTO. The statements of a program are executed sequentially, in the order in which they are submitted to the computer unless a control statement such as one of these is encountered. Compared with some other control mechanisms the IF and GOTO statements are primitive, but they suffice to specify any desired order for the execution of statements within a program. (Languages developed after Fortran provide more readable control statements that are easier to apply to programming problems, but they perform the same function as the IF and GOTO statements.)

More precisely, a conditional statement such as IF (*DISC*) 30, 10, 20 provides a way of choosing among alternative courses of action by comparing the value of the expression shown in parentheses with zero. If that value is less than zero, control is transferred to the program statement whose number is given first after the expression; if it is equal to zero, control is transferred to the statement whose number is given second, and if it is greater than zero, control is transferred to the statement whose number is given third. (On the punched cards on which the early versions of Fortran were implemented space was reserved for numerical labels to identify statements within a program. Newer languages utilize more meaningful symbolic labels for this purpose. In addition in more modern languages the positioning of words in a program serves only to make the program more readable and has no effect on the way it is run.)

To understand how the IF construction applies to the computation of quadratic roots, notice that if *DISC* equals, say, zero, then there is no need to invoke the square-root function, and *X* will be equal to $(-B \pm \text{SQRT}(0))/(2^{*}A)$, or $-B/(2^{*}A)$. It is for this reason that when *DISC* equals zero, the control of the program passes to statement 10, where $X = -B/(2^{*}A)$ is simply calculated and printed out. The GOTO statement that follows passes control to statement 100, STOP, which directs the computer to halt the execution of the program. The following statement, END, directs the compiler to cease translating the program.

Returning to the two remaining cases of the IF statement, if the value of *DISC* is less than zero, then the roots of the quadratic equation are complex numbers of the form $R + SI$, where *R* and *S* are real numbers and *I* equals $\sqrt{-1}$. In this case the IF statement transfers control of the program to statement 30,

```
Algol          IF X < 0 THEN X := -X
APL            X ← X ⌈ -X
Basic    10    IF X = > 0 THEN 30
         20    LET X = -X
         30    . . .
Cobol          IF X IS LESS THAN 0 THEN MULTIPLY X BY -1 GIVING X
Fortran I      IF (X) 10, 11, 11
         10    X = -X
         11    CONTINUE
Fortran IV     IF X .LT. 0 THEN X = -X
Lisp           (SETQ X (MAX X (MINUS X)))
Pascal         IF X < 0 THEN X := -X
PL/I           X := MAX (X, -X)
```

PROGRAM SEQUENCES for replacing a number *X* with its absolute, or unsigned, value demonstrate some of the syntactic differences among programming languages. In Fortran I (the earliest version of Fortran) the conditional statement IF (*X*) 10, 11, 11 compares the value of *X* with zero. If *X* is less than zero, control is transferred to the program statement whose number is given first (10). If *X* is equal to zero, control is transferred to the program statement whose number is given second (11). If *X* is greater than zero, control is transferred to the statement whose number is given third (11). Thus if the value of *X* is negative, *X* is replaced by its absolute value $-X$; otherwise the value is left unchanged. The ability to test an expression and act differently in the event of different outcomes is one of the most important control mechanisms for structuring computer programs, and languages more modern than Fortran I include more elaborate conditionals. For example, the Basic construction shown here, although similar to the Fortran one, is easier to read, and in Algol, Cobol, Fortran IV (a recent version of Fortran) and Pascal the same concept can be expressed far more concisely in an IF THEN statement. (Both < and .LT. stand for "less than.") In addition the conditionals of the more modern languages allow not only for comparing numbers with zero but also for testing many other logical conditions. The absolute-value function has been encoded slightly differently in APL, Lisp and PL/I, making use of those languages' subprograms, or built-in functions, for comparing two numbers and choosing the larger of the two. That is to say, a single key word such as MAX in Lisp invokes a sequence of operations (stored in a library of subprograms) that serves to determine the maximum among the values supplied to it. In languages with this maximum function in order to replace *X* with its absolute value it suffices to set *X* equal to the maximum of *X* and $-X$. (Actually all the languages shown here also include in their library subprograms for computing the absolute-value function.) The program fragments shown also demonstrate some of the differences in notation among the various programming languages. For example, the sign := that appears in several of the languages, the arrow in APL, and SETQ in Lisp all serve the same purpose as the equals sign in Fortran, namely assigning a value to a variable.

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which begins a sequence of instructions for computing and printing out roots of this form. And finally, if the value of *DISC* is greater than zero, then control is passed to statement 20, which begins a sequence of statements for computing and printing out the two real roots of the quadratic equation. This sequence ends with a GOTO statement that passes control to the STOP statement. (The label *C* on the statement that precedes the complex-roots sequence is the Fortran symbol indicating that the statement is a comment and not an instruction to be executed by the computer. More modern languages rely on different kinds of conventions for inserting clarifying comments into programs.)

This program for computing quadratic roots is far more elaborate than the preceding one, but it too introduces simplifications. For example, if the value of *A* in a quadratic equation is zero, the program will call for division by zero. Because such a computation is mathematically undefined it cannot be provided for in the circuitry of the computer. Dividing by zero, then, would elicit a signal of machine error. Therefore another conditional statement to test the value of *A* should really be included early in the program. Moreover, additional statements would be required to specify in detail the way the results of the program are to be printed or displayed, particularly if the output is to be more elaborate than a list of values of *X*.

To be really useful over any substantial period of time the printout of a computer program must be relatively self-explanatory. Hence one might well require the output of the quadratic-roots program to be arranged in a table, with appropriate headings, giving the input values of *A*, *B* and *C* as well as output values of *X*. (It is for this reason Fortran, a language that cannot handle strings of alphabetic characters as data, includes elaborate facilities for printing out and formatting results.)

The development of this simple Fortran program for computing quadratic roots should convey some idea of the difficulties involved in specifying an algorithm for execution by a computer and some of the mechanisms a programming language can provide for simplifying the task: control structures, special functions and so on. The most important technique for limiting the complexity of computer programs is the use of subprograms: self-contained pieces of programming that are named, stored in a library and called on to perform their particular computation as part of the execution of other programs. The invocation of the function SQRT in the quadratic-roots program is an example of a subprogram call.

An elegant device found in all programming languages is that any program written in a particular language can be converted into a named subprogram and stored in a library associated with that language. For example, the quadratic-roots program itself could serve as a general subprogram, say QROOTS, for printing the roots of a quadratic equation. The subprogram would probably be more useful, however, if it was modified so that instead of printing out quadratic roots it simply computed their values and returned them to the main program to be employed in subsequent computations. (The details of how to specify subprograms are complicated and vary from language to language; an example of the way a subprogram is defined in one language will be given below.)

Although the capability of any programming language can be greatly extended with a subprogram library, it is the built-in facilities of a language that essentially determine its character. Some languages are large and elaborate, providing as many fixed mechanisms as possible. Others are small and concise, providing a limited set of basic mechanisms from which the programmer can construct the specific configurations needed for a particular programming task. And there is a great range of languages in between. Generally speaking, however, there are three elements that characterize a programming language: the types of data the language is equipped to deal with, the operations it can perform on those data and the control functions it provides for structuring programs. It will be instructive to consider each of these elements more closely. Because the types of data a programming language can handle determines to a large extent the kinds of programming tasks to which the language can be applied, I shall begin by describing some of the different ways data can be represented in a programming language.

Data Declarations

Virtually all programming languages include statements that describe the type of data that is to be associated with a particular variable. These nonexecutable statements are called declarations, and they perform a number of different functions. To begin with, remember that in the memory of a computer both data and instructions are represented as strings of bits, or binary digits. It is left to the instructions executed by the computer hardware to implicitly adopt one of the possible interpretations for raw binary data. For example, the assembly instruction FETCH 173 implies that the string of 0's and 1's at memory address 173 is data to be transferred and not an instruction to be executed. In the higher-level languages, where it is possible to declare more complex types of data than are physically provided for in the computer, the compiler selects the appropriate machine representation for each declared element.

It is not hard to imagine how disastrous it would be to start executing data as program instructions or vice versa. One of the benefits of working with programming languages is that once a variable has been declared to be of a particular type the compiler not only selects the appropriate representation for the data but also checks for inconsistencies during both the translation of the program and its execution. This arrangement provides a valuable measure of security against programming errors. (In addition in some cases the type of data assigned to a variable determines the precise form of operation that is to be followed with it. For example, many programming languages provide for the definition of complex numbers and include special arithmetical operations for manipulating them. Throughout the course of a computation each time a particular operation is invoked the compiler assigns its correct form by checking the data declarations of the variables to be operated on.)

All programming languages provide at least two distinct ways of representing numerical data. In Fortran the two data types are called integer, or fixed, numbers and real, or floating-point, numbers. In the memory of a computer the binary strings of stored information are organized in terms of the small groups of bits called words and bytes. For example, in modern computers a 32-bit word composed of four eight-bit bytes is typically allotted for each memory location. An integer data element devotes an entire binary word to the representation of a whole number: 152, 59, -6 and so on. A floating-point data element, however, stores in a single binary word a pair of numbers that correspond to the exponent and the mantissa, or fractional part, of a number expressed in exponential notation: 3.24×10^{6}, 21.784×10^{26}, 6.101×10^{-15} and so on. Thus an integer would be stored as a sign bit and a string of 31 bits, whereas a floating-point number would be stored as, say, a sign bit, a string of seven bits representing an exponent and a string of 24 bits representing a mantissa [*see illustration on page 100*]. In most computers the decimal point in the mantissa of a floating-point number is by convention placed at the far left, so that the number 3.24×10^{6} would be represented in floating-point form as $.324 \times 10^{7}$, or the pair of numbers 7, 324.

In a floating-point number, then, the exponent determines how far to the left or the right the decimal point would have to be "floated" if the number were printed out or displayed. The decimal point is not fixed but floating so that the maximum range of values can be squeezed into the finite storage space available in a binary word of fixed length. For example, floating-point representations with exponents in the hundreds can be employed to store in a sin-

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gle word of memory numbers whose integer representations would require thousands of bits.

Integer data elements, as long as they remain within the limited range of a fixed binary word, are represented with complete accuracy, and because they do not lose accuracy in simple calculations they are employed in such programming tasks as counting and indexing. Because the range of floating-point numbers is so much greater than that of integers, however, most numerical computations work with floating-point numbers, although their accuracy (which resides in the mantissa) is limited. Moreover, floating-point numbers tend to lose accuracy in the course of calculations. For example, the product of two floating-point numbers each with 24 significant bits of mantissa has 48 significant bits, but only half of them can be retained for storage. Furthermore, two numbers in exponential form can be added only if their exponents are equal. Hence when two floating-point numbers of different size are added, the exponent of the smaller number must be increased and its mantissa shifted accordingly, a process that generally results in the loss of some bits of accuracy.

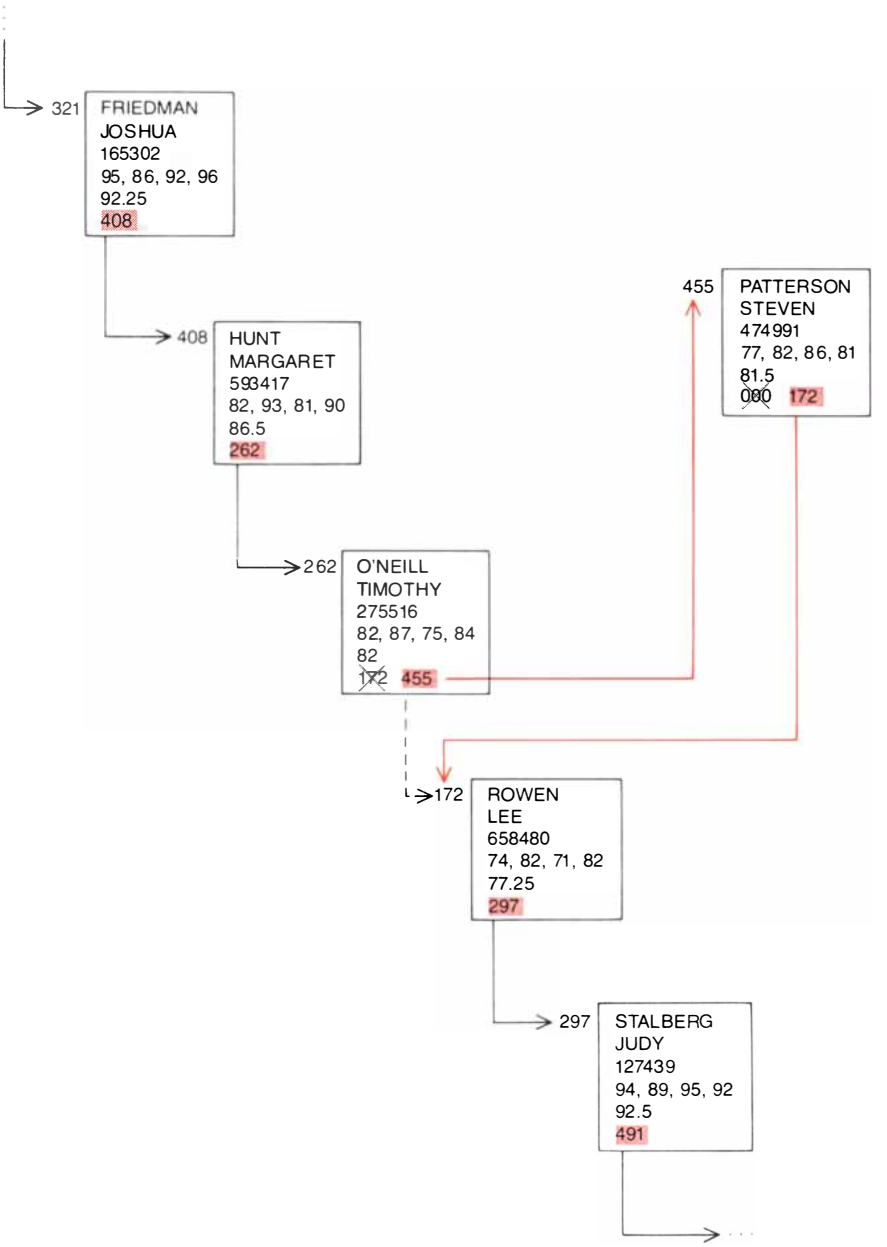
Most programmers assume that the floating-point arithmetic provided in programming languages is sufficiently accurate to meet their needs, and although that is often the case, serious errors in numerical calculations can arise from losses of accuracy. Many people who have worked with hand calculators have encountered such errors. Problems of accuracy are the subject of the branch of computer science called numerical analysis, which seeks to find the most accurate ways of representing and manipulating numerical data.

In the two programs for computing quadratic roots there are no statements that explicitly declare the data type of the variables *A, B, C, X* and so on. The reason is that in some programming languages, including Fortran, variables whose type has not been declared are assumed by the compiler to have particular data types. In Fortran any variable whose name begins with *I, J, K, L, M* or *N* is implicitly declared to be integer and all other variables are implicitly declared to be floating. Thus all the variables in the quadratic-roots program were declared to be of the floating type. Some languages require that all variables be declared; others (including later versions of Fortran) make declarations optional. The general-purpose language PL/I, which was designed to be compatible with Fortran, has the same convention for implicit declarations, but the variables in the quadratic-roots program could also have been declared explicitly by the PL/I statement DECLARE (*A, B, C, X*) FLOAT.

Most programming languages recognize at least two other simple types of data: logical data, which have an extremely small range of values, and character data, which have an extremely large range. Variables that are called logical or Boolean (after the British logician George Boole) take only the values true and false. Because so much of programming is concerned with choosing among alternatives these variables play an important role, often serving to store the results of a test or computation for later use. Finally, character, or alphabetic, data consist of strings made up of the letters of the alphabet and extra symbols such as brackets, blanks, punctuation marks and so on.

Data Types and Structures

There is a tendency to think of computer programs as doing mostly numerical calculations, but operations such as character manipulation, formatting and printing are often at least as important.



LINKED LISTS provide a flexible, convenient way of organizing structures containing mixed types of data such as the files of a large business organization or the collection of student records shown here. Each of these student records includes a surname and first name stored as character data, a student identification number stored as integer data, several examination scores and their average stored as floating-point data and another number (*color*) stored as a special type of data called pointer. A variable of the pointer type holds the address of a location in computer memory, so that it can serve to point, or refer, to an entire complex structure such as a student record. In this case each pointer holds the address of the record of the student whose surname is next in alphabetical order. One advantage of employing a series of pointers to create a linked list is that items can be easily inserted into it or deleted. As colored arrows indicate, to insert a new record into linked list of student records it suffices to change a pair of pointers.

In particular, numerical computation plays a rather small part in commercial data processing. The declaration and use of character data varies much more from language to language than the declaration and use of numerical or logical data, mainly because the length of character data is so variable. Although most programming languages provide only a few simple subprograms for manipulating such data, some programming languages that were designed specifically for complicated text-processing applications include special powerful operations for dealing with strings of arbitrary length. For example, in the language Snobol (from "string-oriented symbolic language"), which deals primarily with text manipulation, there are operations for matching patterns of characters and for inserting or substituting patterns at any point in a string. In addition many programming languages are equipped with special sublanguages for specifying the input and output formats for both numerical and character data.

One of the main advantages programming languages offer over machine and assembly languages is the capacity for dealing with types of data other than those that are explicitly provided for by the hardware of a computer system. For example, all programming languages offer ways of representing character data that are much richer than those provided by most machines. Moreover, almost all programming languages include facilities for building the basic numerical, logical and character data types into more complex structures. The most widely used languages all provide for the declaration of arrays: ordered collections of individual data elements of the same type.

Virtually all programming languages are equipped to deal with vectors, or one-dimensional arrays, and matrixes, or two-dimensional arrays, and in some languages arrays of even higher dimension can be declared. More precisely, in a Fortran program it might be convenient to group 20 test scores, say the scores of each student in a class of 20, into a vector called *SCORE*. The declaration DIMENSION *SCORE* (20) in Fortran serves to reserve 20 consecutive places in the memory of the computer, which are all identified by the variable name *SCORE* but are accessed individually by references to *SCORE* (1), *SCORE* (2) and so on. Or it might be convenient to arrange four test scores and their average for each of 20 students into a 5-by-20 matrix called *TESTS*. In Algol (from "algorithmic language"), a general-purpose language designed as a successor to Fortran that is widely used in Europe, a matrix to store that information could be declared by the statement REAL ARRAY *TESTS* [1 : 5, 1 : 20]. (Another representation for this type of information that is more readable, more flexible and more reliable will be discussed below.) Most versions of Fortran include facilities for constructing arrays of integer or floating values of up to three dimensions. PL/I provides for arrays of arbitrary dimensions and more complex structures of mixed data types, some of which will be discussed here.

Turning from the data declarations of a programming language to its executable statements, remember that these fall into two categories, invoking either basic operations, which manipulate data, or control functions, which alter the order in which the statements of a program are executed. The basic operations that are included in a programming language are for obvious reasons closely related to the types of data that can be declared in the language. Thus in Fortran, which includes few complex data structures, the basic operations are essentially the standard arithmetical and comparative operations on numbers and operations for reading numbers into memory and printing them out. The operations for dealing with arrays simply combine these basic operations with insertion and selection. For example, in *SCORE*, the vector of 20 test scores described above, the third memory location in the array would be identified in Fortran by the expression *SCORE* (3). To insert a value into that location, then, the instruction READ (*SCORE* (3)) would suffice. I shall turn to the basic operations in languages richer than Fortran after discussing some of the basic control functions provided by most programming languages.

Testing and Iteration

The control functions in Fortran, like the basic operations, are not elaborate, but they are representative of the control functions found in all programming languages. For example, the ability to test a relation and pursue different courses of action in the event of different outcomes is probably the most fundamental mechanism for structuring programs. In Fortran the conditional IF statement serves this purpose, and it appears in various forms in many languages. The IF statement given in the quadratic-roots program could only serve to compare the value of variable expressions with zero, but later versions of Fortran and other modern programming languages provide more elaborate conditionals for testing any numerical function. And in some modern languages any logical condition can be tested. For example, PL/I allows comparisons of complex structures and Snobol includes among its basic logical operations elaborate mechanisms for pattern matching. Many programming languages also include an extended conditional called a case statement serving to specify a separate action for each of a large number of alternative situations.

A notion that is almost as basic as testing in determining the structure of programs is that of iteration, or repetition. All programming languages include iterative control statements that, just as conditional statements provide ways of choosing among alternative sequences of instructions, provide ways of repeatedly executing sequences of instructions. The simplest example of an iterative control structure is provided by the Fortran DO statement. Consider its role in the following program for reading 20 test scores into a vector *SCORE* and computing their average:

```
      DIMENSION SCORE (20)
      DO 46 INDEX = 1, 20
   46 READ (SCORE (INDEX))
      TOTAL = 0.0
      DO 78 INDEX = 1, 20
   78 TOTAL = TOTAL
               + SCORE (INDEX)
      AVERAGE = TOTAL/20.0
```

The statement DO 46 *INDEX* = 1, 20 specifies that all the statements that follow through statement 46 are to be executed iteratively, with the variable *INDEX* successively taking on the values 1 through 20. (In this example there is only one statement, 46 itself.) In other words, the computer first executes READ (*SCORE* (1)), then READ (*SCORE* (2)) and so on. After the last of the 20 test scores has been entered into the vector and the variable *TOTAL* is set at 0.0 the program enters a similar DO loop for iteratively summing the test scores so that their average can be taken. (Both of the DO statements in this program could have been replaced by constructions relying on IF tests and GOTO statements, but the resulting program would have been much less clear and concise.)

Operating on Arrays

Iterative mechanisms similar to the Fortran DO statement are found in all programming languages, and languages more modern than Fortran provide for even richer iterative structures. Some languages also include basic operations invoked by a single statement that perform the same function as complicated iterative constructions in other languages. For example, the computational power of a language is greatly enhanced by capacities for operating on large data structures, and PL/I is an example of a language with a substantial number of special functions for operating on arrays of data such as the vector *SCORE*. In PL/I the following concise program would suffice to encode the iterative algorithm for reading and averaging 20 test scores:

```
DECLARE SCORE (20)
GET LIST (SCORE (I) DO
```

```
I = 1 TO 20)
AVERAGE = SUM (SCORE)/20
```

The PL/I instruction GET LIST is the equivalent of the Fortran instruction READ. Although the DO loop for reading values into the vector is expressed more concisely here, it is essentially the same as the one that appears in the Fortran program. SUM, however, is the name of a subprogram in the PL/I library that computes the total of the elements of an array given to it as input, eliminating the need for an iterative construction.

An even more highly developed language in terms of the manipulation of arrays, indeed the most sophisticated of any of the programming languages in this respect, is APL (from "a programming language"). APL is a powerful language that has come to be applied to a variety of programming tasks ranging from engineering calculations to the seminumerical computations needed for business planning. A great many specific operations on arrays, including some that replace iteration, are built into the language, and considerable effort has been devoted to specifying how these primitive operations can be combined into even more complex expressions. As a result some classes of computations can be expressed more compactly in APL than they can in any other language. Consider the following APL version of a program for reading and computing the average of test scores:

```
SCORE ← □
AVERAGE ← (+/SCORE) ÷ ρ SCORE
```

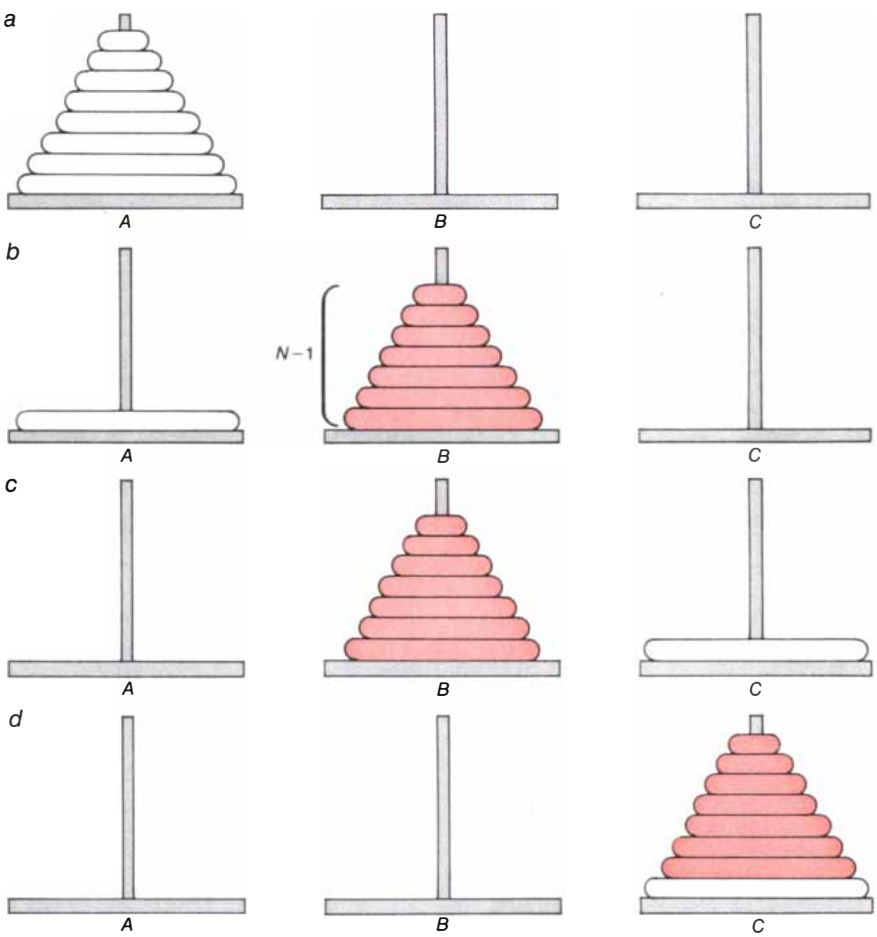
In APL the symbol ← replaces the equals sign that is employed in most programming languages to assign values to variables. The symbol □ denotes the operation for reading values from an input device and storing them in memory. (Terminals and printers with special typographical symbols are available for use in APL programming.) The operation +/, which performs the same function as the PL/I subprogram SUM, is only one of the many compound operations provided in this language. Another special operation is ρ, which computes the length of the vector *SCORE*. Hence the second statement of the program serves to total the elements of *SCORE* and divide by their number, so that the average of the elements is assigned to the variable *AVERAGE*.

In this program, then, each of the iterative sequences in the Fortran program for averaging test scores has been replaced by a single APL statement. Notice that this APL program is not only more concise but also more flexible: because it was never necessary to specify a fixed length for *SCORE* the same program could be applied to take the average of any collection of input values. One drawback of the emphasis on arrays in APL is that programmers working with the language tend to formulate solutions to computational problems in terms of collections of operations on arrays even when such formulations are not at all natural. As the linguist Benjamin Lee Whorf pointed out, the natural-language constructs available to a person have a marked effect on the way that person thinks. In programming there is no doubt that the programmer's choice of language has an important impact on the way a program is written.

Mixed-Data Structures

All the data structures I have discussed so far have involved data elements of a single type, but in many computing situations it is necessary to manipulate several different kinds of data simultaneously. For example, in the filing system of a university the records of a single student in a particular class might include the student's name stored as a character string, his university identification number stored as an integer data element and several test scores stored as floating-point numbers. The computer files of a large business organization might involve hundreds of different kinds of information, each having a distinct type and format. As a result the programming languages designed for such applications place less emphasis on complex numerical calculations and more emphasis on techniques for storing, arranging and retrieving large quantities of data.

The most widely used language for commercial data-processing purposes is Cobol (from "common business-orient-



TOWERS OF HANOI PUZZLE (*a*) requires that the stack of rings on peg *A* be transferred to peg *C* by moving only one ring at a time and never placing a ring on top of a ring of smaller diameter. A program to compute the number of moves *HANOI*(*N*) required to solve this puzzle for *N* rings can be calculated by means of recursion, one of several control mechanisms based on repetition that play an important part in structuring programs. A recursive procedure is one that calls on itself, and in this case the key to calculating *HANOI*(*N*) is the fact that if the puzzle can be solved for $N-1$ rings, it can be solved for *N* rings. Hence *HANOI*(*N*) can be expressed in terms of *HANOI*($N-1$). More precisely, given a solution to the puzzle for $N-1$ rings, that solution can be applied (*b*) to move the top $N-1$ rings (*color*) from peg *A* to peg *B*, a process requiring *HANOI*($N-1$) moves. Then the largest ring can be transferred from peg *A* to peg *C* in one move (*c*), and the solution for $N-1$ rings can be applied again to transfer the $N-1$ rings from peg *B* to peg *C* in another *HANOI*($N-1$) moves (*d*). Thus *HANOI*(*N*) equals 2HANOI*($N-1$) + 1. To implement this recursive formula on a computer it is only necessary to make a provision for the special case $N=1$, where *HANOI*(1) equals 1. For example, in PL/I statement *HANOI*(*N*) = IF $N=1$ THEN 1 ELSE 2**HANOI*($N-1$) + 1 would be sufficient to compute the number of moves required to solve the Towers of Hanoi puzzle for *N* rings.**

ed language"). Cobol can handle large amounts of data and perform the kinds of rather elementary mathematics needed for record-keeping tasks such as computing payrolls. It also includes extensive input facilities for structuring information and output facilities for generating reports. In addition, since Cobol was intended specifically for everyday kinds of data processing, it was designed to be closer to English than most other programming languages are, and as a result it looks quite different from other languages.

Today many large organizations do not rely exclusively on data-processing languages such as Cobol or PL/I (which was designed as the successor to both Fortran and Cobol) to fill their programming needs. Instead they employ those languages in conjunction with large collections of self-contained data-processing programs called data-base management systems. The data-manipulation operations these programs perform are all based on fixed ways of structuring, or representing, large quantities of data within a computer system. Access to the data-base subprograms can be gained by subprogram calls from Cobol or PL/I, so that given data structured according to the conventions of a particular data-base system, additional software can be created in those languages that exactly fits an organization's needs. Giving even an overview of data-base management is beyond the scope of this article, but it is possible to reach some understanding of the issues involved by considering how data of mixed types can be handled in PL/I. All but the earliest programming languages offer comparable data-manipulation mechanisms.

One of the most important devices in non-numerical programming is called a pointer: a variable whose value is the numerical address of another memory location. A pointer is generally made to point, or refer, to an entire complex data structure such as a student record and provides a powerful tool for organizing collections of such structures. For example, in an alphabetical file of student records for a university course the record for each student in the course might include a pointer variable holding the address of the next record in the file. A collection of records connected in this manner is called a linked list.

Linked Lists

A linked list is a far more flexible way of organizing complex data structures than, say, an array. When a collection of student records is arranged in an array, the length of the array must be specified at the outset. Therefore if too many students enter the course, the entire class file has to be completely reorganized. Moreover, even if space is available in an array, when a new record is inserted, it is necessary to move all the records that come after it in alphabetical order into new locations in the array. With a linked list it is not necessary to specify a length in advance, and inserting an additional record is a simple matter of changing a pair of pointers [*see illustration on page 109*].

An example will serve to make some of these ideas clearer. The student records in a course file could be declared in PL/I as follows:

```
DECLARE
  1 STUDENTRECORD
    BASED (STUDENT)
    2 NAME
      3 SURNAME CHARACTER (20)
      3 FIRST CHARACTER (10)
    2 STUDENTNUMBER FIXED
    2 EXAMS (4)
    2 AVERAGE
    2 NEXT POINTER
```

This declaration specifies that each student record will be structured in three levels, the top level being the entire mixed record *STUDENTRECORD* itself. Five different data elements make up the second level, including the student's name represented as two distinct third-level elements (a surname of up to 20 characters and a first name of up to 10 characters), the student's identification number represented as an integer, a vector of four examination grades called EXAMS and the pointer NEXT. By the PL/I convention of implied declaration the four grades and their average (another element on the second level) are floating-point numbers.

The PL/I word BASED, which appears in the second line of the declaration, specifies that the piece of programming *STUDENTRECORD* is to serve as a template, or model, for the organization of each new student record that is generated to be added to the course file. The variable *STUDENT*, which appears in parentheses after BASED, is declared implicitly to be a pointer that serves to hold the memory address of the beginning of each new record in the file as it is created. (*STUDENT* is a standard variable of the pointer type, which, as is shown below, can also be exploited to gain access to the information held in the student records.)

Languages that deal with complex data structures such as student records must include facilities for manipulating not only the structures but also the individual elements in them. A pointer gives access to any level of a structure, as is shown by the following PL/I program sequence for locating the surname "JONES" in the linked list of student records. (In PL/I quotation marks are used to distinguish character strings from variable names.)

```
LOOP: IF STUDENT→SURNAME
        = "JONES"
      THEN STUDENT
        = STUDENT→NEXT
      GO TO LOOP
      END
```

In this program *LOOP* is a statement label, part of the iterative loop created by the IF THEN construction that extends through the statement END. More precisely, a PL/I IF THEN statement specifies that whenever the condition given in it is met, all statements up to the corresponding END statement are to be executed. Here the condition to be met is *STUDENT→SURNAME* ≠ "JONES." *STUDENT→SURNAME* identifies the element *SURNAME* in the data record pointed to by *STUDENT*. If the record pointed to by *STUDENT* does not contain the desired value in *SURNAME*, then the value of the variable *STUDENT* is replaced by the value of *STUDENT→NEXT*, that is, the value of *NEXT* in the record pointed to by *STUDENT*. When the condition in the IF statement is not met, control is passed to the statement following END. Thus the process is iterated until "JONES" is finally located.

The idea of placing within a record structure a pointer to another record structure is a powerful one and is used in a wide variety of applications. Data structures more complex than linked lists can also be created by means of pointers. For example, one might declare a record with two pointers, say *LEFT* and *RIGHT*, and arrange data in a binary tree (a treelike graph with no more than two branches at each intersection). The construction and manipulation of such complex structures is called list processing, a type of programming to which some languages such as Lisp (from "list processor") are primarily devoted.

Indefinite Iteration

In many programming situations it is desirable to have a sequence of instructions repeated not for a fixed number of times but rather until a specified condition is reached no matter how many repetitions are required. Almost everyone is familiar with this kind of situation from cookbooks, which include directions to stir until smooth, heat to a boil and so on. A typical example in programming is the search through a linked list for the record of a student named Jones, described above. In fact, such indefinite iteration is as important as indexed iteration in structuring programs, and many languages provide a number of specific control devices for expressing indefinite iterations more easily. Consider the application of the PL/I DO WHILE control statement to implement a simple iterative algorithm for computing square roots. The algorithm, which was devised by Isaac Newton, begins by

BECAUSE nature provides only the promise of great wine in these delicate Sauvignon Blanc grapes, the winemaker must guide and guard the young wine for it to fulfill that promise. Every step we take, we take with care because THE WINE REMEMBERS

THE WINERY OF
ERNEST & JULIO
GALLO

Ernest & Julio Gallo, Modesto, CA

making a guess that the square root of the number given is half of that number and continues making successively better guesses until an acceptable value is obtained. The following PL/I implementation of this indefinite-iteration algorithm returns a value for the square root of the given number whose square is within 1/10,000 of that number. (The implementation is presented here as a subprogram to demonstrate how a subprogram is specified in PL/I.)

```
SQRT PROCEDURE (GIVEN)
    RETURNS (FLOAT)
    DECLARE GUESS FLOAT
    GUESS = GIVEN/2
  DO WHILE
  ABS (GUESS**2 - GIVEN) > .0001
  GUESS = GUESS -
  (GUESS**2 - GIVEN)/(2*GUESS)
  END
    RETURN (GUESS)
END SQRT
```

The PL/I word PROCEDURE in the first line of the program specifies that the variable *SQRT* is the name of a subprogram that must be supplied a value for the variable *GIVEN* from the main program. The second line declares that the value to be returned to the main program will be a floating-point number. Then once the first guess for the value of the square root of *GIVEN* has been established the program enters the DO WHILE loop, which extends to the first END statement in the program. The loop performs the function of making successive guesses and comparing the difference between *GIVEN* and the square of each *GUESS* with 1/10,000, or .0001. (ABS is a special function in the PL/I library that takes the absolute, or unsigned, value of the expression in parentheses; > is the PL/I symbol meaning "greater than.") When an acceptable value for the square root of *GIVEN* is obtained, control passes out of the iterative loop, a value is returned to the main program and the subprogram ends. The notion of indefinite iteration is a powerful one and adds significantly to the capability of all programming languages. As the example of searching through a linked list suggests, indefinite-iteration structures are frequently applied not only to numerical programming tasks but also to non-numerical ones.

Recursion

PL/I and many other programming languages also incorporate a special form of indefinite repetition called recursion. A recursive procedure is one that calls on itself, and one of the best-known examples of recursion is a definition of the factorial function $N!$. This function can be defined nonrecursively as $N! = 1 \times 2 \times \ldots N$ (the product of all the positive integers up to and including N), which can be implemented by the following PL/I program:

```
PRODUCT = 1
DO INDEX = 1 TO N
PRODUCT = PRODUCT*INDEX
END
```

The same concept is expressed recursively, however, by the definition $N! = N*(N-1)!$. By making successive substitutions in this formula it can be verified that $N!$ equals $N*(N-1)*(N-2)!$, which equals $N*(N-1)*(N-2)*(N-3)!$ and so on. The algorithm is not ready to be submitted to a computer, however, because it assumes the knowledge that the procedure must terminate before N equals 1. (Otherwise the final value of the factorial function would always turn out to be zero.) In other words, $N = 1$ must be treated as a special case. In PL/I that can be accomplished most conveniently by means of the IF THEN ELSE construction, an extension of the IF THEN control structure discussed above. (This conditional statement is similar to the basic Fortran IF statement except that all the alternative actions specified by it appear not in subsequent and perhaps physically remote statements but rather in the IF THEN ELSE statement itself. Such a construction makes a program much easier to read and appears in all modern languages.)

It is now possible to construct a recursive program to compute the factorial function of N as follows:

$$N! = \text{IF } N = 1 \text{ THEN } 1 \text{ ELSE } N*(N-1)!$$

The recursive version (which computes $N!$ by going down from N to 1 instead of up from 1 to N) is shorter than the simple iterative version and perhaps slightly easier to read, but it is not significantly more convenient. The power of the notion of recursion in programming can be better conveyed by a slightly more complicated computation.

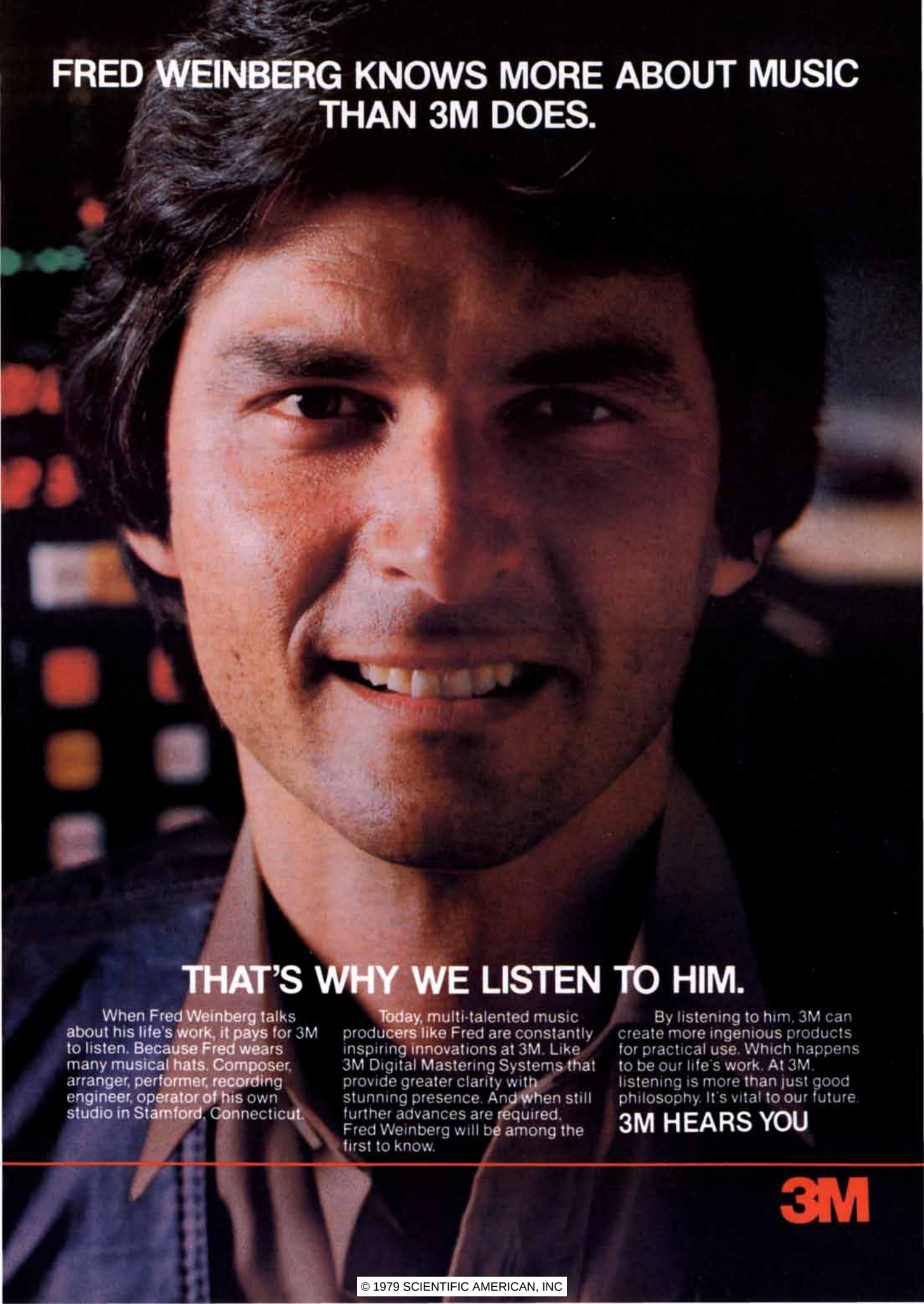
Consider the classic Towers of Hanoi puzzle [*see illustration on page 111*]. In this puzzle N rings with different outer diameters are stacked in decreasing order of size (from bottom to top) on one of three pegs, say *A*, *B* and *C*. The object of the puzzle is to transfer the stack of rings from peg *A* to peg *C*, moving only one ring at a time and never placing a ring on top of a ring of smaller diameter. How many moves will suffice to solve the puzzle for an arbitrary number of rings N? Writing a computer program to answer the question should demonstrate the fundamental advantage of recursive programming, namely that it is often possible to solve a complex problem by breaking it down into smaller problems that are similar to it.

Even if the most efficient strategy is followed, when the number of rings N is moderately large, quite a large number of moves are required to complete the task presented in the Towers of Hanoi puzzle. The key to solving the problem of computing the number of moves is the fact that if the puzzle can be solved for $N-1$ rings, then it can be solved for N rings. More precisely, given a stack of N rings the technique for transferring $N-1$ rings could be applied to move the top $N-1$ rings from peg *A* to peg *B*; then the bottom, or largest, ring could be moved to peg *C*, and the technique for transferring $N-1$ rings could be applied again to move the $N-1$ rings from peg *B* to peg *C*. If the number of moves required to solve the puzzle for $N-1$ rings is called $HANOI(N-1)$, then the number of moves $HANOI(N)$ required to implement the solution for N rings is equal to $HANOI(N-1)$ plus 1 (for moving the bottom ring) plus $HANOI(N-1)$. Hence $HANOI(N)$ equals $2*HANOI(N-1)+1$. Once again the formula cannot be submitted to the computer because $N = 1$ must be treated as a special case. That is taken into account in the following recursive program to compute the number of moves needed to solve the Towers of Hanoi puzzle:

$$HANOI(N) = \text{IF } N = 1 \text{ THEN } 1 \text{ ELSE } 2*HANOI(N-1)+1$$

It is important to note that in this instance recursion provided not only a simple form in which to state the solution to the problem but also the major intellectual tool for deriving the solution. In fact, there is a wide range of problems (particularly in the fields of artificial intelligence and symbolic computation) that are best solved by recursive methods. For example, the rules for taking derivatives in mathematics are best expressed recursively, and so programs for symbolic differentiation generally depend on recursive techniques. Another kind of program that is often written recursively is a compiler, because the syntax for arithmetical expressions can be specified by a small set of recursive rules (analogous to those used to define the grammar of natural language) that can be applied to analyze and translate programs.

The programming language that relies most heavily on recursion is Lisp. Lisp can be defined by a simple and elegant set of recursive rules, a characteristic that in some cases gives it an important advantage over languages having more powerful operations. More precisely, Lisp can be totally defined by a small number of operations on binary trees of symbols together with conditional expressions and the concept of recursion. Furthermore, because Lisp programs are themselves represented as lists of the Lisp type it is not difficult to design Lisp programs to read and write other Lisp programs. This capability has



been valuable in certain specialized applications of computing and will surely become more important with the increased effort to develop more automatic programming systems.

Programming Standards

The development over the past quarter century of high-level programming languages has certainly been an important determining factor in the proliferation of computer technology throughout modern society. In some ways, however, the languages are still quite primitive, and in laboratories all over the world much work is being done to create a new generation of programming languages of greater power and reliability. One of the important features of this evolutionary trend is the effort to generate programming standards.

When high-level programming languages were first developed, it was generally held that they would make programs machine-independent. In other words, no matter what machine a program had been written to run on it would be possible to run it on any other machine with the appropriate compiler. With the partial exception of Cobol programming that has not turned out to be the case. Most programs cannot be moved easily from one machine to another that theoretically supports the same language, a situation due mainly to slight variations in the implementation of programming languages. The variations that can keep a program from running altogether or from running efficiently on different computers range from trivial issues of notation (for example concerning the use of parentheses around variable expressions in program statements) to deep mathematical problems (for example concerning the rules for rounding off numbers in arithmetic). To solve these problems it will be necessary to develop standard programming languages that are so effective that all temptation to alter them is removed.

At the present time there are many powerful computers emulating computers 20 years older either because it does not pay to rewrite programs to run efficiently on them or because no one understands the programs well enough to rewrite them. The Federal Government, which spends an enormous amount on computers and programs each year, has been the main force in encouraging the development of programming-language standards. There is much activity in this area. Over the past several years the Department of Defense has enlisted a considerable fraction of the world's experts on programming languages in an effort to develop a standard language for programming real-time control tasks. (In real-time programming the results of computations are employed to influence ongoing physical processes such as the operation of an airplane.) This language, called Ada (after Lady Ada Lovelace, Lord Byron's daughter, who worked with Charles Babbage on his analytical engine), has been through a dozen iterations and now appears ready to be launched.

Another problem with current programming languages is that they offer relatively little in the way of capacities for certifying the behavior of programs. Critical tasks such as the control of transportation and energy facilities and the evaluation of threats to national security are currently being entrusted to long and complex computer programs, and one would like to have some assurance that the programs operate correctly. One method that has been proposed for enhancing the verifiability of programs is to greatly extend the facilities for checking provided by data declarations. For example, in the PL/I declaration of the student record given above, the variable *NEXT* was declared to be simply a pointer, although it was intended to point only to structures with the exact *STUDENTRECORD* form. In a more strongly typed language such as Pascal (named for Blaise Pascal) it would be necessary to specify exactly what type of structure *NEXT* should be pointing to, and the compiler would check to see that no errors were being made. (Pascal is a new and relatively simple language that emphasizes the clear expression of concepts.)

Extensive declarations can lead to programs of increased complexity, with nearly identical subprograms operating on different combinations of data types. In the department of computer science at the University of Rochester my colleagues and I are experimenting with mechanisms for specifying "properties" of data elements that may serve to avoid the increase in complexity that accompanies strong typing. Only certain kinds of programming error can be detected by checking mechanisms of this type, however, and such mechanisms certainly cannot serve to verify that a program totally meets its specifications. More comprehensive verification methods are now being studied in many laboratories, but it will be some time before any practical method is available.

Increasing modularity in programming is another means of creating more reliable programs. The use of the function SQRT in the program for computing quadratic roots demonstrated how the details of a calculation can be separated from the application of its results, and modular programs are basically an extension of this idea. The model for the languages that facilitate this effort is Simula (from "simulation language"), a language that was developed in Norway for the purpose of simulating systems such as traffic flow. In Simula each object of interest (say each road intersection) is represented as a separate module with its own subprograms and data. The student records described above could be made into modules by including procedures for printing, updating and similar tasks in their definition. Programs that required information from the records would then invoke those procedures.

Replacing data structures by modules serves the same purpose as replacing a roomfull of records with a clerk who can answer specific questions. This type of arrangement makes it possible to exploit data structures without knowing the details of their internal structure, and it allows for filing systems that ensure greater privacy. In addition smaller, self-contained sections of programming are much easier to certify than large, complex programs, and so the modular programs tend to be more reliable. Much of my own work is devoted to modular programming languages, particularly as they apply to distributed processing and computer networks.

Current Trends

In addition to the research I have already mentioned, work is now in progress on programming languages (called very-high-level languages) that enable the user to work directly with problem-related concepts (such as a class list or mathematical expressions) without concerning himself with the details of how the concepts are being represented in the computer. Another significant current trend in programming is the allocation of substantially more computing resources to aid the programmer in his task. An important aspect of this trend is the development of personal computers (often built to execute a particular programming language such as Pascal or Lisp) designed to give a single programmer the kind of computing power that was provided for an entire laboratory just a few years ago. These new machines also make it possible for a programmer to work on several parts of a problem simultaneously and still monitor the process of each computation. In addition data-base facilities for coordinating the efforts of large teams of programmers working on a single problem are now coming into wide use.

With the expanding role of distributed processing and computer networks there is currently much interest in programming languages that make it easier to work with several machines at once. And the continuing revolution in integrated-circuit technology is making it practical to include more of the capabilities of programming languages directly in computer hardware, an advance that is giving rise to radically different experimental designs for computers themselves. All these trends indicate that the second quarter century of the development of programming languages will be just as interesting and important as the first.

FOR SPECIAL FRIENDS, IT'S WORTH GOING OVERBOARD.

The Neanderthals

They flourished from western Europe to central Asia between 75,000 and 35,000 years ago. The differences between them and later peoples are not as great as was once thought but still call for an explanation

by Erik Trinkaus and William W. Howells

The Neanderthals were first recognized in 1856, when workmen uncovered fossil human bones in the Neander Valley near Düsseldorf in Germany. At the time and for some time thereafter the idea of early men, of men different from those now living, was so unfamiliar that the Neanderthals were regarded either as a freakish variant of modern men or as beings that were not quite human. They came to be classified not as members of our own species, *Homo sapiens,* but as a separate species, *Homo neanderthalensis.*

Today the Neanderthals cannot even be regarded as particularly early men. They arose long after other members of the genus *Homo* and longer still after the hominid genus *Australopithecus.* The Neanderthals belong to a rather late stage of the Pleistocene epoch. Indeed, their lateness is the main reason so much is known about them.

In recent years this knowledge has been simultaneously extended and refined. To look broadly at the new picture, the Neanderthals appear on the scene as competent hunters of large and small game, taking their prey in ways that might seem primitive to us but would nonetheless be familiar. They were able to deal with the rigors of a cold climate during the last phase of the Pleistocene. They flourished from western Europe to central Asia. They must have used animal skins for clothing and shelter, because there is clear evidence that earlier people had used them.

They took shelter in caves, where most of their bones have been found. The reason few Neanderthal bones are uncovered elsewhere, however, is that caves preserve bones as open-air sites rarely do. Neanderthals lived in the open as well, as is indicated by open-air sites with masses of the kind of stone tools that are associated elsewhere with Neanderthal bones. Moreover, hearths and rings of mammoth bones at certain sites point to their occupants' living in skin tents. Indeed, it is probable that Neanderthals lived more in the open than they did in caves.

Most of the Neanderthals' tools were flakes of flint, struck from a "core" and trimmed into the projectile points, knives and scrapers that make up the Mousterian (or Middle Paleolithic) tool complex. This complex is not a uniform assemblage of tools everywhere it is found but manifests itself in local variations on a theme of similar manufacture. François Bordes of the University of Bordeaux has distinguished five such "subcultures" in France alone, and other variant assemblages, all loosely classified as Mousterian, stretch off to the east through central Europe and into Asia. The Mousterian culture was a long-lived one appropriate to this late period in the cultural evolution of the Paleolithic.

It is important to note that whereas all Neanderthals made Mousterian tools, not all Mousterian toolmakers were Neanderthals. The Mousterian tool complex is a general level of achievement in the making of stone tools rather than an expression of a specifically Neanderthal intellect and skill.

From about 40,000 years ago in eastern Europe and about 35,000 in western Europe the Mousterian tool assemblages were succeeded by those of somewhat more varied cultures that belong to what is designated the Upper Paleolithic. When these later tools are found with human fossils, the bones are those not of Neanderthals but of anatomically modern human beings. The basic innovation in the tools is that the flakes struck from the core were long, narrow blades. This made it easy to vary the final form of the tools and thus to have a larger assortment of tools. The innovation was also more economical of flint, often a scarce raw material.

In some early manifestations of the Upper Paleolithic certain technical ideas first seen in the Mousterian persist. In others, such as the Aurignacian, the break from the Middle Paleolithic is more complete. The Upper Paleolithic also introduces art: cave paintings, engravings on bone, statuettes of bone and stone, and such personal decoration as strings of beads. The Middle Paleolithic is devoid of such expressions except possibly for a few rock carvings. The Neanderthals did, however, bury their dead and place grave offerings with them. Goat horns have been found in a boy's grave in central Asia and flowers (identified from their pollen) in a burial at Shanidar Cave in Iraq.

In spite of such distinctions it would be unwarranted to decide on the basis of the Neanderthals' tools that their way of life differed radically from that of hunting peoples living into our own times. If the Neanderthals' stone implements were limited to flakes technically inferior to those of the Upper Paleolithic, the same is true of tools made over a period of perhaps 30,000 years by members of one modern population: the Australian aborigines. Again, whereas the Eskimos have had tools of great refinement and variety, comparable in their development to those of the Upper Paleolithic, the first people to occupy the New World certainly did not. It therefore seems safest to speculate that the Neanderthals were formed into hunting bands similar to those of recent hunting peoples, probably linked loosely into tribal groupings, or at least groups with a common language. To judge by the wide distribution and homogeneity of Neanderthal remains, the Neanderthals formed a distinct and major human population that was not a particularly

FRONT AND SIDE VIEWS of the skull of an adult male Neanderthal appear in the photographs on the opposite page. The skull is Shanidar 1, which was discovered at the Iraq cave site of the same name in 1957 by Ralph S. Solecki of Columbia University and his colleagues. The left side of the individual's head had suffered an injury of the eye socket and the bone around it that had healed before his death. Specimen is in the Iraq Museum in Baghdad. Photographs were made through the courtesy of Muayed Sa'id al-Damirji, Director General of Antiquities.

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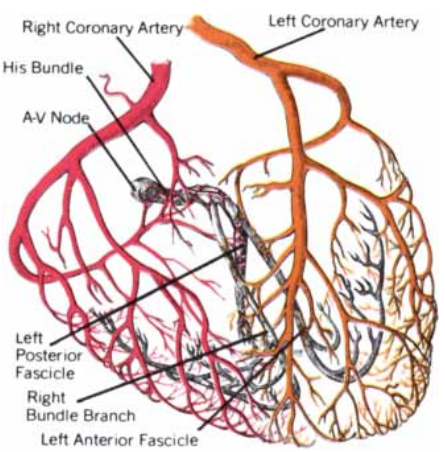

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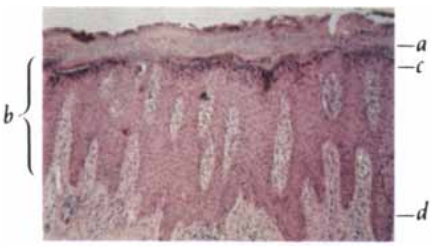
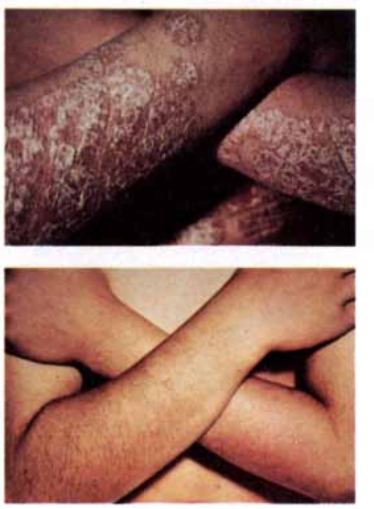


Histopathologic changes in psoriasis.



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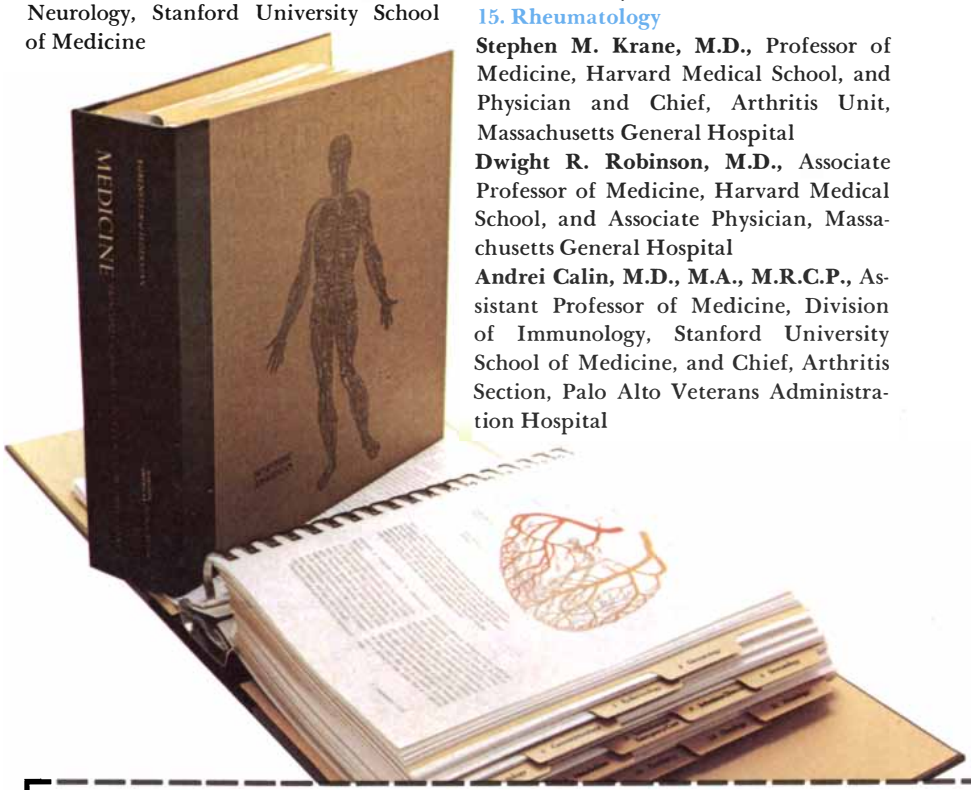


sparse one. Finally, whereas the organization of human populations in the Middle Paleolithic is necessarily a subject of speculation, the evidence of the fossil remains is concrete. Here the question becomes not what is meant by "Mousterian" but what is meant by "Neanderthal."

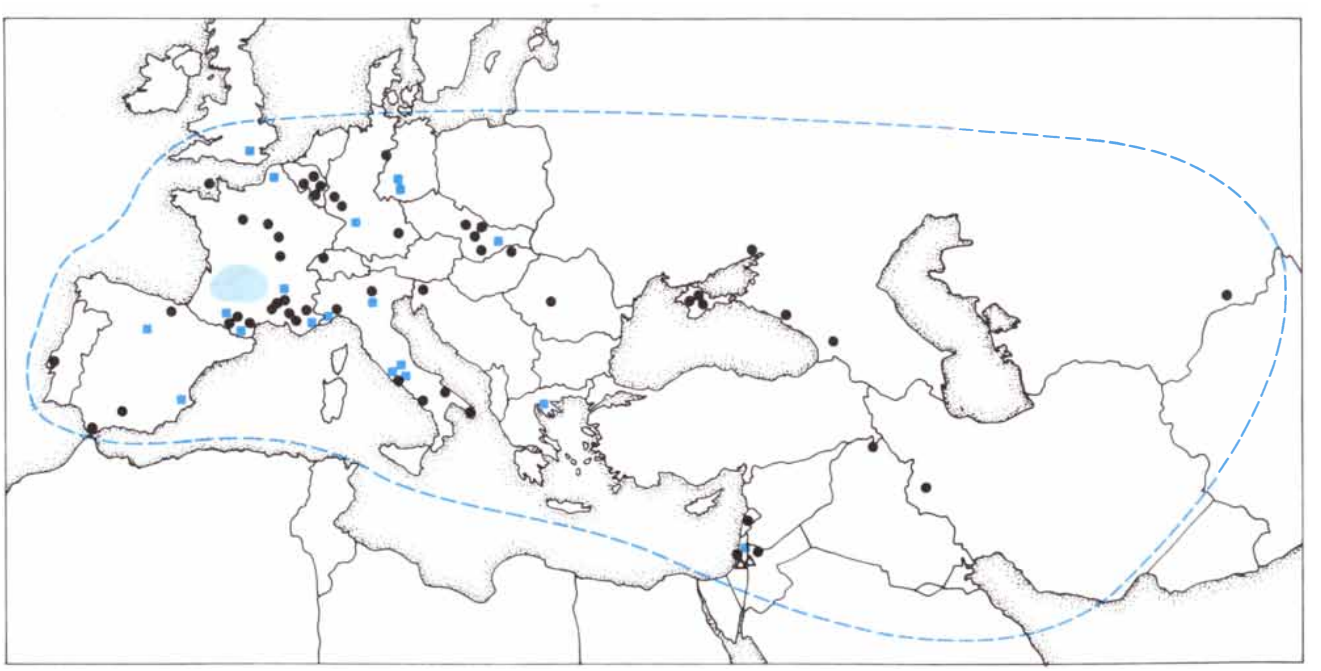
Although the Neanderthals were first recognized well over 100 years ago, the evolutionary significance of the original Neanderthal discovery and of other human remains uncovered at Paleolithic sites was not apparent until the turn of the 20th century. At that time a number of sites in Europe yielded new Neanderthal fossils, most of them partial skeletons. Among them were the remains of a man aged between 40 and 50 uncovered in a cave near the village of La Chapelle-aux-Saints in France. With this skeleton as a point of departure Marcellin Boule, the leading French anthropologist of his day, published in 1913 a monograph that reviewed all known Neanderthal remains. Boule's monograph included what soon became the standard description and interpretation of the Neanderthals.

At the time no older human fossils were known except those of "Java man," or "Pithecanthropus," which Boule did not regard as being human. He therefore inserted the Neanderthals taxonomically somewhere between chimpanzees and modern men. In this framework the differences between the Neanderthals and modern men tended to make the Neanderthals seem apelike. Boule was further misled, both by anatomical views then current and by his own evolutionary preconceptions, into seeing the Neanderthals as being somewhat stooped and having knees slightly bent and feet rolled in such a way that the outer edge of the foot, rather than the sole, formed the walking surface. Other experts either did not disagree or enthusiastically agreed, and Boule's view of the Neanderthals as an aberrant branch of humanity prevailed. He gave his stamp of approval to their classification as a species distinct from and not ancestral to *Homo sapiens.*

Some two decades later there was a reaction against this view as many other human fossils were discovered, notably in Java and China. Most of these fossil forms were earlier and more primitive than the Neanderthals. Some anthropologists now inserted the Neanderthals not between men and apes but between modern man and such probable ancestors as the Indonesian and Chinese fossils now classified as *Homo erectus.* The Neanderthals were thus viewed as a stage of human evolution, well up on the scale of time and development: a "Neanderthal phase." By extension some earlier fossils were considered to be representative of the same phase in other areas. For example, the Broken Hill skull from Zambia ("Rhodesian man") was classified as an African Neanderthal and the Solo skulls from Java were classified as Eastern Neanderthals. The classification was based on their common possession of large, bony brow ridges and a low-vaulted brain case. In addition two important human populations, relatively recent but still making Mousterian tools, were interpreted as being in transition between the Neanderthals and modern men. These populations were represented by skeletal samples from the caves at Mugharet es-Skhūl and Jebel Qafzeh in Israel.

In this picture the populations of the earliest anatomically modern men arose separately from such immediate predecessors in various parts of the Old World and in association with cultural advances such as those of the Upper Paleolithic of Europe. All these predecessors were taken to be "Neanderthals" of one kind or another, and in contrast to Boule's view most if not all of them were accepted as being the ancestors of various living peoples.

Today a more noncommital attitude is conveyed by the practice of classifying the Neanderthals as a subspecies within our own species. Thus they are commonly referred to as *Homo sapiens neanderthalensis,* and all living human beings are referred to as *Homo sapiens sapiens.* Such taxonomic distinctions, however, are merely an aid to grouping related individuals. They are not particularly useful as a guide in exploring the actual relations between the Neanderthals and modern men. To arrive at an



SPATIAL DISTRIBUTION of sites where Neanderthal fossils have been found is plotted on this map. The westernmost site is in Portugal and the easternmost is in Uzbekistan in Soviet Central Asia. The greatest concentration of Neanderthal remains is in the western Massif Central of France (*colored area*), where at least 10 early Neanderthal sites and 25 later Neanderthal ones are situated. Elsewhere on the map early sites appear as colored squares and later sites as black dots. The 19 early sites have yielded the partial remains of some 75 individuals and the 52 later sites the remains of at least 200 more, ranging from a few isolated teeth to complete skeletons. Two open triangles in the Levant locate Mugharet es-Skhūl and Jebel Qafzeh; some of the 30 fossils there were formerly classified as being Neanderthal.

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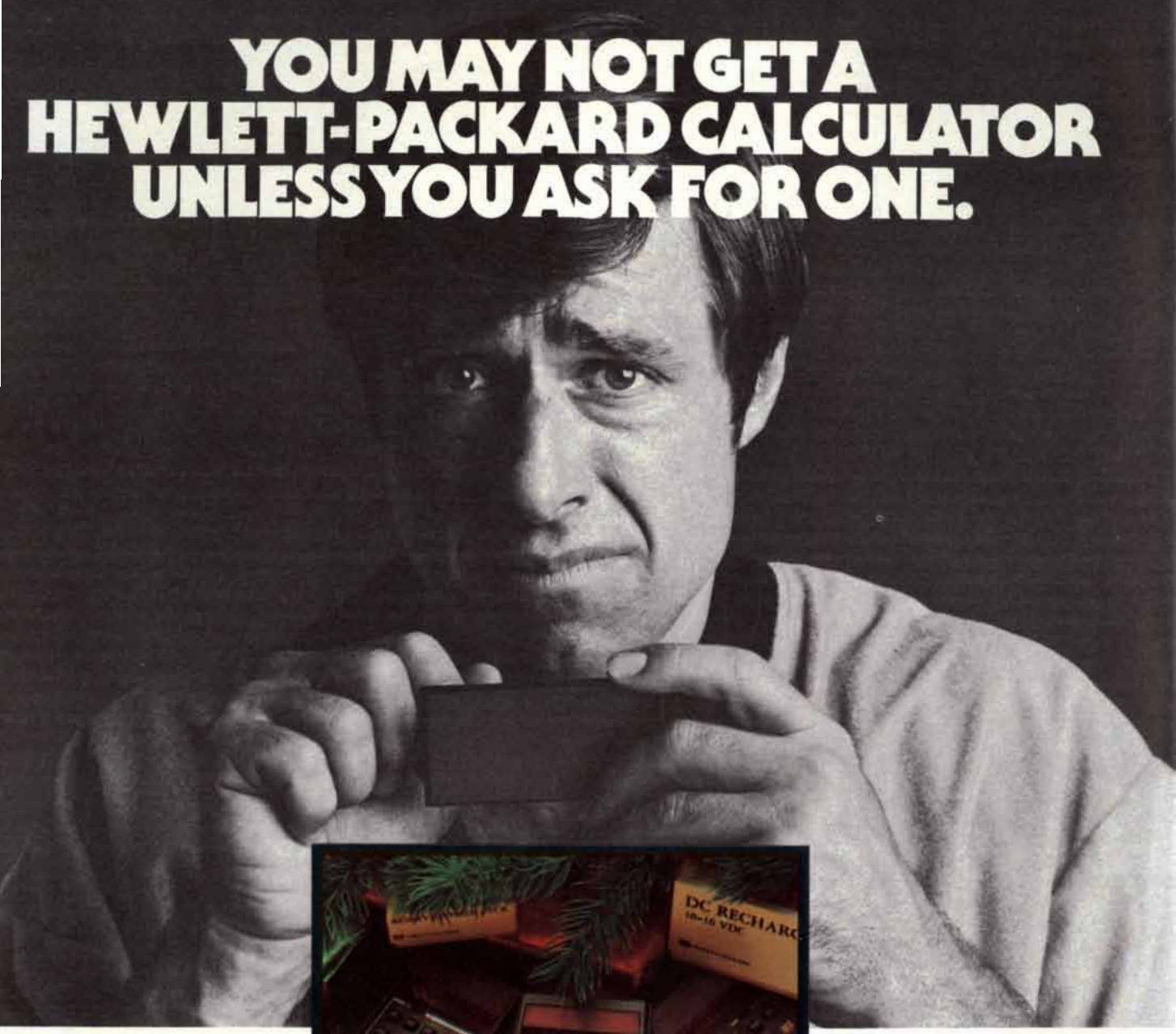

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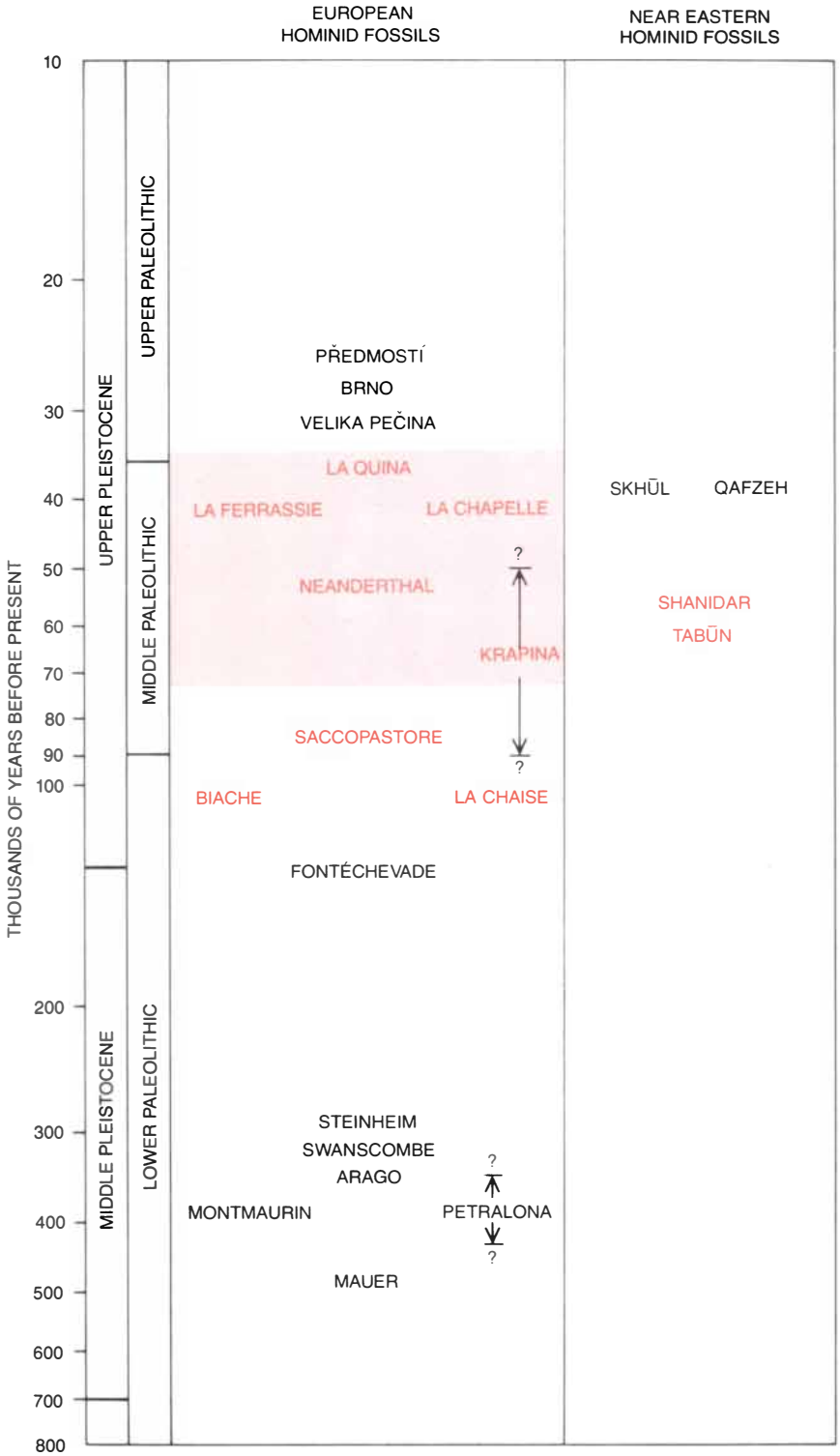
understanding of what the term Neanderthal means one should ignore past controversies and take account of everything that is known today. For example, one can systematically examine the large corpus of Neanderthal fossils in the light of present knowledge of the anatomical functions of bone and muscle. Furthermore, the fossils can be examined against a fuller chronological background based on carbon-14 dating and on recent archaeological work. When this is done, the picture that emerges is quite clear. It reveals a human population complex with a special pattern of anatomical features that extends without interruption from Gibraltar across Europe into the Near East and central Asia. That population complex occupies a span of time from about 100,000 years ago (or at least before the beginning of the last Pleistocene glaciation) down to 40,000 or 35,000 years ago (depending on the locality). Within that space and time only remains recognizable as belonging to this population complex have been found.

The Neanderthal anatomical pattern, or combination of skeletal features, can now be distinguished from that of modern human populations and from the patterns of the European Upper Paleolithic and the Near Eastern late Mousterian. The Neanderthals can also be consistently differentiated from the human beings who lived at the same time in Africa and eastern Asia. Although some of the pattern's individual features grade into those of neighboring populations, its important aspects appear to be distinctively Neanderthal. Moreover, the Neanderthal population is at least as homogeneous as the human populations of today. The people of this anatomical pattern have often been called "classic Neanderthals." In our own view they are the only Neanderthals. To apply the term to specimens of any other time and place is only to invite confusion.

The anatomical pattern must be carefully defined. To begin with, the Neanderthal skull and skeleton exhibit a specific overall pattern. Compared with its modern counterpart the long Neanderthal skull is relatively low but not exceptionally so. The low cranium and the prominent brow ridges give an appearance resembling that of *Homo erectus,* and they are probably derived from such ancestry. Here, then, is the basis for the belief in a "Neanderthal stage" between *Homo erectus* and modern man. The brain encased in the Neanderthal skull, however, was on the average slightly larger than the brain of modern men. This anatomical feature is undoubtedly related to the fact that the musculature of the Neanderthals was more substantial than that of modern men; it does not suggest any difference in intellectual or behavioral capacities.

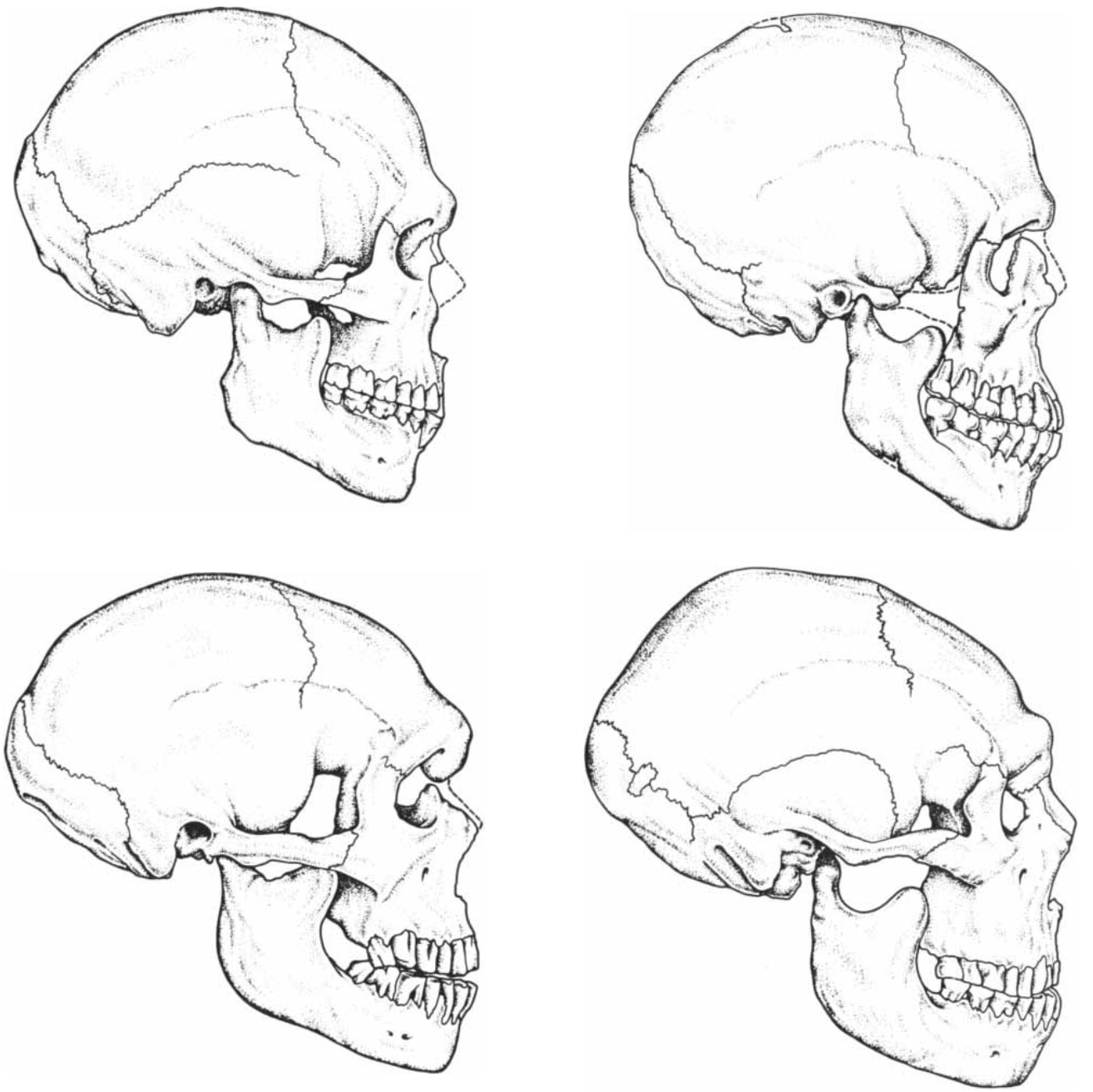
The Neanderthal face is unique. A



TEMPORAL DISTRIBUTION of the Neanderthals is shown on this chart, which extends from 10,000 years ago to 800,000. The time scale is logarithmic, which expands the space available for the Middle and Upper Paleolithic and the Upper Pleistocene. The last glacial phase of the Upper Pleistocene lasted from 80,000 years ago to 10,000 and was interrupted by a warm interval 35,000 years ago. Although many Neanderthal sites in Europe are not precisely dated, most are between 75,000 and 35,000 years old (*colored band*). The oldest of the fossils from Krapina are slightly older than other European Neanderthals, but most are contemporaneous. These Neanderthal site names appear in color, as do others more than 80,000 years old containing fossils that can be classified as early Neanderthals: Saccopastore, Biache and La Chaise. Still earlier European fossils, from Fontéchevade to Mauer, show varying degrees of affinity with both the Neanderthals and *Homo erectus*. The Upper Paleolithic sites of Velika Pečina, Brno, Předmostí, Skhūl and Qafzeh all contain human fossils of the modern type.

prominence down the midline brings the nose and the teeth farther forward (with respect to the vault of the skull) than they are in any other human fossil, either older or younger. The cheek arches slope backward instead of being angled, as they are in modern "high cheekbones." The forehead slopes instead of rising abruptly as it does over the tucked-in face of modern men. The Neanderthal midfacial prominence may be related to the teeth. The dentition is positioned so far forward with respect to the face that in a profile view there is a gap between the last molar (the wisdom tooth) and the edge of the ascending branch of the mandible, or lower jawbone. This is something seldom seen except in Neanderthals. A distinct bony chin, supposedly a hallmark of modern men, is variably developed among Neanderthals. Its prominence may have been largely obscured by the forward position of the lower teeth with respect to the mandible below them.

The spectacular forward position of the teeth in the Neanderthal skull remains unexplained. The cheek teeth were not significantly larger than those of modern men. The front teeth were somewhat bulkier than is common today, with the result that the arch at the front of the jaws is broader and opener. C. Loring Brace of the University of Michigan has suggested that the front teeth were regularly employed for something more than routine biting: for holding objects or perhaps for processing skins. Indeed, the crowns of the



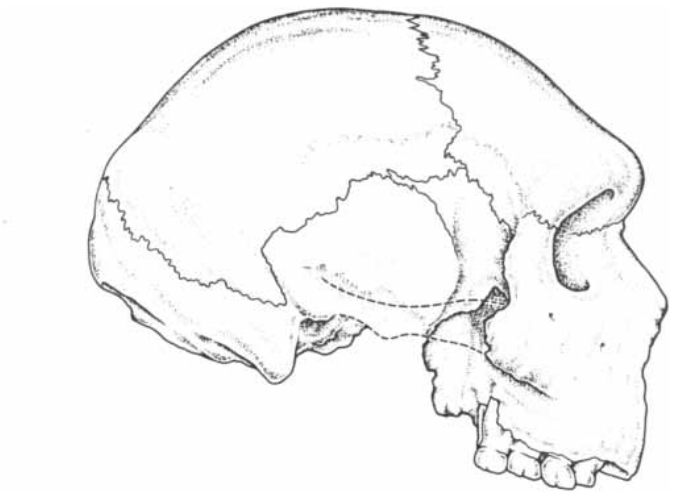
FOUR FOSSIL SKULLS are shown in profile, all slightly restored. The top two, anatomically modern, are Předmostí 3 from Czechoslovakia and Qafzeh 9 from Israel. The bottom two, both Neanderthals, are La Ferrassie 1 from France and Shanidar 1 from Iraq. (A profile photograph of the latter is on page 119.) Compared with the modern skulls the Neanderthal skulls are long, low and massive and their faces project, particularly around the nose and teeth. The anatomically modern skulls have a higher and rounder brain case, and their nose and teeth are more in line with their eye sockets. All should be compared with the Neanderthal precursor illustrated on opposite page.

front teeth of elderly Neanderthals are worn down in an unusual rounded way. Brace's hypothesis is that with the appearance of better tools in the Upper Paleolithic such uses of the front teeth became obsolete, and so the front teeth and jaws became smaller. It would seem, however, that the Mousterian tools were not so inferior as to account for the difference. Furthermore, some Mousterian toolmakers, the Skhūl people, already had front teeth that were like those of Upper Paleolithic populations in size and form.

The Neanderthal face as a whole is large, although it is not as large as the face in earlier members of the genus *Homo*. The front part of the upper jaw was generously proportioned; it accommodated the relatively long roots of the front teeth, particularly the canines. The nasal cavity and the rounded eye sockets are capacious. The sinus cavities are also large. For example, the frontal sinuses fill the brow ridges from above the nose out to the middle of the eye sockets with multichambered "cauliflower" cavities. They do not, however, reach up into the frontal bone above the brows, as is the case in earlier members of the genus *Homo*. In modern skulls the frontal sinuses are flattened, often extend above the brows and are quite irregular in size and shape.

In order to explain the Neanderthals' large, projecting face scholars have invoked a variety of causes, most often adaptation to cold. Carleton S. Coon and others have suggested that the Neanderthal midfacial prominence was such an adaptation. The nasal cavities were placed well away from the temperature-sensitive brain, and at the same time the enlarged size of the cavities may have provided additional space for warming inhaled air. The same Neanderthal facial shape, however, is found in Europe before the last onset of subarctic glacial cold and also in the Near East, where subarctic conditions never arrived. The unique Neanderthal facial configuration is more probably the result of a combination of factors: a highly complex interaction of forces from the chewing apparatus, a response to climatic conditions and a variety of other factors as yet undetermined. Sorting out these factors is one of the principal goals of current research on the Neanderthals. Meanwhile no coherent adaptive explanation for the total Neanderthal cranial pattern has been offered.

For the rest of the skeleton the situation is different. The postcranial skeleton, after all, is the structure that enables a large animal to maintain an erect posture, and *Homo* is a large animal. It is also the structure that allows the muscles to place enormous stresses on the bones while driving the body through the complex characteristic movements of the animal. A 150-pound man standing still needs to support only that much weight with his legs, but if he starts to run, the forces generated by muscle contraction and momentum are greatly increased and amount to several times the weight of his body. The bones of the skeleton must sustain these great stresses structurally, and the tendons must be attached to the bones strongly enough to produce the desired motion (or resistance to motion) effectively and efficiently. The tendon attachments leave characteristic marks on the bones that are clues to the power and action of the muscles. Equally significant, living bone under habitual stresses will reshape itself, within limits, to accommodate the stresses more efficiently.



PETRALONA SKULL, from Greece, is undated but may be 400,000 years old. It shows a number of features reminiscent of *Homo erectus:* a low, wide brain case, a large, heavily built face and a large area at back of the skull for attachment of strong neck muscles. Although it has no specific Neanderthal character, it represents Neanderthal ancestral stock in Europe.

There are many differences between the skeletons of Neanderthals and those of modern men. Some of the differences were formerly interpreted (as, for example, they were by Boule) as evidence of Neanderthal primitiveness. They were easily misinterpreted, and it was not possible to judge which might be more significant and which less so. Today, systematically examined in the light of functional anatomy, the skeletal differences present a coherent and satisfying picture.

To summarize, Boule and others were mistaken: Neanderthals were not less human than modern men, nor were their heads hung forward, their knees bent and their feet rolled over. A touch of arthritis in the neck bones of the La Chapelle-aux-Saints Neanderthal helped to lead Boule astray, but what misled him most was faulty anatomical interpretation. It is now clear that the Neanderthals had the same postural abilities, manual dexterity and range and character of movement that modern men do. They nonetheless differed from modern men in having massive limb bones, often somewhat bowed in the thigh and forearm. The skeletal robustness evidently reflects the Neanderthals' great muscular power. Everything indicates that for their height both Neanderthal men and Neanderthal women were bulkily built and heavily muscled. Furthermore, signs of this massiveness appeared early in their childhood.

Many skeletal parts testify to this conclusion. For example, the talus, or anklebone, differs slightly in shape from the modern human talus. This difference was once taken to be a sign of primitiveness. It consists, however, only in just such an expansion of the joint surfaces at the ankle as would resist greater stress under load. The bones of the foot arches and the toes show stronger tendon attachments for the muscles that support the arches and propel the body in walking and running. The finger bones show similar attachments for the tendons of the powerful muscles that flexed the fingers. They also show an enlargement of the tuberosities that supported the pads at the fingertips. Both features indicate a much stronger grip than that of modern men, but there was nothing gorillalike in it; the control of movement was evidently the same as ours.

This kind of refined control, coupled with great power, also appears in a curious feature of the scapula, or shoulder blade. The feature has long been recognized but not explained. In modern individuals the outer edge of the scapula usually has a shallow groove on the front, or rib, surface. In Neanderthals a deeper groove characteristically appears on the back surface. This feature seems to reflect the strong development in Neanderthals of the teres minor muscle that runs from the scapula to the upper end of the humerus, or upper-arm bone. Part of the action of the muscle is to roll the arm (with the hand) out-

ward. This action would have balanced and counteracted the major muscles that pull the arm down. In throwing or pounding motions, for example, all these muscles roll the arm inward. In balancing this tendency the teres minor muscle would have made possible a finer control of the arm and the hand in throwing a spear or retouching a flint tool, without any loss in the great muscular strength of the limb.

Other Neanderthal body parts repeat the theme. For example, quantitative analysis of the shape and cross-sectional area of the upper and lower bones of the leg shows that the difference between Neanderthal and modern human bones can also be explained in terms of resistance to the higher stresses of weight and activity in Neanderthals.

One difference still calls for explanation. In Neanderthals the pubic bone, at the front of the pelvis, has a curiously extended and lightened upper branch that forms a part of the rim of the pelvis. This is true of every Neanderthal specimen, male or female, from Europe and the Near East, in which the fragile bone is preserved. Possibly the feature is an adaptation for increasing the size of the birth canal in females. That would have allowed easier passage of an infant's head (which was presumably large) at birth. The presence of the same feature in males as well as females might be explained in terms of close genetic bonding between the two sexes. In any event it is not a trait that lends itself to explanation in terms of patterns of muscle action and movement. The peculiarity seems to be a significant Neanderthal anatomical marker. The pubic bones from Skhūl and Qafzeh are modern in form, as are those of the earliest Upper Paleolithic fossils from Europe. How the feature originated remains an unanswered question, because the pubic bones of earlier members of the genus *Homo* have not been preserved.

It now seems likely that the Neanderthals' antecedents can be traced in at least one section of the Neanderthal range, namely western Europe. Early human fossils from Europe are still few and fragmentary, but their number has increased greatly in recent years. Moreover, certain important specimens were formerly held to be more "progressive," or more modern in appearance, than Neanderthal specimens. These specimens now appear, on reexaminations that include multivariate statistical comparisons, to ally themselves more closely with the Neanderthals than with any other known human type. The specimens include the well-known Swanscombe skull from England, the Fontéchevade skull from France and the Steinheim skull from Germany.

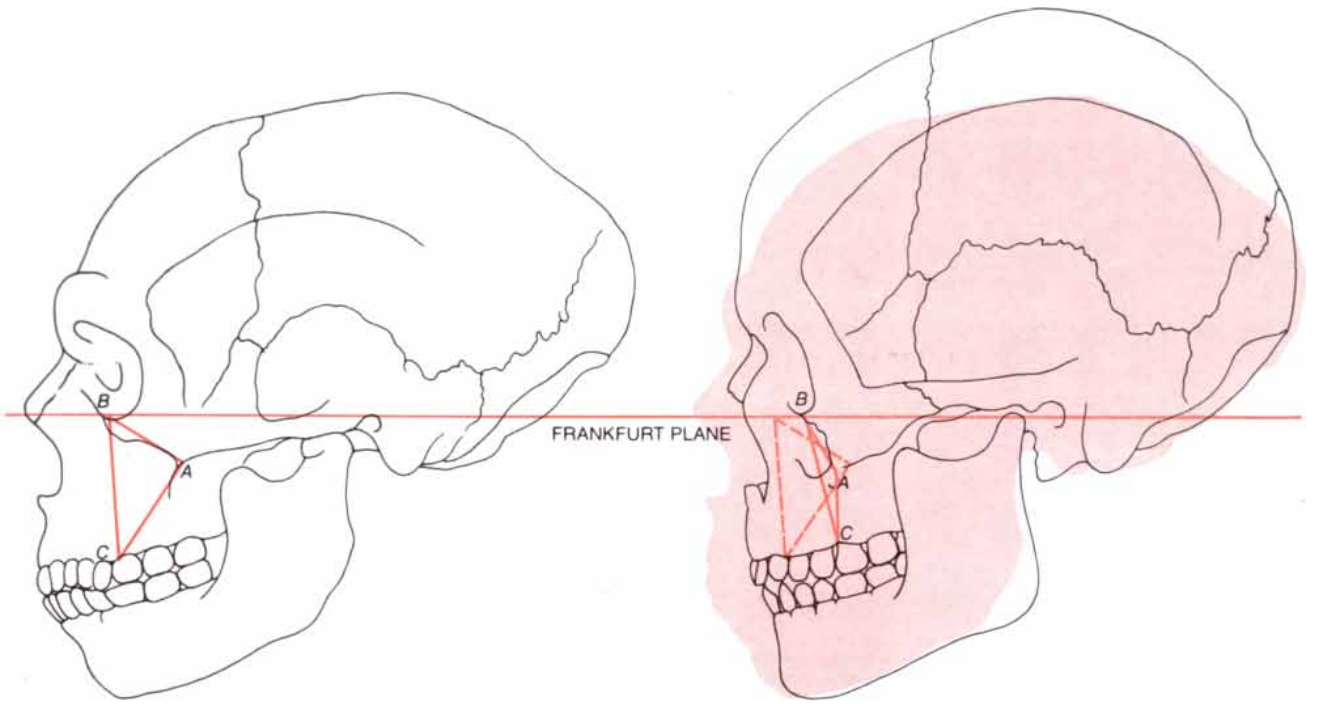
In summarizing the evidence for the origins of the Neanderthals one can begin with the Petralona skull from Greece. It is of uncertain age but is probably as much as 400,000 years old. It shows no specifically Neanderthal character, looking more like an advanced *Homo erectus*. Next in line are the early jaws from Montmaurin in France and from Mauer (near Heidelberg) in Germany. Neither jaw shows any sign of a forward extension of the face such as the Neanderthal postmolar gap. A facial skeleton and two mandibles from Arago, a site in the French Pyrenees, are some 300,000 years old. Like the Swanscombe and Steinheim skulls, the Arago fossils show some suggestions of Neanderthal form, but the projection of the face and the tooth row is not as strongly developed.

From the last interglacial period, which began about 130,000 years ago, come several fossils that show clear signs of the Neanderthal pattern. They include the rear half of a skull, recently found at Biache in northeastern France, that has the lowness of the vault and the protruding rear characteristic of the Neanderthals. A mandible from another French site, the cave of Bourgeois-Delaunay near La Chaise, shows the typical Neanderthal position of the teeth. Two other skulls, from Saccopastore in Italy, clearly approach the typical Neanderthal pattern. Toward the end of the last interglacial the Neanderthal physique is seen in its complete development among the Krapina people. Found in a rock-shelter at Krapina in Yugoslavia, these fossil remains are believed to have accumulated over a considerable span of time both before and after the onset of the last glaciation. All the typical Neanderthal traits are visible: the shape of the skull, the projection of the face, the form of the limbs and the peculiarities of the shoulder blade and the pubic bone.

Why this physical pattern evolved can only be guessed at. The activity of the Neanderthals' massive muscles would have supplied their chunky body with more heat in a chill climate, but the pattern existed before the cold of the last glacial period began in Europe, and it was also present in the more temperate Near East. The robust physique was undoubtedly inherited from populations of *Homo erectus*. Those early men had a massive skull, and the few *H. erectus* limb bones that have been discovered are also massive. Such a heritage does not, however, explain the details of the Neanderthal pattern, particularly the skull pattern.

Whatever the origins of the Neanderthal physique, the fact that it was successful as an evolutionary adaptation is evident from its long stability. From the time of its full establishment perhaps 100,000 years ago down to 40,000 or 35,000 years ago this physical pattern continued without any evidence of evolutionary change. One possible exception is tooth dimensions. The teeth of the Krapina people are larger than those of more recent Neanderthals, which suggests that over a period of time there was a reduction in Neanderthal tooth size. In their details, however, the Krapina teeth are typically Neanderthal, and

"BRUTISH" NEANDERTHAL, the "Old Man" from La Chapelle-aux-Saints in France, was discovered in 1908. The base of the skull was altered by arthritis and damaged after burial; this led to incorrect conclusions about the head posture of Neanderthals in general. Most of the teeth had been lost before death, so that the lower jaw acquired an abnormal rounded contour. This specimen is one of the longest Neanderthal skulls known and has one of the most projecting faces. Because the "Old Man" was for a long time the most complete and best-described Neanderthal specimen it became the stereotype of subspecies *Homo sapiens neanderthalensis*.



PROJECTING FACE of a Neanderthal (*left*) is annotated by the triangle connecting *A*, *B* and *C*. The forward edge of the first molar tooth (*C*) is well ahead of the lower edge of the cheekbone (*A*) and almost directly below the upper end of the cheekbone (*B*). The horizontal line passing above the triangle defines the Frankfurt plane, a standard orientation. The face of an anatomically modern skull (*right*), with point *B* and the Frankfurt plane superposed on a silhouette of the Neanderthal skull, has a tucked-in appearance; point *A* lies above the first molar tooth, and all three points in the triangle are nearly in the same vertical plane. The Neanderthal specimen used for this comparison is an idealized restoration of the "Old Man" of La Chapelle-aux-Saints. This specimen is shown unrestored on the opposite page.

the evidence of a trend toward a reduction of tooth size elsewhere among the Neanderthals is equivocal. It is possible that the Krapina people merely represent an extreme of tooth size, as the Australian aborigines do among modern populations.

After a stability lasting for perhaps 60,000 years the Neanderthal physical pattern was rapidly replaced by one similar to that of modern men. The first anatomically modern groups showed little difference from the Neanderthals in size. For example, the change in the teeth came not in average size but in details of form. The modern reduction in tooth size began later and has continued down to the present day. In general the anatomically modern people of the Near Eastern late Middle Paleolithic (Skhūl and Qafzeh) and the European early Upper Paleolithic had large bones and robust skulls. Fugitive signs of Neanderthal features appear in some of the Skhūl craniums, but they are rarely found in the Qafzeh group or in Upper Paleolithic specimens. The Neanderthal complex of traits is simply not there; these were ordinary robust representatives of modern humanity, like the Polynesians and northern Europeans of today. Indeed, the Upper Paleolithic skulls are specifically like those of later Europeans, or Caucasoids.

These are not subjective judgments: recent studies based on refined measurements, in particular those of Christopher Stringer of the British Museum (Natural History), make the separation between the cranial pattern of Neanderthals and that of early anatomically modern human beings quite clear. Moreover, both populations have skulls that are distinct from those of other fossil hominids. Other skeletal details, including the features of the scapula and the pubic bone mentioned above, fortify the distinction between the Neanderthals and their successors.

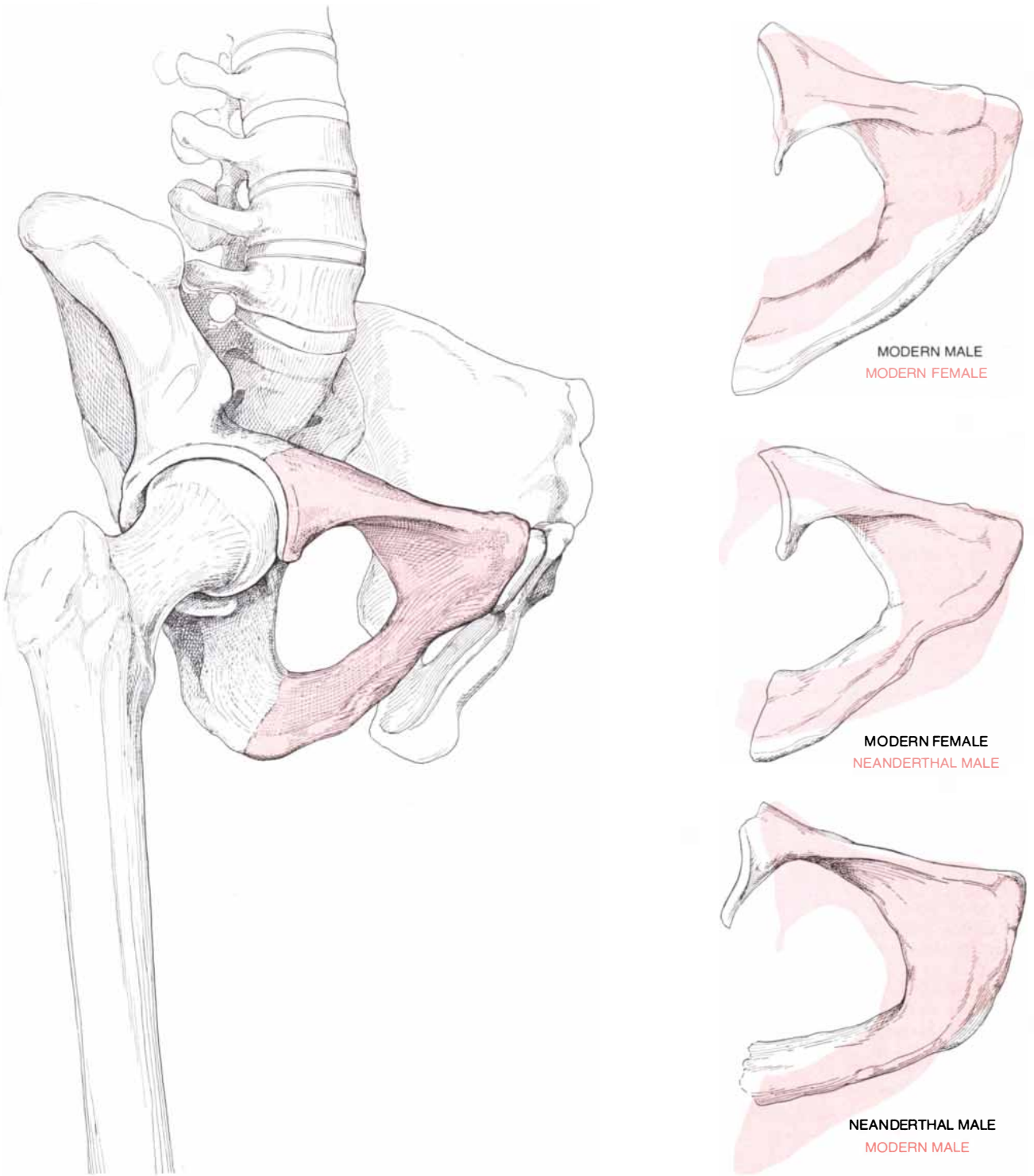
A transition from Neanderthals to their immediate successors undoubtedly took place, but there is little evidence for the actual course of events. The problem is dating. The period of time falls near the limit of accuracy of carbon-14 dating, and in any case samples suitable for carbon-14 analysis have been meager. The problem is particularly difficult in the Near East, and it is only beginning to be solved by the work of Arthur J. Jelinek of the University of Arizona and others. From what is known the most recent Neanderthals at Tabūn Cave in Israel and Shanidar in Iraq are at least 45,000 years old, but they may be considerably older. On the basis of archaeological comparisons the undated Skhūl skeletons are later, being probably no more than 40,000 years old and possibly younger. The Qafzeh remains are undated at the moment, but it seems reasonable to suppose they are about the same age as the Skhūl ones. We shall therefore assume for the moment, but with no great confidence, that in the Near East anatomically modern men replaced the Neanderthals between 45,000 and 40,000 years ago.

In Europe the dating is a little clearer. Carbon-14 dates for sites that hold late Mousterian artifacts (taken as evidence of Neanderthal occupation) come as close to the present as about 38,000 years ago. A date of 35,250 years ago has been determined for the final Mousterian layer in the rock-shelter of La Quina in France. A frontal bone of modern form, found at Velika Pečina in Yugoslavia, has been dated to about 34,000 years ago. Meanwhile a series of carbon-14 dates obtained at sites across Europe place the beginnings of the culture level known as the Aurignacian (inferentially associated with people of modern physique) at about 33,000 years ago or slightly earlier. Hence in Europe the interval between Neanderthals and anatomically modern populations appears to have been extremely short.

What is important here is to contrast the departure of the Neanderthals with their arrival. The pace is totally different. From what is known about the arrival it can be seen as a gradual evolution. The departure can only be called abrupt; it probably took a tenth as much time as the arrival. Can the two transitions be assessed in the same terms? To answer the question one must accept some guidelines from current knowl-

edge of evolutionary processes. These processes have been notably neglected in the two prevailing explanations of the Neanderthals' disappearance.

One of the two explanations, favored today by anthropologists in the U.S.S.R. and elsewhere in eastern Europe and by many in the U.S., is a restatement of the old "Neanderthal phase" hypothesis. In this view the Neanderthals evolved directly and on the spot into the anatomically modern people of the Upper Paleolithic. Its adherents see Neanderthal or "transitional" anatomical traits in the Skhūl population and in certain Upper Paleolithic specimens such as those from Brno and Předmostí in Czechoslovakia. One of those specimens has not only heavy brow ridges but also a lower jaw with the characteristic gap between the wisdom tooth and the jaw's ascend-



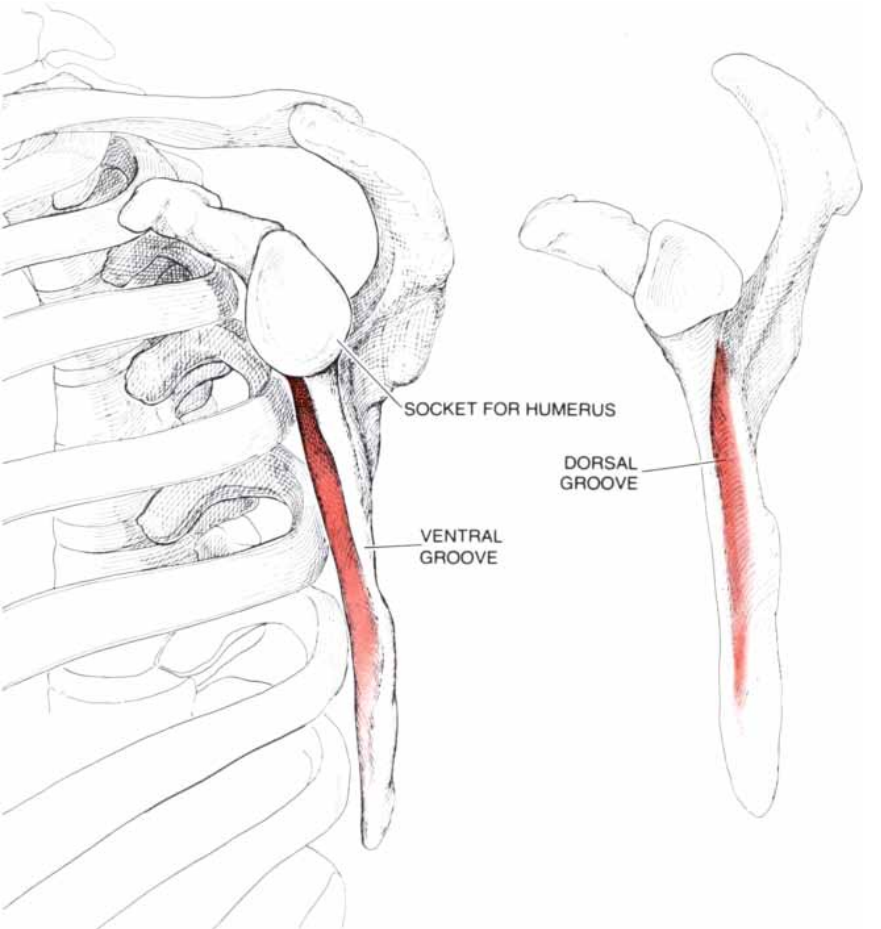
PUBIC BONES of a Neanderthal male and an anatomically modern male and female are compared. The pubic bone is the portion of the pelvis (*left*) that extends from the hip socket to the front midline; here the right pubic bone is seen from the front in all instances. First (*top right*) the pubic bone of a modern female is silhouetted in color. It is wider and less massive than the pubic bone of an anatomically modern male (*black*). The pubic bone of a Neanderthal male, Shanidar 1, is silhouetted in color (*center right*). It is even wider and slenderer than that of a modern female (*black*). Finally (*bottom right*) the slenderness of the Neanderthal pubic bone is even more evident when it is compared with that of a modern male (*silhouette in color*). All Neanderthal pubic bones, male and female, show this characteristic.

ing branch. These features do not, however, make up the full Neanderthal pattern. Both are found in some prehistoric skulls from Australia. Moreover, the brow ridges are not Neanderthal in form; they probably represent an extreme among the generally rugged skulls of Upper Paleolithic people in Europe. Finally, when the measurements of the overall skull shape and of several limb-bone features are subjected to statistical analysis, they indicate that the specimens lack any particularly close Neanderthal affinity. In general, then, fossil specimens from the early Upper Paleolithic, although they are robust and rugged, show no convincing sign of a total morphology that is transitional between Neanderthals and modern men. Nor do late Neanderthal fossils show signs of having begun an evolutionary trend in a modern direction.

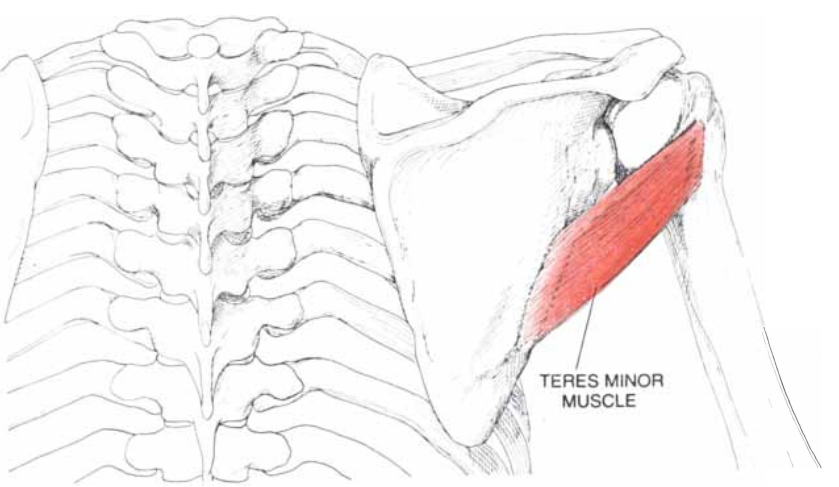
The second interpretation ascribes the disappearance of the Neanderthals not to local evolution but to invasion by new peoples of modern form. If there were a cave containing the remains of killed Neanderthals in association with Upper Paleolithic tools, one might entertain the hypothesis of replacement. The hypothesis might also be supported if there were evidence of a homeland for the alleged invaders or for their migration route. Current archaeological and paleontological information, however, is far too fragmentary to support the hypothesis. One can only point out that human populations of modern, although not European, anatomical form certainly occupied the distant continent of Australia 32,000 years ago and probably 8,000 years earlier than that. Signs of even older modern men are found in sub-Saharan Africa. Hence if anatomically modern men sprang from a single original main population, a point that many dispute, then it was not a population of Neanderthals, since anatomically modern men were in existence elsewhere when the Neanderthals still inhabited Europe.

Any attempt to choose between these two interpretations is sterile unless evolutionary principles are taken into account. In evolutionary terms a significant change in a physical pattern, such as the one separating the Neanderthals from their Upper Paleolithic successors, normally comes in two steps. First the change arises as a consequence of new selective forces acting on the individuals of a particular population. Then the change somehow becomes established as the norm in all populations of the species. Since the skeletal differences among all living human populations are less than the differences between the living populations and the Neanderthals, there is little doubt that the new pattern has become established throughout *Homo sapiens* today.

More specifically, a widely distrib-



SHOULDER BLADES of a Neanderthal and an anatomically modern man are compared. These are left scapulas seen from the side. The modern scapula, at the left, shows a single groove on the ventral, or rib, side of the outer edge (*color*). This ventral-groove pattern is present in four out of five modern men; it is related to the development of a shoulder muscle, the teres minor, which in anatomically modern men connects the upper arm to the scapula by attaching to a small portion of the dorsal scapular surface (*see illustration below*). The Neanderthal scapula, at the right, has a single large groove on the dorsal, or back, side of the outer border (*color*). This dorsal-groove pattern appears in more than 60 percent of Neanderthal scapulas; the scapula illustrated is that of Shanidar 1. All of outer edge of the bone and part of the dorsal surface provided attachment for the teres minor muscle, indicating that it was well developed.

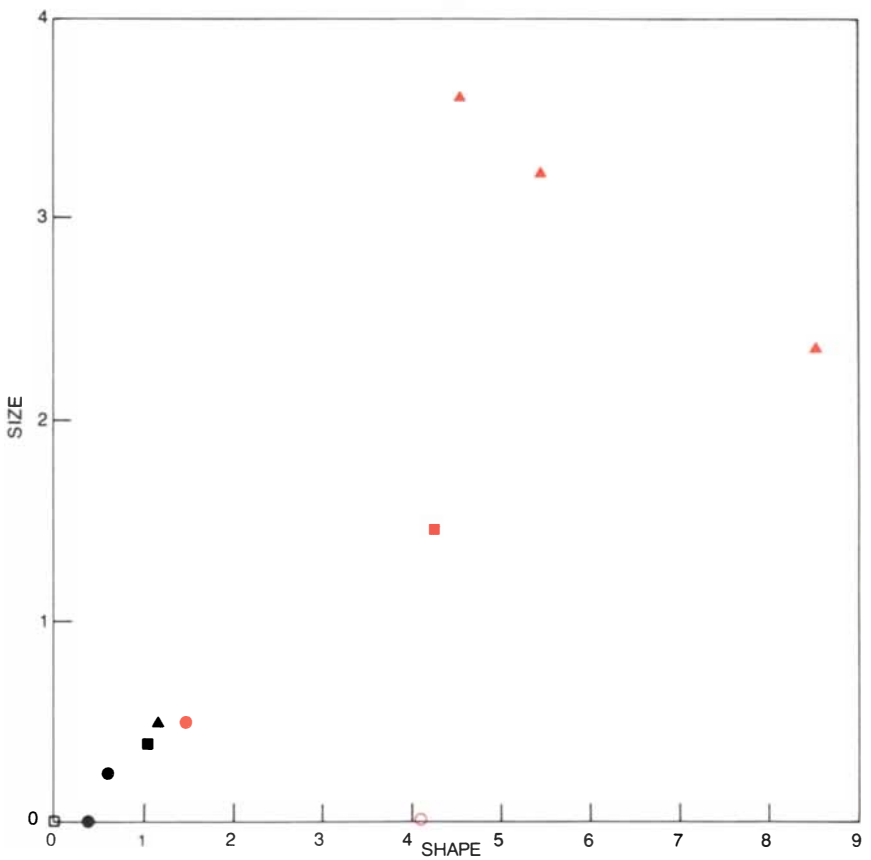


LINE OF ACTION of the teres minor muscle (*color*) is indicated in this dorsal view of the right scapula and part of the right upper arm bone, or humerus. When the muscle contracts, it pulls the humerus in toward the scapula, thereby strengthening the shoulder joint; at the same time it turns the upper arm, forearm and hand outward. All the major muscles of the shoulder that pull the arm downward, as in throwing or striking a blow, tend to turn the arm and hand inward. By countering this rotation the teres minor muscle gave Neanderthals more precise arm control.

uted species that interbreeds freely is likely to be relatively static in the evolutionary sense. It changes quite slowly because the lack of barriers to gene exchange between populations encourages a species-wide genetic homogeneity. Moreover, if the species has a common adaptation, and human culture can be so viewed, then selection will be similar for most of its features, which further promotes its general uniformity.

If, on the other hand, the species is more fragmented, perhaps by various degrees of geographical isolation, an increase in diversity is more likely. In small, isolated populations the substitution of genes under the pressure of natural selection will be faster. Only by some advantage in adaptation, for example a better adaptation to a new ecological situation or a better exploitation of the old one, can a new pattern in one population of a species become the dominant pattern of the species as a whole. The adaptive pattern may be propagated by the flow of genes to other populations or by the simple replacement of part or all of the old populations, with the new population expanding and successfully competing for existing resources. How is Neanderthal history to be seen in the light of such processes?

We have outlined two eventualities: either evolution throughout an entire species (or a large population) because of a common selective pressure or a faster evolution in one element of the population toward a specific adaptation, after which that element of the population replaces other elements because of its adaptive advantage. The two eventualities correspond generally to the two customary interpretations of why after a certain time men of the modern type came to the fore and the Neanderthals disappeared. The two interpretations also imply different degrees of complexity in the genetic basis of the observed anatomical differences. If, on the one hand, the Neanderthals evolved locally into early Upper Paleolithic people, one would expect that relatively few simply coded genetic traits were responsible for the anatomical differences in order for them to appear and spread across the Near East and Europe in a few thousand years. The rate of such evolution within local populations might have been accelerated by the influence of behavioral adaptations on certain aspects of growth, such as the robustness of limb bones; this characteristic is known to be sensitive, within limits, to patterns of individual activity. If, on the other hand, there was significant migration of non-Neanderthal peoples, together with interbreeding and replacement, then a far more complex set of circumstances of genetic substitution and change might be involved.



MULTIVARIATE ANALYSIS of fossil and modern skulls compares 18 measurements in terms of size (*ordinate*) and shape (*abscissa*). An average of European Upper Paleolithic skulls (*open square*) is used as the point of departure. Farthest removed from the starting point in terms of shape and well removed in terms of size is the Middle Pleistocene skull from Petralona (*colored triangle at far right*). More removed in terms of size but nearer in terms of shape are the skulls of Rhodesian man (*colored triangle to right of center*) and a Near Eastern Neanderthal, from Amud (*colored triangle at top center*). The colored square near the center represents the average of European Neanderthal skulls; the Middle Pleistocene European fossil from Steinheim (*open colored circle*), although it is smaller than the Neanderthal average, is quite close to the Neanderthal average in shape. The Saccopastore skulls (*colored dot*), most recent of the early Neanderthals, are surprisingly close to the averages of two modern skull samples (*black dots*): Norwegians and Zulus. The same is true of two skulls from Qafzeh (*black triangle*) and another specimen from the Levant, Skhūl 5 (*black square*). The modern and the Levant specimens diverge only trivially from the European Upper Paleolithic average. This Penrose size and shape analysis was done by Christopher Stringer of the British Museum (Natural History).

The fossils themselves furnish some hint of the complexity of the genetic basis for the anatomical differences. First, the Neanderthal pattern seems to have coalesced slowly during the late Middle Pleistocene and the early Upper Pleistocene. This suggests that the kind of complex genetic basis that could build up over many millenniums may well have been responsible for the Neanderthal pattern. Second, the fossil remains of Neanderthal children show that the characteristic Neanderthal morphology had developed by the age of five, and perhaps earlier. Since it is difficult to see how activity could seriously affect the developmental pattern of an infant, it appears likely that there was a complex genetic determination of the development of many details of the Neanderthal morphological pattern.

Broadly, then, the Neanderthal physical pattern evolved in 50 millenniums or more; thereafter it remained relatively constant for about another 50 millenniums. Then came the observed transition, within Neanderthal territory, to an essentially modern human anatomy in about 5,000 years. The various evolutionary and anatomical considerations seem to fit best a model that presents the evolution of populations of anatomically modern men (the early Upper Paleolithic people of Europe and the final Mousterians of the Near East) in partial isolation from the majority of the Neanderthals. These populations may have arisen from a strictly Neanderthal population or a non-Neanderthal one. At any rate they undoubtedly spread, absorbing and replacing various local Neanderthal populations across the Near East and Europe. The time and place of the establishment of these earliest modern people within the Neanderthal area are not yet known.

The main selective force that favored

the modern physique over the Neanderthal one also remains to be discovered. Was it perhaps climatic change? Actually the last glacial period reached its coldest point more than 10,000 years after the transition from the Neanderthal physique to the modern one, and there is no consistent correlation between the transition and any major climatic change. Was it ecology? Both kinds of men hunted the same game and presumably collected the same plant foods.

Was it cultural advance? Here we have the best evidence in the form of the stone tools. It is hard to see that the specific Upper Paleolithic tools have much of an advantage over the Mousterian ones, for hunting, for gathering or for any other subsistence activity. It is more likely that, as the Mousterian tools were beginning to suggest the Upper Paleolithic forms, there arrived a threshold in human subsistence patterns, and that the only indication of the threshold appears in the tools themselves. One might hypothesize that crossing this threshold made the bulky Neanderthal physique both unnecessary and too costly in its food requirements, thereby initiating a rapid reduction in body size and conceivably even a change in all the special Neanderthal traits. Alternatively the improvement in stoneworking techniques and the associated behavioral changes may have given a significant adaptive advantage to the less heavy-bodied Upper Paleolithic people.

It is interesting that between 40,000 and 35,000 years ago there was a marked increase in the complexity of the sociocultural system of these hominids. Soon thereafter various forms of art are a regular feature at archaeological sites, implying the existence of well-established rituals for various kinds of social behavior. Although ritual existed considerably earlier among the Neanderthals, as is indicated by their burial practices, a rapid increase in its complexity would suggest that some threshold had been reached in the evolution of the sociocultural system. The crossing of such a threshold may well have had significant influence on the biological evolution of these prehistoric human populations.

The problems remain: on the theoretical side the nature of the advantage giving rise to the transition and on the factual side the lack of datable fossils that would make the real story clear. Yet the importance of the Neanderthals is that so much is now known about them, incomparably more than is known about other human populations that lived at the same time. Reconciling this wealth of information with what is known about evolution in general presents by far the best opportunity for the scientific study of human development in the late Pleistocene.

Electrical Responses Evoked from the Human Brain

Minute voltage shifts generated by the sensory regions of the brain can be recorded from the scalp. These recordings yield clues to the functioning of the human brain in health and neurological disease

by David Regan

What are the neural processes underlying human perception and behavior? One experimental approach to this question has been to insert microelectrodes into the brain of experimental animals in order to study the activity of single neurons, or nerve cells, in response to specific sensory stimuli. Single-cell recording is limited, however, by the small number of neurons that can be examined simultaneously, so that it is difficult to extrapolate from single-neuron studies to the complexities of human conscious perception. Moreover, in its present form the technique clearly cannot be used with human subjects.

An alternative experimental approach has been to measure the electrical activity of localized populations of neurons in the brain during the performance of specific perceptual or behavioral tasks. This neuronal activity generates electric currents that pass through the skull and give rise to minute voltage changes, known as evoked potentials, that can be recorded with noninvasive disk electrodes taped to the scalp. The evoked-potential technique, which has been much refined over the past 20 years, provides a bridge between detailed qualitative measurements of conscious perception in human subjects and recordings from individual neurons in the brain and sensory pathways of experimental animals.

The combined electrical activity of the billions of neurons in the brain as a whole is recorded in the familiar electroencephalogram, or EEG. Such recordings reveal little about sensory perception because they are not usually correlated with specific perceptual stimuli. That is not the case with the evoked-potential technique. For example, when the image of a checkerboard pattern is focused on the retina, signals pass from neurons in the retina at the back of the eye through way stations in the midbrain to the visual area of the cerebral cortex in the rear of the brain. There they activate neurons that process pattern information. These neurons in turn generate weak evoked potentials that can be picked up by scalp electrodes placed over the visual cortex. Similarly, evoked potentials can be recorded from the auditory area of the cerebral cortex following a sudden auditory stimulus, such as a click or the onset of a tone.

The evoked-potential technique has three principal applications. First, it has helped to reveal specific brain activities in which different types of information are handled simultaneously in separate channels. Second, it has provided an objective indicator of sensory function where perceptual tests are impractical or unreliable (as they are with infants). Third, it can distinguish organic disorders from psychogenic ones.

The main problem in recording evoked potentials is detecting them at all. They are so weak that they are completely buried in the spontaneous electrical activity of the brain as a whole. Whereas the signal recorded by the electroencephalogram commonly reaches an amplitude of between 50 and 100 microvolts, evoked potentials are often no larger than five microvolts and may be as small as .5 to one microvolt. To the evoked-potential investigator the electroencephalogram signal is unwanted and overwhelming background noise.

There are two widely employed methods for enhancing the signal-to-noise ratio of evoked potentials. The first method is transient signal averaging. A stimulus (such as a click, a tap on the skin or the sudden presentation of a visual pattern) is repeated many times, separated by intervals that are long enough for the brain to settle down to its resting state between repetitions. Each brain response is called a transient evoked potential, and its amplitude can be measured by a computerized instrument. When a large number of individual transient evoked potentials have been summed and stored, the computer calculates the average amplitude of each point on the trace and displays the averaged curve. The experimenter assumes that all the individual transient evoked potentials are identical and occur at exactly the same time after the stimulus. Since the electroencephalographic background activity is not correlated with the stimulus but varies randomly in relation to it, the summed background noise builds up much less rapidly than the summed evoked potentials. As a result, although in single responses the evoked potential is completely buried in background noise, it emerges clearly in the computed average response to, say, 200 stimuli. Quite different evoked potentials can be elicited by different sensory stimuli, such as the appearance and disappearance of a pattern or the motion of an object in depth.

The first automatic averaging device for recording transient evoked potentials was constructed in the early 1950's by George Dawson of the University of London. The device was partly mechanical but was nonetheless sufficiently effective to provide research findings that are still valid today. An all-electronic averaging computer was subsequently developed by Manfred Clynes and Michael Kohn of the Rockland State Hospital in New York. Commercial production of this machine enabled hundreds of laboratories and hospitals to embark on research on transient evoked potentials in the mid-1960's.

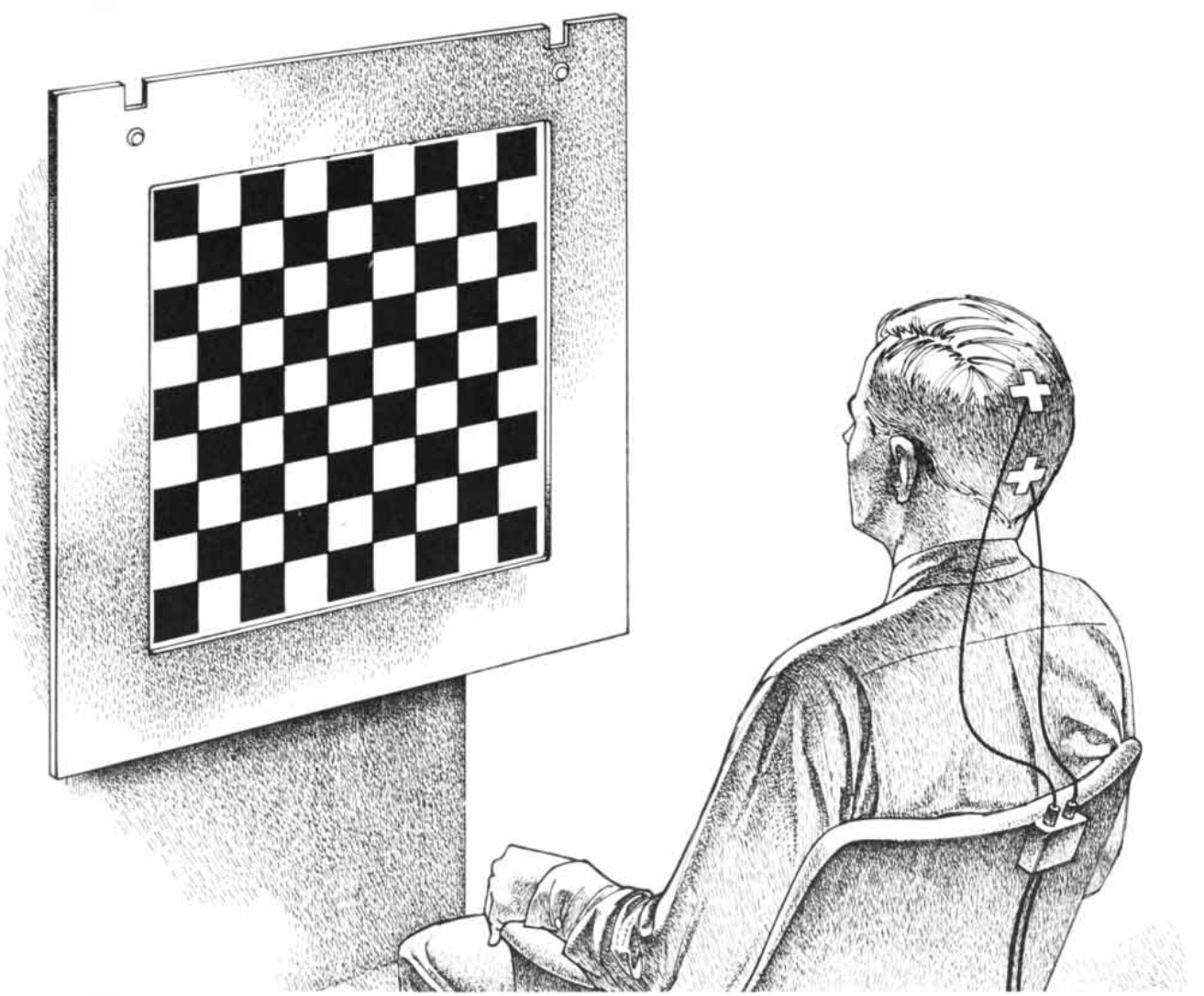
The second recording method calls for generating steady-state evoked potentials, which are quite different from transient evoked potentials. Some time after a rapidly repeating stimulus has been switched on, the successive evoked potentials, running into one another, become a series of identical waves of electrical activity that repeat at the same frequency as the sensory stimulus. In the steady-state method it is intended that the brain not have time to

regain its undisturbed state between successive stimuli. Examples of such repetitive stimulation include a flickering light, a rapidly clicking electronic metronome or a bar oscillating in depth. In some studies the views of brain function given by transient and steady-state evoked potentials are complementary. From a practical point of view the steady-state method has the advantage of speed: it is as much as 100 times faster, which can be particularly important in clinical studies.

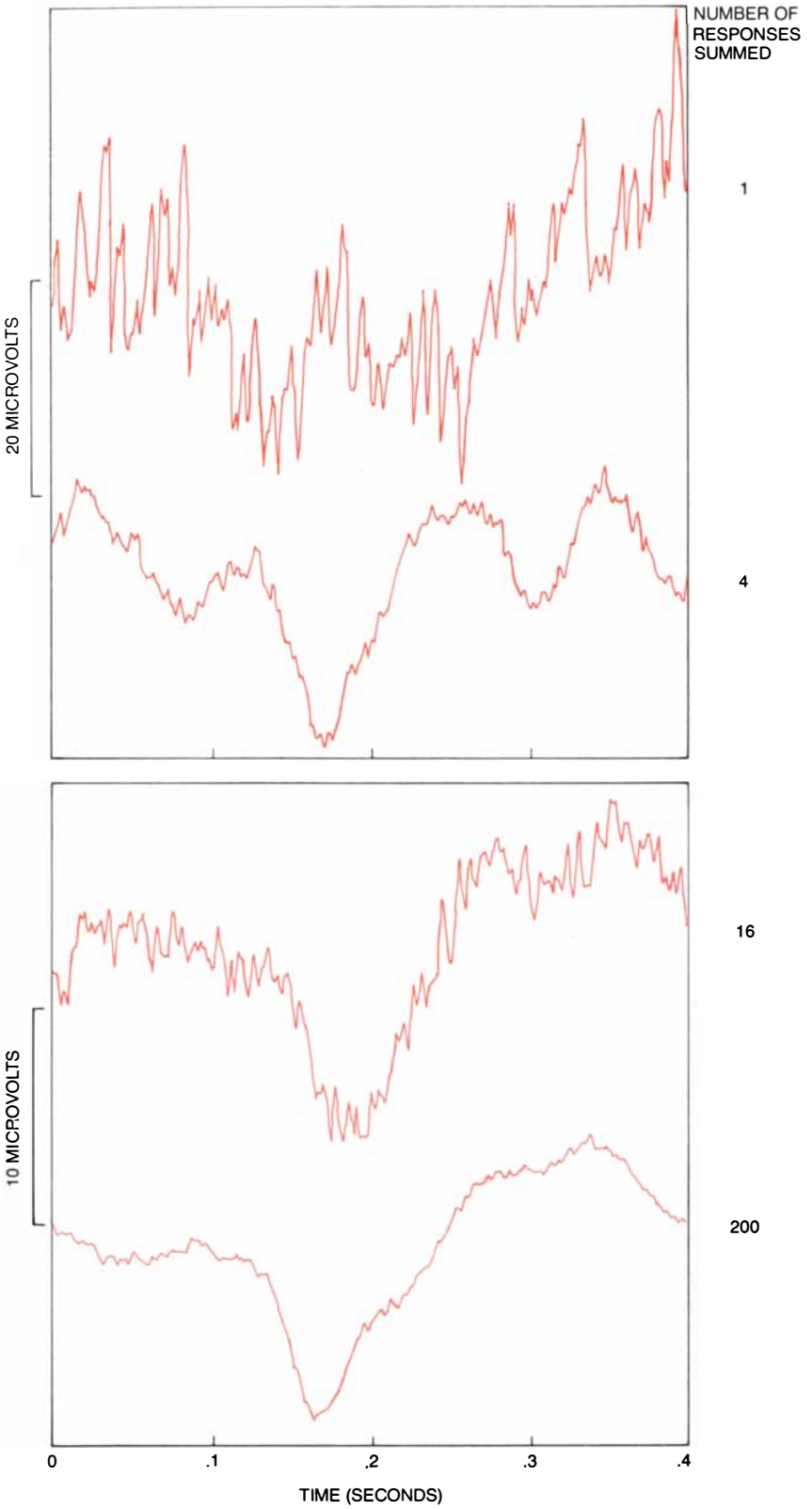
Steady-state evoked potentials recorded from the scalp must also be extracted from the higher-amplitude electrical activity of the brain as a whole. In 1961 I showed that this could be done with the aid of a Fourier analyzer. Although my analyzer was a crude device, constructed from modified phonograph cartridges and a domestic electricity meter, its operation was securely based on the mathematical procedure developed by J. J. Fourier in 1807. I predicted that a light flickering f times per second would elicit a steady-state evoked potential from brain neurons sensitive to flicker, and that the frequency of the response would be exactly f hertz (cycles per second). Fourier analysis shows that a signal that repeats itself f times per second does not consist of all possible frequencies. Rather it consists of a limited number of narrow frequency bands centered on f hertz, $2f$ hertz, $3f$ hertz and so on. The signal is therefore made up of a finite number of harmonics.

A Fourier analyzer rejects all frequencies that are not precisely at one of these harmonics. In effect the rejected activity amounts to most of the unwanted noise, since there is no reason for appreciable amounts of random noise to occur at exactly f hertz, $2f$ hertz, $3f$ hertz and so on. It is therefore possible to extract a steady-state evoked potential from the electrical activity of the brain as a whole by exploiting the prior knowledge that the frequency of the evoked potential will be exactly the same as the frequency of the repetitively varied stimulus.

Evoked-potential recording has become an important tool in research on human perception. (It is also an important tool in research on cognition, but that will not be discussed here.) In general the evoked-potential technique has supported the hypothesis that the sensory pathways of the brain break down complex sensory stimuli into a number of abstract features that are processed virtually independently in different channels. The channel hypothesis was originally based on the evidence of a great many psychophysical studies of vision and can be traced as far back as 1801, when Thomas Young proposed that the infinite number of wavelengths in the spectrum are analyzed by a small number of color channels. One reason for the modern surge of interest in the channel hypothesis is that technical de-



SCALP ELECTRODES placed over the visual cortex at the back of the head detect visual evoked potentials: localized patterns of nerve-cell activity induced by specific visual stimuli. In this experiment, done in the author's laboratory at Dalhousie University, a checkerboard pattern appeared abruptly on the screen in front of the subject. The stimulus elicited an evoked potential in the visual cortex, which was picked up by the electrodes. An averaging computer was required to extract the evoked potential from background activity of the brain.



TRANSIENT EVOKED POTENTIAL can be elicited by a single abrupt stimulus, such as a flash or an auditory tone. Because the amplitude of the background activity of the brain is usually much higher than that of the evoked potential the response must be extracted from the background noise by an averaging process. The top trace shows the activity of the visual cortex for .4 second after the appearance of the checkerboard pattern; the deflections in the trace are due almost entirely to the background activity of the brain as a whole. The second trace shows the sum of four evoked potentials; a visual response can just barely be detected. After 16 summed responses the evoked potential is clearer, but appreciable noise is still present. Bottom trace is sum of 200 responses to the pattern stimulus. The evoked potential is almost noise-free.

velopments in neurophysiology have led to discoveries of different types of cells in the brain whose various properties might provide a physical basis for the channels of visual perception. For example, in the early 1960's William B. Marks, W. H. Dobelle and Edward F. MacNichol, Jr., of Johns Hopkins University and Paul K. Brown and George Wald of Harvard University showed directly that the eye really does possess the three different classes of photoreceptors (for red, green and blue) whose existence had been hypothesized a century and a half earlier by Young.

More recently Fergus W. Campbell, John G. Robson and Colin Blakemore of the University of Cambridge showed that form or shape information is processed in parallel channels that analyze the visual scene into narrow spatial-frequency bands of different orientations. A physical basis for these orientation channels may be classes of neurons sensitive to orientation that were discovered in the late 1950's by David H. Hubel and Torsten N. Wiesel of the Harvard Medical School recording from microelectrodes in the visual cortex of the cat.

Much other evidence obtained from psychophysical, evoked-potential and single-neuron studies over the past 15 years supports the channel theory of perception. Kenneth Beverley, Max Cynader and I combined these three techniques to demonstrate that the visual pathway processes motion in depth and position in depth in parallel channels that are almost independent [see "The Visual Perception of Motion in Depth," by David Regan, Kenneth Beverley and Max Cynader; SCIENTIFIC AMERICAN, July]. There is also a good deal of evidence that the visual pathway has channels for changing size and for flickering stimuli.

The auditory pathway seems to process information in channels as well. Studies on human subjects carried out in 1972 by R. H. Kay and D. R. Matthews at the University of Oxford and more recently by Brian W. Tansley and me at Dalhousie University showed that changes in the frequency and intensity of a tone are processed in parallel channels. A possible physical basis for these channels had been discovered several years earlier in 1964 by Edward F. Evans and Ian C. Whitfield of the University of Birmingham, who found that some single neurons are activated by changes in the frequency of a tone but respond little if at all to a steady tone, whereas other neurons are strongly excited by a steady tone.

The channel hypothesis is currently providing guidelines for the design of new sensory tests to aid in the detection and diagnosis of disease. In cases where a disease affects one channel but leaves other channels unaffected a conventional test that misses the affected channel

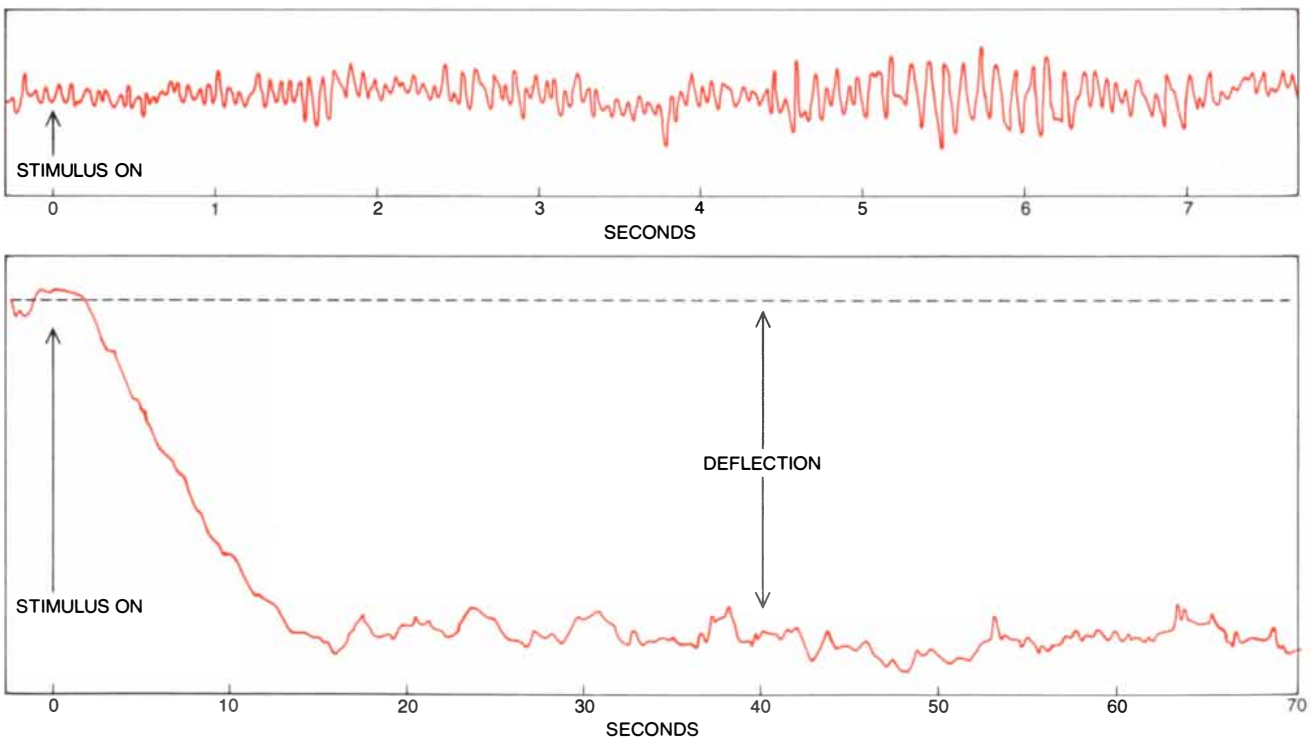
may fail to detect the disease. Testing individual channels can provide more sensitive and specific diagnostic aid. In this context evoked-potential recording offers an objective method for testing channels when (as with infants) perceptual tests are impractical or ineffective. This practical possibility stems from the finding that for every perceptual channel so far identified there is a corresponding type of evoked potential.

Evoked potentials are not merely a complicated way of studying perception. It is easy to overlook the fact that much of the neural output from the ears and eyes does not reach conscious awareness at all. For example, many visual signals are concerned with "housekeeping" activities of the body, such as adjusting the size of the pupil of the eye in response to changing light intensities. Because evoked-potential recording methods detect these brain activities they can be employed to investigate aspects of brain function that cannot be studied directly by testing what is seen or heard.

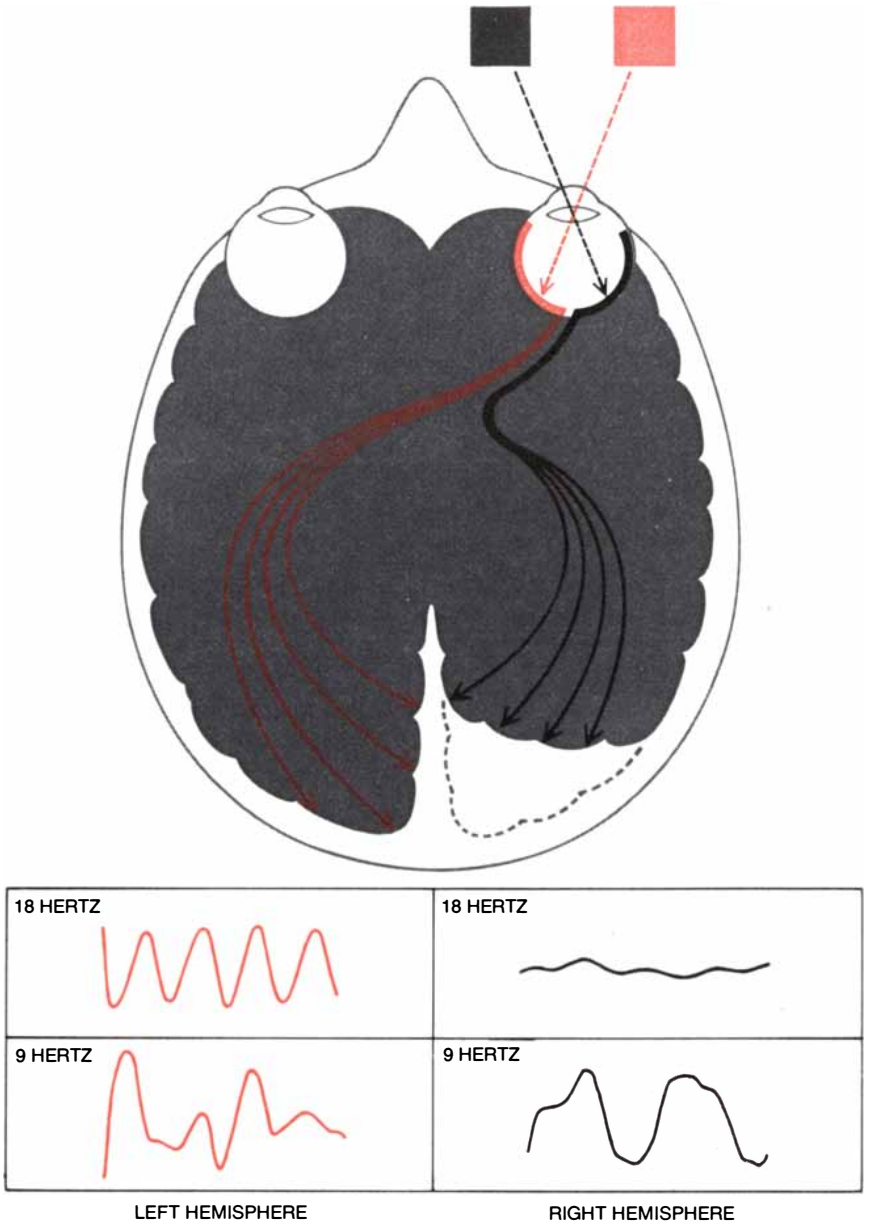
We came across an illustration of this point while we were attempting to develop an evoked-potential method for aiding neurosurgeons to locate brain tumors. A female patient had a small tumor removed from the rear part of her right cerebral hemisphere. During the operation it was necessary to remove the primary visual cortex from the right side of her brain, and as a result she became blind in the left part of the visual field of each eye. Not surprisingly, a light flickering 18 times per second in the left visual field of one eye elicited no evoked potential, although the same flicker in the right visual field of the same eye elicited a normal evoked potential. Much to our surprise, a light flickering nine times per second elicited clear evoked potentials from both sides of the brain. It therefore appeared that the evoked potential elicited by the 18-hertz flicker arose from a part of the visual cortex whose activity is necessary for visual perception, but that the evoked potential elicited by the nine-hertz flicker originated in a part of the visual cortex that by itself is not capable of supporting visual perception.

Complementary findings were recently described by Ivan G. Bodis-Wollner, Adam Atkin, Edward L. Raab and Murray A. Wolkstein at the Mount Sinai School of Medicine in New York. They recorded clear pattern-evoked potentials from a patient in whom computerized X-ray brain scans had shown that visual-association cortex had been damaged, although primary visual cortex was spared. In this patient primary visual cortex by itself was evidently insufficient to support visual perception but sufficient to generate pattern-evoked potentials (although somewhat abnormal ones).

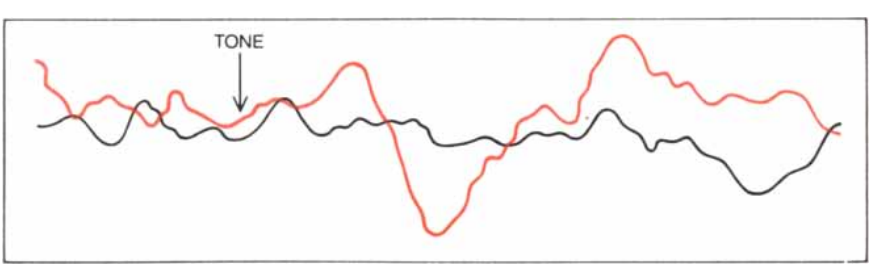
So far the chief practical application of evoked-potential recording has been sensory testing in medicine. One such application was described in 1967 by Isabelle Rapin and L. J. Graziani of the Albert Einstein College of Medicine in New York. Some infants whose mothers were infected during pregnancy by the rubella ("German measles") virus are born with defective hearing. In such cases it can be important to assess the degree of hearing impairment early so that an effective hearing aid can be fitted before the infant is ready to learn to understand speech and to talk. Rapin and Graziani attempted to assess hearing damage caused by rubella in a 21-month-old female infant. They found that no evoked potential could be recorded from the infant's auditory cortex, even when a very loud tone (109 decibels) was employed as the stimulus. When the infant was fitted with a hearing aid, however, they found that the device could be adjusted to give clear auditory evoked potentials not only for loud tones but also for those of lower intensity (89 decibels). The hearing aid ensured that the signals reaching the brain were strong enough to elicit an evoked potential similar to the one induced in normal infants. Although most evoked-potential stud-



STEADY-STATE EVOKED POTENTIAL can be elicited by a repetitive sensory stimulus, such as a flickering light. The upper trace shows a continuous record of whole-brain activity (the electroencephalogram, or EEG) recorded from scalp electrodes placed over the visual cortex. Powerful bursts of alpha-wave activity with a frequency of 10 hertz (cycles per second) and an amplitude of about 50 microvolts are evident. For the first second of the recording there is no visual stimulation; then a light starts to flicker 15.5 times per second. No evoked potential can be detected in the EEG trace because the response is buried in the background noise. The lower trace shows the output of a Fourier analyzer whose input was the EEG trace. When the light starts to flicker, the analyzer shows the presence of an evoked potential. Amplitude of the deflection is about five microvolts. The evoked potential remains approximately constant for the entire recording period and is not affected by bursts of alpha activity in the EEG. Recording was made by author at the University of London.



VISUAL EVOKED POTENTIALS were recorded from a female patient whose right primary visual cortex had been surgically removed, leaving her blind in the left visual field of each eye. Stimulating the blind left visual field with a light flickering 18 times per second elicited no evoked potential from the blind brain hemisphere. Surprisingly, stimulating the left visual field with a light flickering nine times per second elicited potentials of similar amplitude in both the blind and the normal hemisphere. Slower flicker apparently activated a region of the cortex that receives visual information but does not by itself give rise to conscious visual perception.



FITTING OF A HEARING AID in an infant with defective hearing was facilitated by evoked-potential recording. Without the hearing aid the infant showed no detectable evoked potential in the auditory cortex, even in response to a very loud tone of 109 decibels (*black trace*). When the hearing aid was fitted, however, it could be adjusted to give a clear evoked potential even for a tone with an intensity of 89 decibels (*colored trace*). This potential is similar to one recorded from infants with normal hearing. The two traces were recorded by Isabelle Rapin and L. J. Graziani of the Albert Einstein College of Medicine of the City University of New York.

ies do not yield such clear-cut results, the example illustrates what can be achieved with the method once the technical problems have been overcome.

Not all evoked potentials originate in the cortex of the brain. Recently it has become routine in many laboratories and hospitals to record evoked potentials from the brain stem. For example, a click elicits a sequence of evoked potentials in a series of way stations in the brain stem that can be recorded from electrodes placed over the mastoid bone behind the ear. Because these potentials are very small (they seldom exceed one microvolt) it is essential to minimize the electrical noise generated by nearby neck muscles. Brain-stem recordings are therefore made from drowsy subjects lying in a darkened soundproof room.

Auditory brain-stem responses were recorded for the first time in 1970 by Donald L. Jewett, M. N. Romano and John S. Williston of the University of California Hospital in San Francisco. Seven discrete waves were detected within the first 10 milliseconds after the stimulus click, representing the successive activation of auditory nuclei in the brain stem. Research in several laboratories has been directed to finding the precise locations within the brain stem where the seven waves are generated. Data from human patients with brain lesions of known location have been compared with data obtained by placing recording electrodes within the brain of experimental animals. A widely accepted interpretation is that as neural signals leave the cochlea, wave 1 is generated by the synchronous firing of nerve impulses in the eighth (auditory) nerve, wave 2 coincides with activity in the cochlear nucleus, wave 3 originates in the superior olive and waves 4 and 5 coincide with activity in the inferior colliculus (although some workers believe more than one site can contribute to a given wave). The origin of waves 6 and 7 is not known.

Auditory brain-stem responses are more consistent between individuals than cortical evoked potentials and are less affected by such factors as whether the subject is paying attention to the stimulus. In particular the delay between the stimulus and the appearance of the individual waves does not vary by more than .5 millisecond between normal adult subjects, although the amplitudes of the waves are somewhat variable. The reliability of brain-stem recording is a major reason the technique has rapidly proved itself as a useful clinical tool. A second reason for its rapid adoption is the developmental work done by Robert Galambos and Steven A. Hillyard of the University of California at San Diego, Arnold Starr of the University of California at Irvine and Terry Picton of the University of Ottawa.

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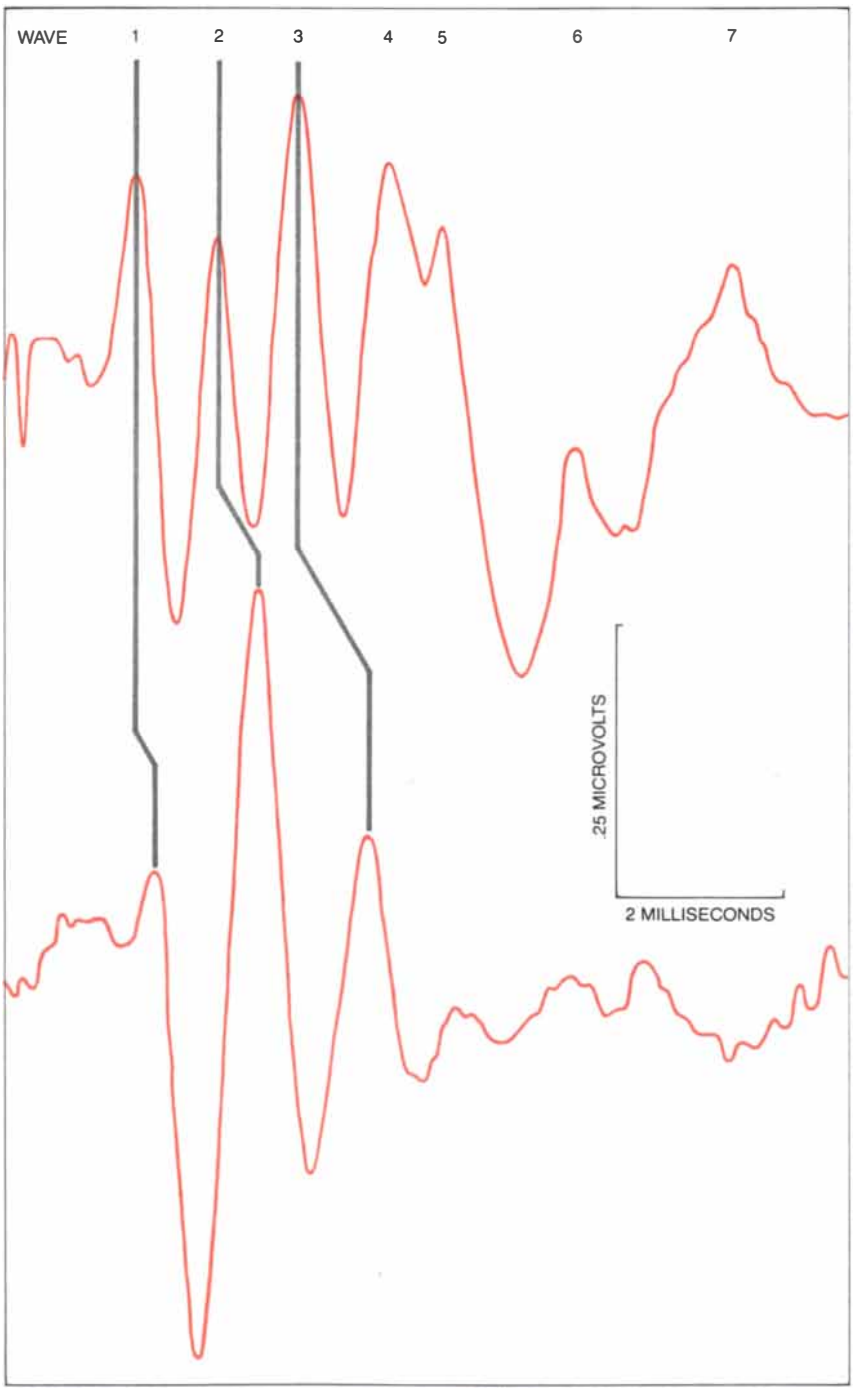
The detection and location of brain tumors is an example of the clinical application of auditory brain-stem potentials. Starr and Joseph Achor recorded brain-stem evoked potentials from a patient with a brain tumor of uncertain location. By comparing the patient's record with a normal brain-stem evoked potential it became evident that wave 2 (cochlear nucleus) and wave 3 (superior olive) were abnormally delayed and that all the waves after wave 3 were missing. The patient was later shown to have a tumor of the pineal gland that had destroyed structures in the midbrain but had spared the eighth nerve and the cochlear nucleus. Abnormally delayed brain-stem responses are also seen in some patients with multiple sclerosis, the disease in which the insulating myelin sheath of nerve fibers is progressively destroyed. Such abnormal evoked potentials, when they are added to other clinical signs and symptoms, can support a firm diagnosis of multiple sclerosis at an early stage of the disease.



BRAIN-STEM EVOKED POTENTIALS can be elicited by abrupt auditory stimuli. The upper trace shows a typical normal response. Seven distinct waves arise in the first 10 milliseconds after the stimulus click. The waves represent the sequential activation of nerves and auditory way stations in the brain stem. The lower trace was recorded from a patient with a tumor that had damaged his brain stem. All waves after third are absent and waves 2 and 3 are delayed. Recordings were made by Arnold Starr and Joseph Achor of University of California at Irvine.

Another application of brain-stem recording is in demonstrating an organic cause for symptoms that might otherwise be thought to be entirely psychogenic or even malingering. For example, Thomas J. Murray, John Noseworthy, John Miller and I studied patients with postconcussion syndrome. This syndrome is a group of distressing symptoms that occasionally follows a traumatic blow to the head and has the puzzling feature that there seems to be no physical injury adequate to account for the symptoms. We found that brain-stem evoked potentials were abnormally delayed in postconcussion patients, suggesting that the potentials might be a useful objective method for detecting organic damage in such patients.

Visual evoked potentials too can provide an aid to the diagnosis of multiple sclerosis. Even in patients who show no clinical signs of damage to the visual system the disease can slow the speed at which signals are transmitted from the eye to the visual cortex. In 1972 A. M. Halliday, W. I. MacDonald and Joan Mushin of the National Hospital in London and Geoffrey Arden of the Institute of Ophthalmology in London showed how this slowing could be measured by recording pattern-evoked potentials. The major response to visual-pattern stimulation is a wave that peaks about 100 milliseconds after the stimulus. In normal people the delay between the stimulus and the wave is virtually identical in the left and right eyes, but in patients with multiple sclerosis the positive wave is abnormally delayed in the affected eye. Pattern-evoked-potential recording has now been adopted in many hospitals throughout Europe and North America as an aid to the diagnosis of multiple sclerosis.

Although the first averaged evoked potentials recorded by Dawson were elicited by tactile stimulation, such somatosensory responses were until recently eclipsed by the study of visual and auditory responses. Over the past five years, however, there has been a revival of interest in somatosensory evoked potentials. They can be elicited either by a vibrating mechanical stimulator applied to the skin or a mild electric shock delivered immediately over a nerve in an arm or a leg. Roger Q. Cracco's group at the Jefferson Medical College in Philadelphia has developed methods of recording somatosensory evoked potentials in the spinal cord by means of surface electrodes placed over the spine. In addition W. B. Matthews and D. G. Small of Oxford and Cracco's group have succeeded in recording so-

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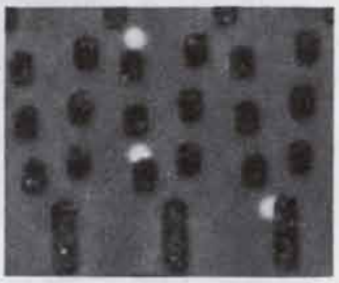

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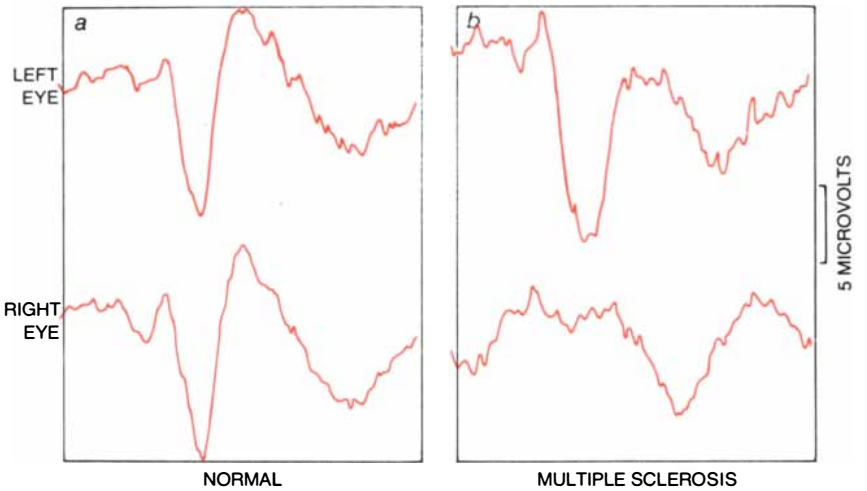


MULTIPLE SCLEROSIS gives rise to alterations in visual evoked potentials, which can aid in the early diagnosis of the disease. The evoked potentials elicited by stimulating the left and right eyes of a normal subject with a checkerboard pattern are shown in *a*. The major wave downward occurs at almost exactly the same moment in both eyes. Evoked potentials in a patient whose right eye had been affected by multiple sclerosis are shown in *b*. The major wave is considerably delayed in the affected eye, and its amplitude is reduced as well. Delayed evoked potentials are observed even when there is no other sign of visual damage. Recordings were made by A. M. Halliday, W. I. MacDonald and Joan Mushin of National Hospital in London.

matosensory responses from the brain stem. This research promises to provide a useful means of monitoring the development of the spinal cord and of testing its function at an early age. The fact that such methods are entirely free from risk or discomfort justifies determined efforts to overcome the formidable technical problems they present.

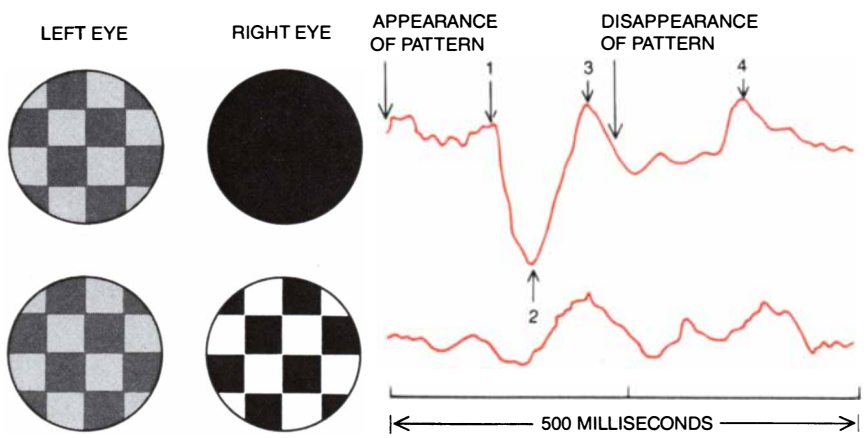
Perhaps the most promising medical application of evoked-potential recording is in assessing vision, hearing and brain function in infants and children. For example, pattern-evoked potentials have been employed to monitor the development of visual acuity during the first weeks and months of life. In 1971 Russell Harter of the University of North Carolina at Greensboro used evoked-potential recording to show that in the normal infant visual acuity is poor shortly after birth but that (given an appropriate visual environment) it improves progressively as the infant gets older, coming close to the adult level by the age of six months.

If in early life one eye sends degraded signals to the brain while the other eye sends normal signals, the visual cortex may not develop normally. (For example, infants with uncorrected farsightedness in one eye grow up with an imbalance between the left and the right eye.) Although vision in the defective eye could be corrected by the wearing of eyeglasses from early in life, eventually the poor vision cannot any longer be corrected by glasses because the visual cortex of the brain has developed abnormally. This condition, called amblyopia, is often associated with squint. Amblyopia can be cured if the correction is applied when the child is sufficiently young, but if the condition is left uncorrected too long, it is irreversible.

It is an easy matter to assess an adult's visual acuity by means of the familiar Snellen letter chart, but assessing an infant's acuity is much more difficult. In 1971, however, Henk Spekreijse, L. H. van der Tweel and Lee H. Khoe of the University of Amsterdam showed that pattern-evoked potentials could provide an objective measure of visual acuity. They found that patterns of small checks (with sides about .3 degree in length) elicit relatively weak evoked potentials in an amblyopic eye, but that patterns of larger checks (with sides about one degree in length) elicit evoked potentials of similar amplitude from both good and bad eyes. Samuel Sokol of the Tufts–New England Medical Center subsequently developed evoked-potential recording into a valuable tool for studying amblyopia.

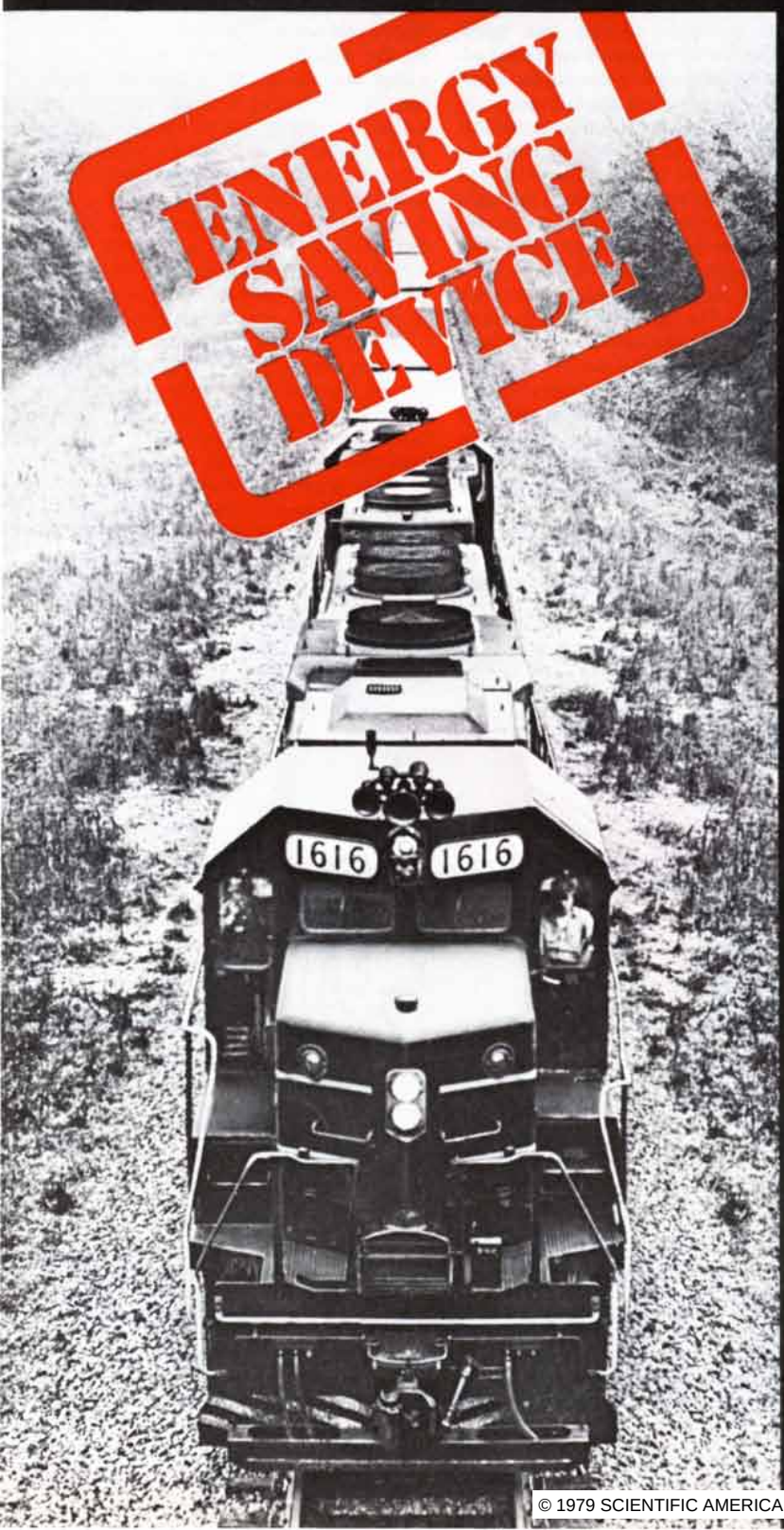
In medical studies on very young patients the investigator must immediately come to grips with the fact that infants have a limited reserve of patience and may become uncooperative if the recording session is not completed fairly quickly. The conventional recording method is for the infant to look at a pattern of small checks for about a minute while an evoked potential is being recorded and then to view a pattern of larger checks while a second potential is being recorded. In 1973 I developed a faster way to examine amblyopic children. The procedure differs from the conventional one in that the size of the checks is not fixed but changes continuously while the evoked potentials are being recorded. The pattern of checks oscillates from side to side four times per second, while simultaneously the size of each check increases from a six-minute arc to a 60-minute arc every 30 seconds. (A motion-picture cartoon is also superposed on the check stimulus to hold the child's gaze.) The evoked-potential analyzer plots a graph of the evoked potential over time; the graph is also a plot of the amplitude of the potential with respect to the size of the checks. With this method two evoked potentials, one for the child's good eye and one for the amblyopic eye, can be recorded in four minutes. Such evoked potentials can help the ophthalmologist to monitor the progressive improvement of an infant's vision during therapy for amblyopia.

When the visual acuity of one eye is severely degraded (and particularly



DEFECTIVE BINOCULAR VISION in children with amblyopia (poor vision that cannot be corrected with eyeglasses) can be detected with the aid of pattern-evoked-potential recording. The upper trace shows the evoked potential elicited in a subject with normal vision whose left eye was stimulated with a checkerboard pattern while the right eye was covered. Waves 1, 2 and 3 are components of the response to the presentation of the pattern; wave 4 is the response to the removal of the pattern. In the lower trace the right eye was steadily stimulated with a checkerboard pattern, which almost entirely suppressed the evoked potential elicited by stimulation of the left eye. Subjects with defective binocular vision do not show this effect. Traces were recorded by L. H. van der Tweel, Henk Spekreijse and the author at University of Amsterdam.

Myth:
Railroads waste a lot of energy.



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Surprise:
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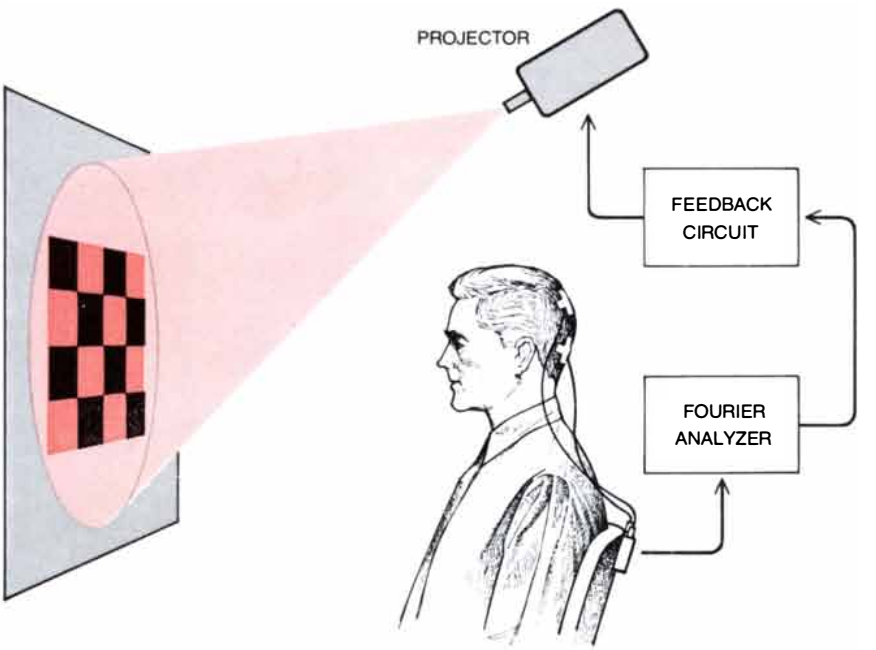
if that eye develops a squint), the ability to coordinate the left and right eyes may be reduced, with a consequent loss of stereoscopic depth perception. Although the ability to perceive objects in depth is a subtle visual function that is not easy to quantify, evoked-potential techniques have been refined to the stage where they can offer an objective assessment of stereoscopic vision in adults and even children.

First it is necessary to find out whether signals from the left and right eyes interact or whether the link between the two eyes has been entirely lost. Spekreijse, van der Tweel and I used evoked-potential recording to measure the interaction of signals from the left and right eyes when they came together in the visual cortex. We found that stimulating the left eye alone with a pattern elicited a clear evoked potential. When the right eye simultaneously viewed a bright, static checkerboard pattern, however, the evoked potential elicited by the stimulus to the left eye was almost entirely suppressed. The intensity of the static stimulus to the right eye that is sufficient to suppress the evoked potential in the left eye is a measure of the interaction of the two eyes. This suppressing effect is not present at all in people who lack binocular vision, and the effect is intermediate in individuals whose binocular vision is weak.

Even if the signals from the left and right eyes of a child can be shown to interact, however, it does not necessarily follow that the child has depth perception. Stereoscopic vision is mediated by specific nerve cells in the brain that are sensitive to the minute geometrical displacements between left and right retinal images arising from the seven-centimeter horizontal separation of the two eyes. Spekreijse and I, working at the University of Keele in England, showed that evoked-potential recording could be employed to measure specifically the activity of these cells.

Our major difficulty was proving that our evoked potentials were caused by changes in the location of the object in depth and not by associated movements of the object that could be seen with either eye alone. We solved the problem by employing a computer-generated pattern of the type developed by Bela Julesz of Bell Laboratories. When such a pattern is viewed through a pair of red and green glasses, each eye sees a pattern of randomly arranged dots. When the pattern is viewed with both eyes, however, a square region near the center of the pattern appears to be suspended in depth above the plane of the pattern.

With the aid of three slide projectors we were able to make the central square in the stereoscopic image appear to move back and forth in depth. Separate evoked potentials were elicited each time the square moved in depth toward or away from the subject. Kenneth Beverley and I found that the toward-and-away movements gave rise to slightly different evoked potentials, suggesting the existence of separate groups of neu-



EVOKED-POTENTIAL FEEDBACK has a number of speculative applications. In this experiment one eye of the human subject was stimulated with a pattern of red and black checks that moved up and down five times per second. A Fourier analyzer set at the same frequency recorded moment-to-moment values of the amplitude of the steady-state evoked potential from the visual cortex. By means of a feedback circuit the amplitude of the evoked potential was kept constant at about six microvolts by controlling the visibility of the checkerboard stimulus. (This was done by varying the brightness of a patch of yellow light projected on top of it.) Subject was thus in a feedback loop in which his brain responses controlled strength of stimulus.

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rons that are sensitive to the two directions of movement in depth. Cynader and I subsequently verified this prediction by recording from single neurons in the visual cortex of an anesthetized cat. Recording stereoscopic evoked potentials from infants with our technique would be impractical because it is difficult to control the direction of an infant's gaze, but Julesz and Dietrich Lehmann recently developed a method that makes such tests possible. With the aid of a computer they can create a stereoscopic stimulus on the six-foot screen of a television projector. The infant views the screen at close range, so that the direction of its gaze is relatively unimportant.

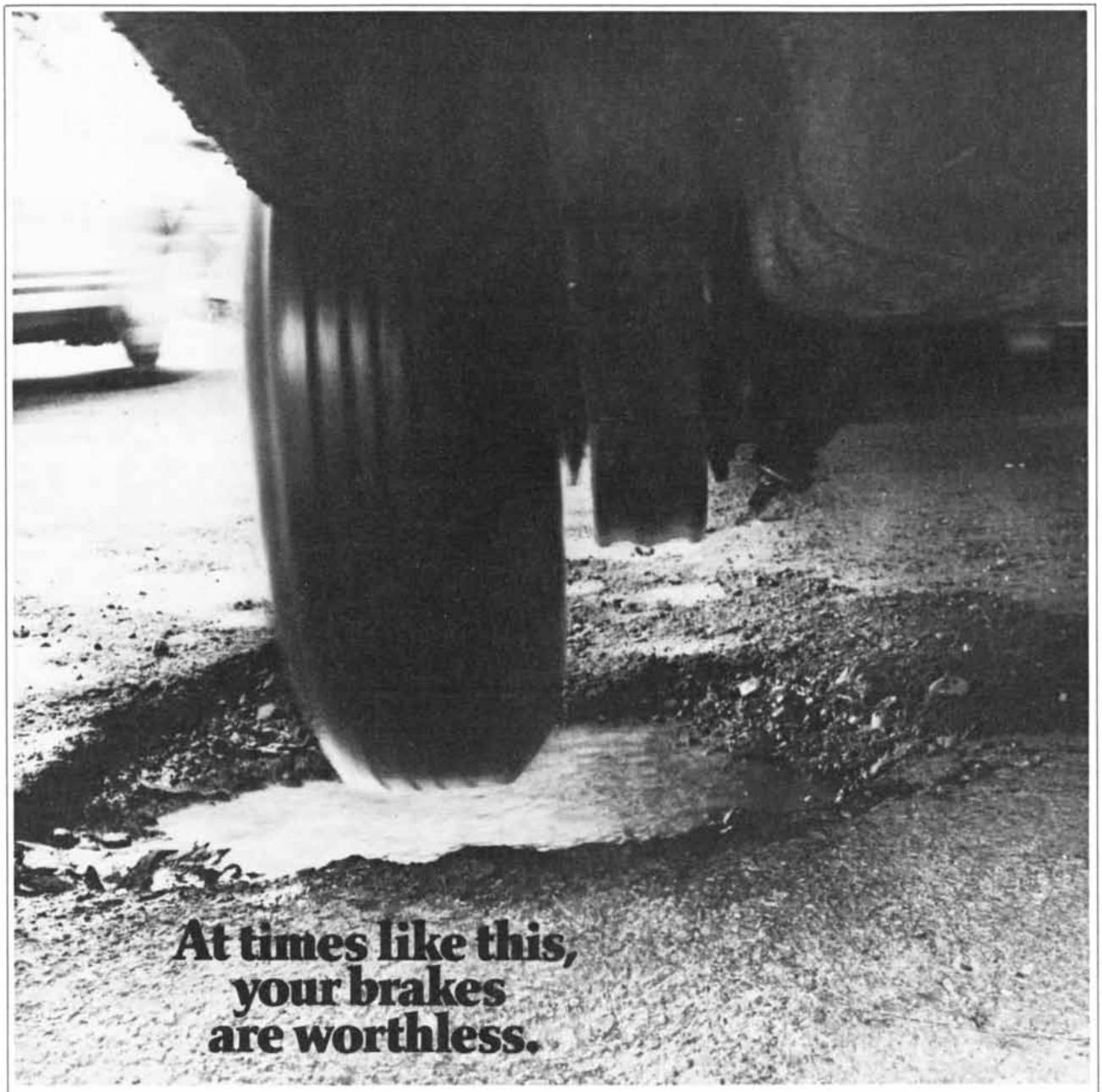
Evoked potentials can also be employed to test color vision. About 8 percent of the total male population are born with defective color vision. In everyday life this congenital disorder is seldom more than inconvenient, but acquired defects of color vision are an early symptom of several eye diseases and hence can provide a useful aid to diagnosis. Although it is fairly easy to roughly assess the color vision of a cooperative adult, it is difficult to do so in infants, and even with adults precise quantitative measurements of color vision are lengthy and difficult.

With these problems in mind, Harry G. Sperling of the University of Texas, Spekreijse and I developed an evoked-potential test for color vision. The stimulus was a yellow patch of light that changed abruptly into a pattern of small red and green checks. The brightness of the red, green and yellow areas was exactly equal, so that the pattern was entirely defined by the color differences. Any evoked potential elicited by the pattern would therefore be due entirely to the color change. As we had predicted, evoked responses to the color pattern were present in subjects with normal color vision but not at all in color-blind subjects. The technique provides a sensitive objective test for color blindness that reveals both the type and the severity of the defect.

This work led to a more exotic experiment: a feedback loop in which the subject's electrical brain responses directly control what he sees. I developed such a system in order to study the perceptual channels involved in the sensitivity of the visual system to fine detail. In the device one eye was stimulated with a pattern of red and black checks that moved up and down five times per second. Electrodes attached to the scalp over the visual cortex fed into a Fourier analyzer, which extracted the steady-state evoked potential from the electroencephalogram. The frequency of the evoked potential was also exactly five cycles per second. Moment-to-moment measurements of the amplitude of the potential drove a feedback circuit that controlled the intensity of a disk of yellow light that was superposed on the checkerboard stimulus. If the amplitude of the evoked potential got larger than some preset value (say six microvolts), the feedback circuit increased the intensity of the yellow disk of light until the checkerboard pattern was less apparent, so that the amplitude of the pattern-evoked potential dropped back to six microvolts. Conversely, if the amplitude of the evoked potential fell below six microvolts, the feedback circuit reduced the intensity of the yellow light until the amplitude of the pattern-evoked potential returned to the preset level.

The brain was therefore in a feedback loop, in which the fluctuations of the amplitude of the pattern-evoked potential were automatically corrected by changes in the intensity of the yellow disk. The subjective experience was strange and slightly disturbing. If the subject consciously tried to blur the stimulus pattern by defocusing his eye, the pattern became fainter and blurred for only a moment; then the feedback circuit altered the stimulus and the pattern returned to its former contrast. In this situation the subject became aware that he had lost some of the conscious control over the visual environment that is normally taken for granted. Evoked-potential feedback had transferred some of this control to the primary visual cortex.

Over the past 20 years devices for recording evoked potentials have progressed from pioneering instruments (often constructed from World War II junk) to powerful computers, which can be employed not only to dissect the perceptual activities of the brain but also to explore higher mental functions such as attention and expectancy. One aspect of evoked-potential research, however, has remained unchanged: the search for objective methods of detecting and diagnosing diseases of the central nervous system. Over the past five years evoked-potential recording has become widely accepted as a valuable diagnostic aid in patients with multiple sclerosis, deafness and suspected brain tumor. Current research is aimed at making evoked-potential tests more specific, and the impact of the new microprocessor-chip technology will shortly provide new and powerful evoked-potential analyzers at low cost. It seems likely that over the next five years some of the more specific evoked-potential tests will begin to replace some of the traditional sensory tests used by neurologists, ophthalmologists and otolaryngologists, and that evoked-potential methods will be employed routinely to examine child patients with diseases of the central nervous system that affect vision, hearing and the spinal cord, such as squint, "minimal brain damage" and disorders of learning.



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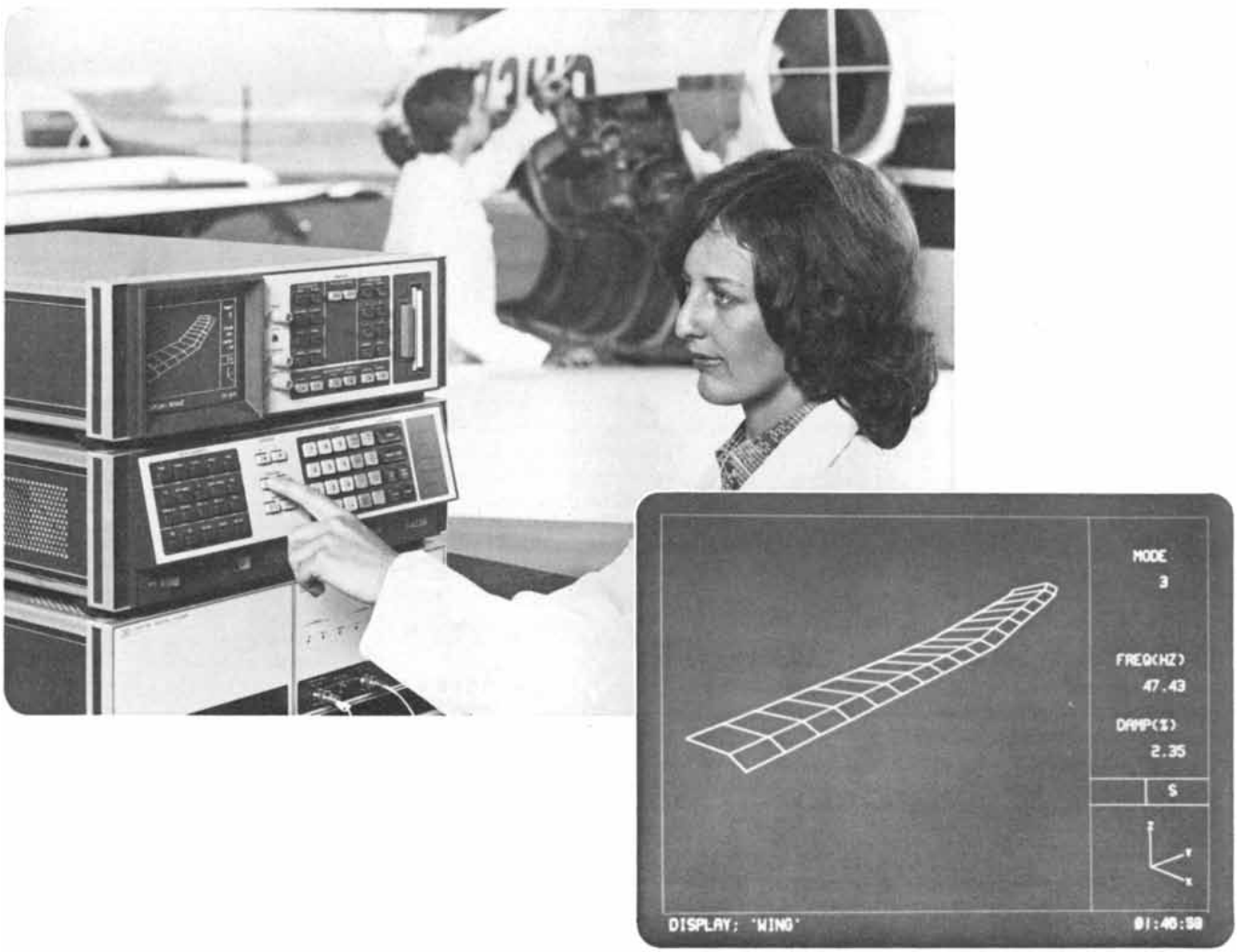

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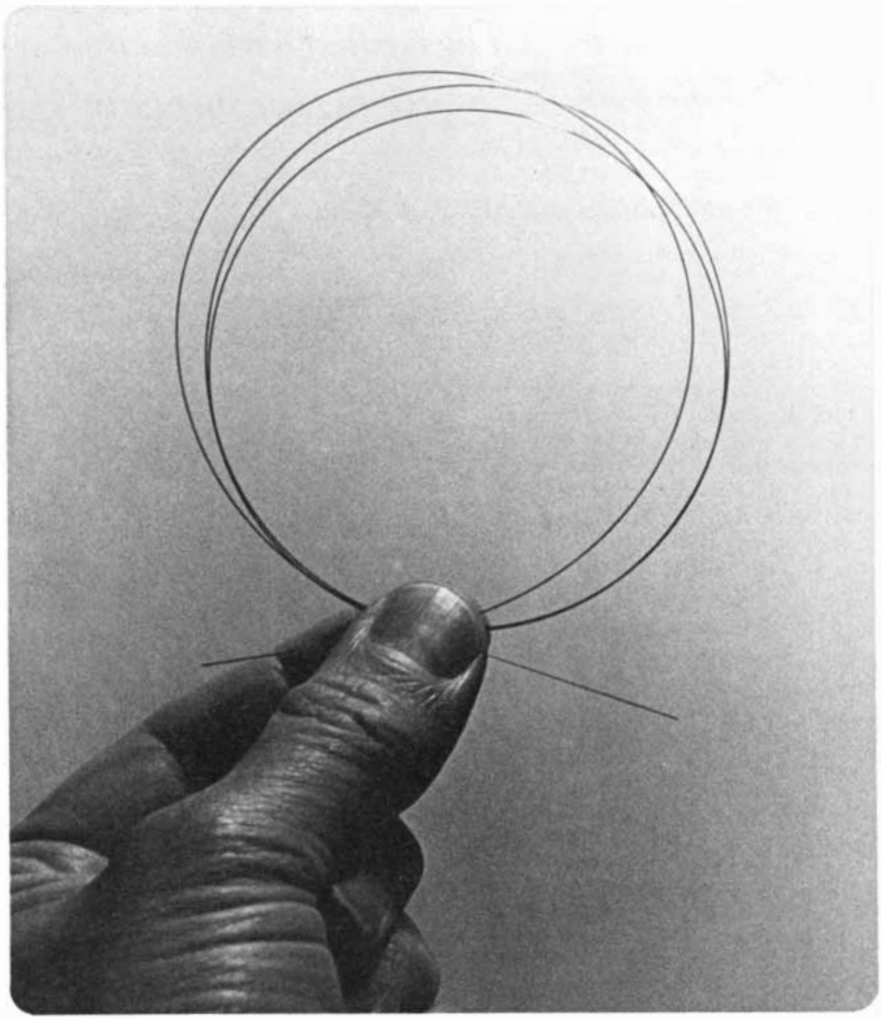

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The Decay of the Vacuum

Near a superheavy atomic nucleus empty space may become unstable, with the result that matter and antimatter can be created without any input of energy. The process might soon be observed experimentally

by Lewis P. Fulcher, Johann Rafelski and Abraham Klein

The vacuum is ordinarily defined as a state of absence: a vacuum is said to exist in a region of space if there is nothing in it. In the quantum field theories that describe the physics of elementary particles the vacuum becomes somewhat more complicated. Even in empty space matter can appear spontaneously as a result of fluctuations of the vacuum. For example, an electron and a positron, or antielectron, can be created out of the void. Particles created in this way have only a fleeting existence; they are annihilated almost as soon as they appear, and their presence can never be detected directly. They are called virtual particles in order to distinguish them from real particles, whose lifetimes are not constrained in the same way and which can be detected. Thus it is still possible to define a vacuum as a space that has no real particles in it.

One might expect that the vacuum would always be the state of lowest-possible energy for a given region of space. If an area is initially empty and a real particle is put into it, the total energy, it seems, should be raised by at least the energy equivalent of the mass of the added particle. A surprising result of some recent theoretical investigations is that this assumption is not invariably true. There are conditions where the introduction of a real, massive particle into an empty region of space can reduce the total energy. If the reduction in energy is great enough, an electron and a positron will be created. Under these conditions the electron and positron are not vacuum fluctuations but are real particles, which exist indefinitely and can be detected. In other words, under these conditions the vacuum is an unstable state and can decay into a state of lower energy, in which particles exist.

The essential condition for the decay of the vacuum is the presence of an intense electric field. As a result of the decay of the vacuum the space permeated by such a field acquires an electric charge, and it can be called a charged vacuum. The particles that materialize in the space make the charge manifest. An electric field of sufficient intensity to create a charged vacuum is likely to be found in only one place: in the immediate vicinity of a superheavy atomic nucleus, one with about twice as many protons as the heaviest natural nuclei known. A nucleus that large cannot be stable, but it might be possible to assemble one for long enough to observe the decay of the neutral vacuum. Experiments that will test this possibility are now under way.

The process that gives rise to the charged vacuum can be understood by considering the binding energy of an electron in an atom. The binding energy is the energy needed to remove the electron to an arbitrarily large distance from the nucleus. The same quantity of energy is given up (as light or some other form of electromagnetic radiation) when a remote electron binds to the nucleus. For the hydrogen atom the binding energy of an electron in the ground state is 13.6 electron volts. (One electron volt is the energy acquired by an electron when it is accelerated through a potential difference of one volt.) Hence 13.6 electron volts must be supplied in order to remove the electron, or ionize the atom; when a proton and a distant electron combine to form a hydrogen atom, electromagnetic radiation with a total energy of 13.6 electron volts is given off.

Because of the equivalence between energy and mass expressed by the formula $E = mc^2$ (energy equals mass times the speed of light squared) the binding energy can also be interpreted as a binding mass. Indeed, it is convenient simply to express all masses in the same units employed for energies. Accordingly if a proton and an electron are both weighed separately, and if the hydrogen atom formed when they combine is then weighed, the total mass will be found to be 13.6 electron volts less; the intact atom weighs less than its constituent parts. As stated above, the mass difference is carried away as energy by electromagnetic radiation.

The hydrogen binding energy of 13.6 electron volts is a small fraction of the rest mass of the electron, which is 511,000 electron volts, or about .5 MeV. (One MeV is a million electron volts.) The binding energy increases, however, along with the positive charge of the atomic nucleus. Such an increase is to be expected since a greater nuclear charge gives rise to a more intense electric field, and so the electron is bound more strongly. The nuclear charge is given by the atomic number, Z, which is equal to the number of protons in the nucleus. For light nuclei the binding energy grows in proportion to Z^2, and for heavy nuclei relativistic effects lead to a still more rapid increase. As a result the binding energy becomes a significant quantity for electrons bound to large nuclei. For the heaviest stable elements, which have atomic numbers approaching 100, the binding energy of the electrons nearest the nucleus is more than 20 percent of the electron's rest mass

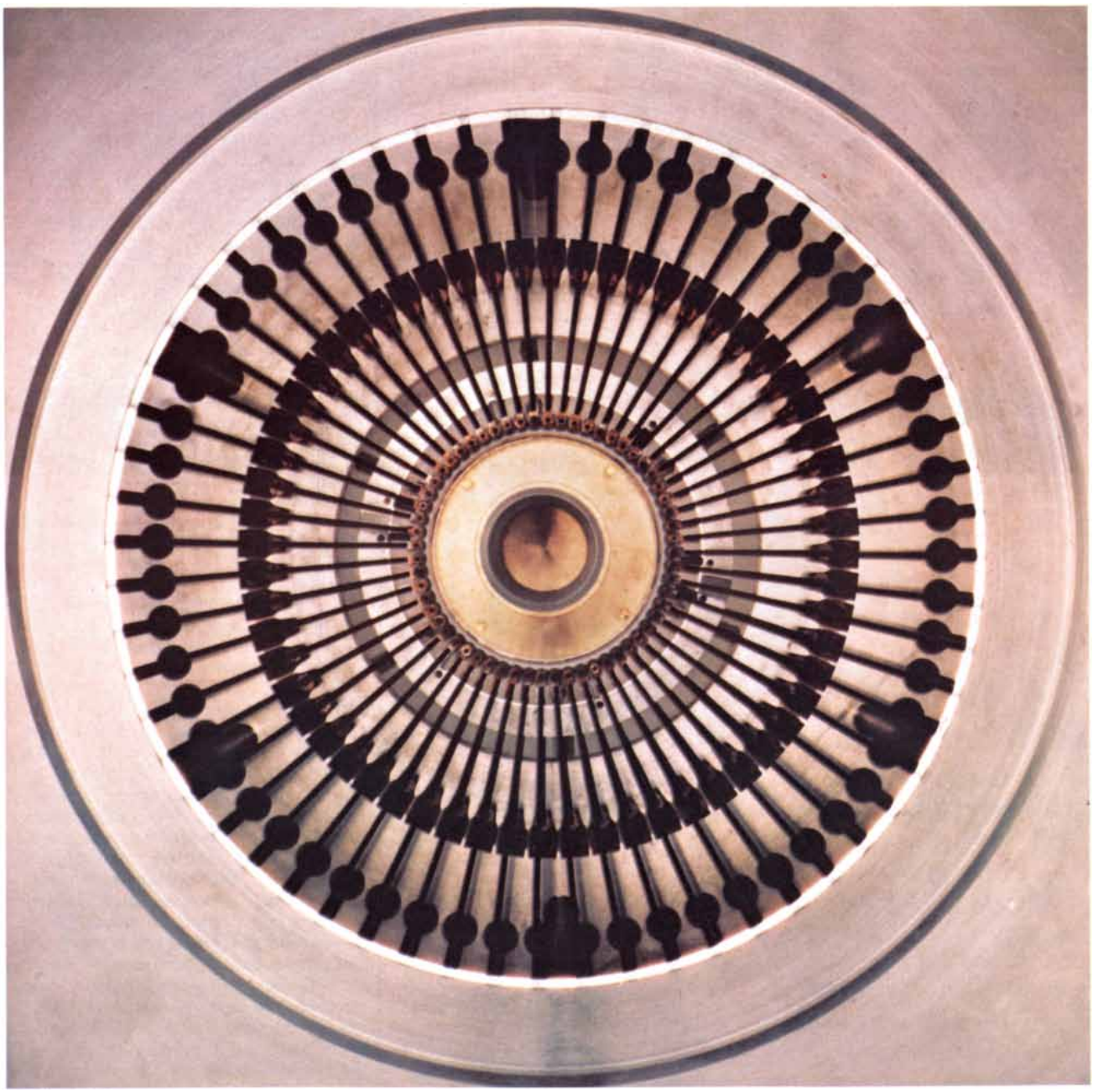
What would happen if Z could increase without limit, so that very highly charged nuclei could be created? The calculation of the binding energy is simplest if all the nuclear charge is considered to be concentrated at a point. Given that condition, the binding energy is found to be equal to the rest mass of the electron for a nucleus with Z equal to 137. At this point the theory begins to make ambiguous predictions, whose interpretation is uncertain. The source of the difficulty can be traced to the assumption of a point nuclear charge. It is a reasonable approximation for the hydrogen atom, where the nucleus is small (a single proton) and the electron spends most of the time far away from it. As Z increases, however, the nucleus itself grows somewhat larger and, what is more important, the orbitals that define the spatial distribution of the electrons shrink dramatically. For atomic numbers greater than 100 the electrons in

the innermost orbitals spend a significant fraction of their time near the nucleus. The point-charge assumption is therefore unrealistic.

By taking into account the effects of a finite nuclear size the calculation of the binding energy can be extended to values of Z greater than 137. The importance of the nuclear radius to the validity of the theory was first noted by Isaak Y. Pomeranchuk and Ya. A. Smorodinskii and was discovered independently by several other investigators. The work of W. Pieper and Walter Greiner in 1968 was particularly important in that it stimulated much of the subsequent study of the strong fields near superheavy nuclei.

One effect of spreading the charge of the nucleus throughout a small volume instead of concentrating it at a point is to reduce the intensity of the nuclear electric field. As a result the binding energy for a given value of Z is also reduced. For the electrons in the orbital designated $1s_{1/2}$, which is the innermost, lowest-energy orbital, the binding energy becomes equal to the rest mass of the electron when Z reaches a value near 145.

It is intriguing to contemplate the electronic structure of such an atom. Suppose it could be stripped of all its electrons, so that the $1s_{1/2}$ orbital was



DETECTOR OF POSITRONS, or antielectrons, has been employed in the experimental search for events signaling the decay of the vacuum. The portion of the detector visible here consists of 60 small coils, each of which generates a toroidal magnetic field. Positrons are directed by the fields into the central well, where they encounter electrons and are thereby annihilated. The resulting gamma rays, or high-energy photons, give rise to scintillations that can be registered electronically. The device is called the orange spectrometer because of its segmented structure and because it focuses the positrons at a point that is structurally analogous to the navel of an orange. It is one of three detectors constructed for such experiments at the Gesellschaft für Schwerionenforschung (GSI) at Darmstadt in West Germany.

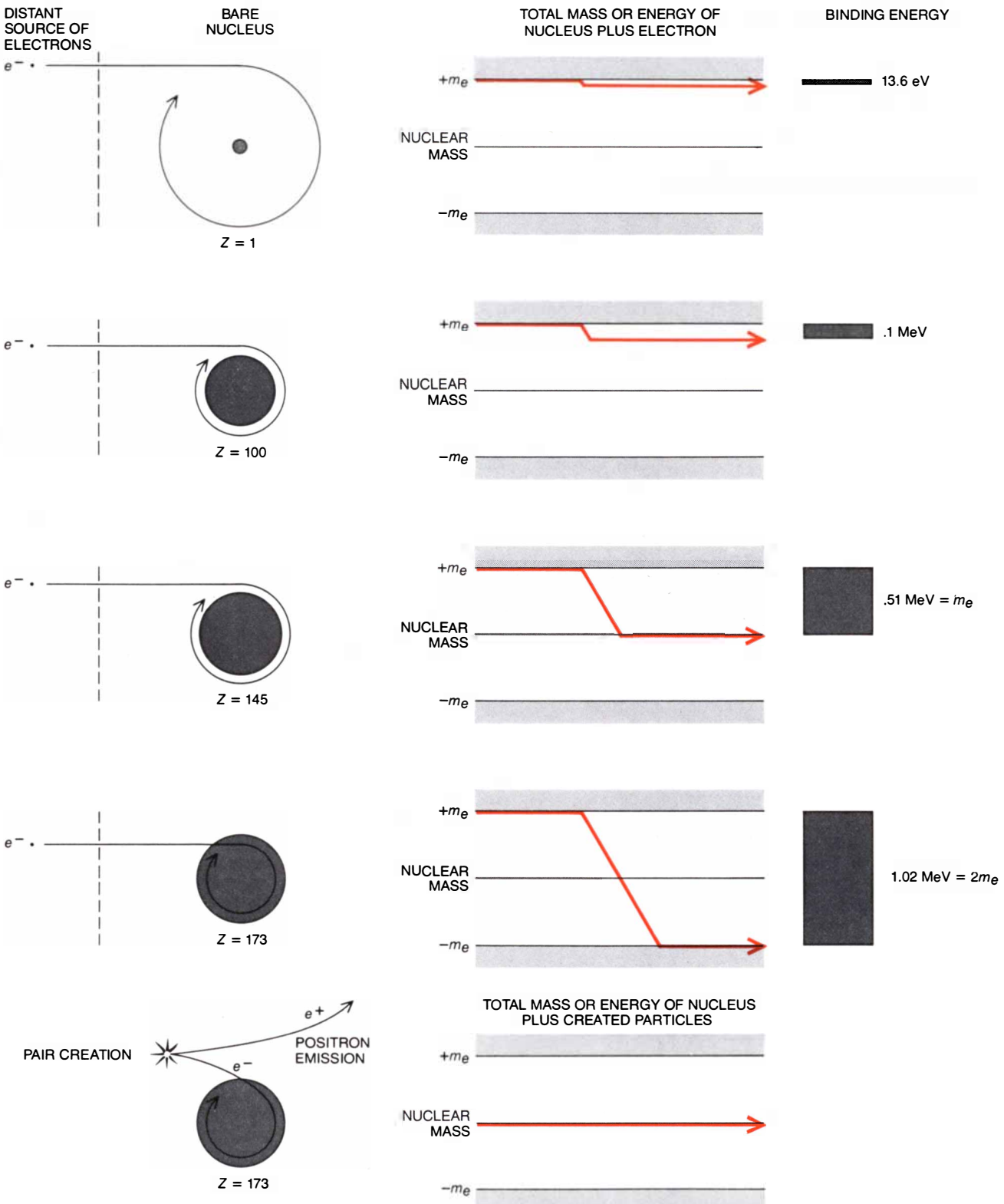
vacant. An electron could then be allowed to approach the bare nucleus from some distant site and fall to the $1s_{1/2}$ level. In the course of binding to the nucleus the electron would radiate away an amount of energy equivalent to its entire mass, with the curious result that no mass would be added to the atom. The presence of the electron could be detected by a decrease in the net positive charge of the atom, but the mass of the nucleus would remain the same whether the electron was present or absent. Indeed, two electrons could be added or removed without alteration of the atomic mass, since the $1s_{1/2}$ orbital can hold two electrons, which have the same energy.

Still stranger phenomena can be expected when the atomic number is increased further. When Z exceeds 145, the binding energy for the $1s_{1/2}$ orbital is greater than the mass of an electron; adding the electron therefore diminishes the mass of the atom. A system made up of more particles weighs less. It would be energetically advantageous for an electron to be created in the vicinity of the atom, thereby reducing the total energy embodied in the nucleus and the electron, but that is not possible. The law of nature that requires electric charge to be conserved forbids it. For the reduction in mass or energy to be achieved, the electron must be supplied from some external source.

When Z reaches 173, another threshold is crossed. For nuclei with a charge greater than that the binding energy of an electron in the $1s_{1/2}$ orbital is equal to or greater than the rest mass of two electrons. It is at this point the neutral vacuum becomes unstable and the charged vacuum appears. The value $Z = 173$ is called the critical charge.

The rest mass of two electrons is exactly equal to the rest mass of one electron and one positron. It follows that when Z is equal to 173, an electron-positron pair can be created with no expenditure of energy. When Z is greater than 173, the creation of the particle and antiparticle reduces the total energy of the system. The spontaneous appearance of such a pair is not forbidden by any conservation law; most notably electric charge is conserved in this process, since a particle and its antiparticle are created simultaneously. Hence pair creation is to be expected as soon as Z exceeds the critical charge. The electron becomes bound in the $1s_{1/2}$ orbital and the positron, being repelled by the nucleus, escapes.

The same process can be analyzed from another point of reference. The minimum energy needed to create an electron-positron pair near a nucleus is the rest mass of the pair minus the binding energy of the electron. For the hy-



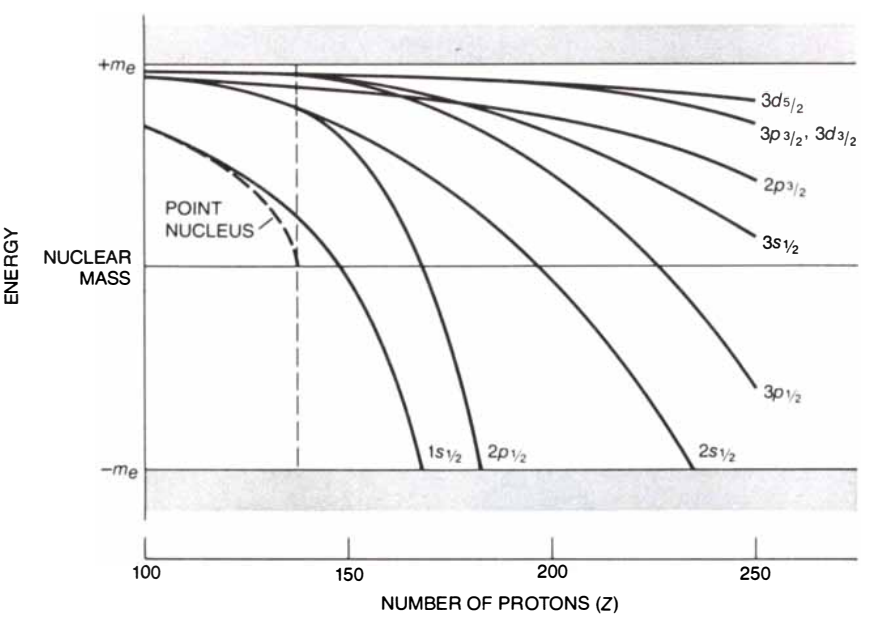
BINDING ENERGY is given up when an electron becomes bound in an atom, so that the mass of the atom is less than the combined masses of the electron and the nucleus. For the hydrogen atom, where Z, the number of protons, equals 1, the loss of mass is 13.6 electron volts. (The electron volt is a unit of energy, and so it expresses a mass in terms of the equivalent energy.) That is a small fraction of the electron's rest mass (m_e), which is about .5 MeV (million electron volts). For the largest stable nuclei, with Z approaching 100, the binding energy is about 20 percent of m_e, and at $Z = 145$ the binding energy becomes equal to m_e. Thus an electron would radiate away all its energy when binding to a nucleus with 145 protons, and the mass of the atom would not be increased by the addition of the electron. At $Z = 173$ the binding energy reaches twice m_e and it becomes energetically favorable for an electron and a positron to be created. The electron remains bound to the nucleus and the positron is repelled, so that it can escape and be detected. For any nuclear charge greater than 173 the state of lowest possible energy includes at least two such electron-positron pairs. The spontaneous creation of matter and antimatter can be interpreted as the decay of the vacuum surrounding the nucleus; the state that results is called the charged vacuum.

drogen atom this energy amounts to twice the electron mass, or 1.02 MeV, minus 13.6 electron volts, a trivial quantity. As the binding energy increases, the energy deficit that must be made up from some external source diminishes. At $Z = 145$ it is equivalent to one electron mass and at $Z = 173$ it falls to zero, so that no energy is needed to create an electron-positron pair. With a still larger nuclear charge energy is liberated when the pair materializes.

If events of this kind could be observed under ideal conditions, they would have a simple appearance. The ideal experimental system would be a bare nucleus (one without bound electrons) whose charge increased slowly from just under the critical value to just over it. Pair creation would be signaled by the appearance of the positron, which would be expelled from the atom and could be detected with a suitable instrument. The electron, remaining bound in the innermost orbital, would not be observed directly, but it would cause the effective charge of the nucleus to decrease by one unit. Thus all that can be perceived is that the atom loses one unit of positive charge, which is carried off by the positron.

The critical charge marks the boundary between two realms of disparate phenomena. Below this threshold, energy is required to create an electron-positron pair, and in the absence of externally supplied electrons the neutral vacuum is the state of lowest energy: the ground state. When the critical charge is exceeded, an electron-positron pair can be freely created, and the state of lowest energy includes these particles. One of us (Rafelski), Berndt Müller and Greiner have suggested the name "charged vacuum" for this latter state. It is important to note that the overall charge remains zero, since the particles created have opposite charges. The electron and the positron can become widely separated, however, leaving an effective negative charge in the region near the nucleus.

The charged vacuum differs fundamentally from the charged state associated with an electron bound to an undercritical nucleus, such as the $1s_{1/2}$ electron of a hydrogen atom. If the electron is removed from a hydrogen atom, the result is a stable neutral vacuum, which will persist indefinitely as long as the electron is not restored. If, on the other hand, the electronic charge is removed from the vicinity of an overcritical nucleus, the neutral vacuum that results is inherently unstable. It will decay spontaneously by pair creation, restoring the electronic charge and emitting the positron. In the intense electric field surrounding an overcritical charge the neutral vacuum is no longer the ground state. The favored state of lowest energy, to which the system will always return after it has been perturbed, consists



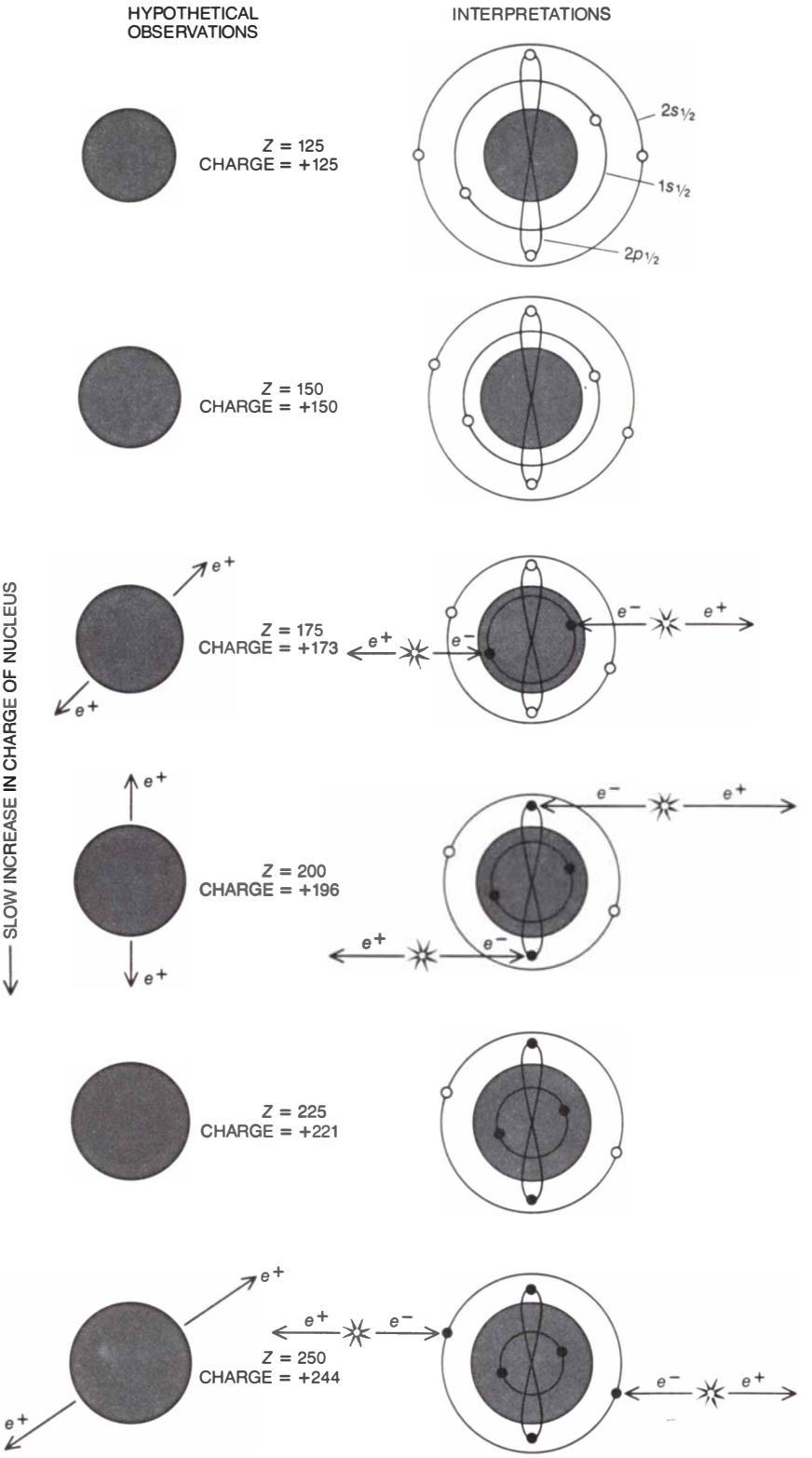
ENERGIES OF BOUND STATES of electrons in atoms decline steadily as the nuclear charge increases. The bound states are identified by the orbitals that define the distribution of the electrons. The innermost orbital, which has the lowest energy, is labeled $1s_{1/2}$; the next-lowest is $2p_{1/2}$, and the next is $2s_{1/2}$. If all the nuclear charge is assumed to be concentrated at a point (*broken curve*), the theoretical prediction of the electronic structure becomes ambiguous at $Z = 137$. With the more realistic assumption of a finite nuclear size (*solid curve*) the binding energy of the $1s_{1/2}$ orbital reaches twice m_e when Z is equal to about 173. That value of Z is the critical charge for the innermost orbital, where any vacancies can be filled by spontaneous creation of an electron and a positron. Orbitals at a greater distance from the nucleus have a higher critical charge. For the $2p_{1/2}$ state it is about 184, for the $2s_{1/2}$ state about 235.

of the charged vacuum and a positron. Paradoxically the vacuum near an overcritical charge is a vacuum that cannot be emptied.

The decay of the neutral vacuum cannot take place instantaneously. Like all events in quantum mechanics the creation of the electron-positron pair is a probabilistic event, and there is no way to predict exactly when it will happen; all that can be stated is the probability of pair creation at any given moment. The expected or typical time required for positron emission is determined indirectly by the energy available for the process. When the nuclear charge is precisely equal to the critical value, it is a matter of indifference, with respect to the energy of the system, whether the pair is created or not. As the nuclear charge continues to grow beyond $Z = 173$ the decay of the vacuum is not merely allowed energetically but becomes favorable. In other words, excess energy is given up when the electron-positron pair materializes. The time required for the decay varies in inverse proportion to the energy excess. For nuclei whose charge is well above the critical level positron emission becomes a very rapid process. At $Z = 184$, for example, the expected decay time is about 10^{-19} second.

When the charge of a bare nucleus first exceeds the critical value, two positrons should be emitted. Again the reason is that the $1s_{1/2}$ orbital can accommodate two electrons. With further increases in charge the binding energy of other orbitals becomes greater than twice the electron mass, and so additional electron-positron pairs are created in stages. The next orbital to join the charged vacuum is the one designated $2p_{1/2}$; the binding energy for electrons in this orbital exceeds the rest mass of an electron and a positron at a nuclear charge of about 184. At a nuclear charge of about 235 a third orbital, labeled $2s_{1/2}$, goes under. Hence if the charge of a bare nucleus could be gradually increased at will, two positrons would be emitted at $Z = 173$, two more at $Z = 184$ and two more at $Z = 235$; at the conclusion of this experiment the vacuum in the region surrounding the nucleus would have a charge of -6.

Some 60 units of charge must be added to the nucleus in order to engulf the first three atomic orbitals in the charged vacuum. It would therefore appear that the vacuum charge cannot keep up with the charge of the nucleus. Higher orbitals, however, are more closely spaced in energy and on the average can hold larger numbers of electrons per orbital, so that they reach the critical level for the decay of the neutral vacuum faster. The calculation of the properties of the electrons in still higher orbitals then be-



DECAY OF THE NEUTRAL VACUUM surrounding a superheavy nucleus would proceed in stages as the critical charge for each orbital was exceeded. A bare nucleus (one without bound electrons) is to be imagined as slowly increasing in positive charge. Nothing is observed until Z exceeds 173; then two positrons are emitted and the effective nuclear charge, observed at long range, decreases by two units. The interpretation of these events is that two pairs of electrons and positrons were created. The positrons escaped, but the electrons filled the two vacancies in the innermost, $1s_{1/2}$ orbital, where they effectively screen or cancel part of the nuclear charge. When Z passes 184, two more positrons appear, and the corresponding electrons fill the $2p_{1/2}$ orbital. No more positrons are observed until the number of protons is greater than 235, where pair creation fills the $2s_{1/2}$ orbital. The effective nuclear charge is then diminished by six units.

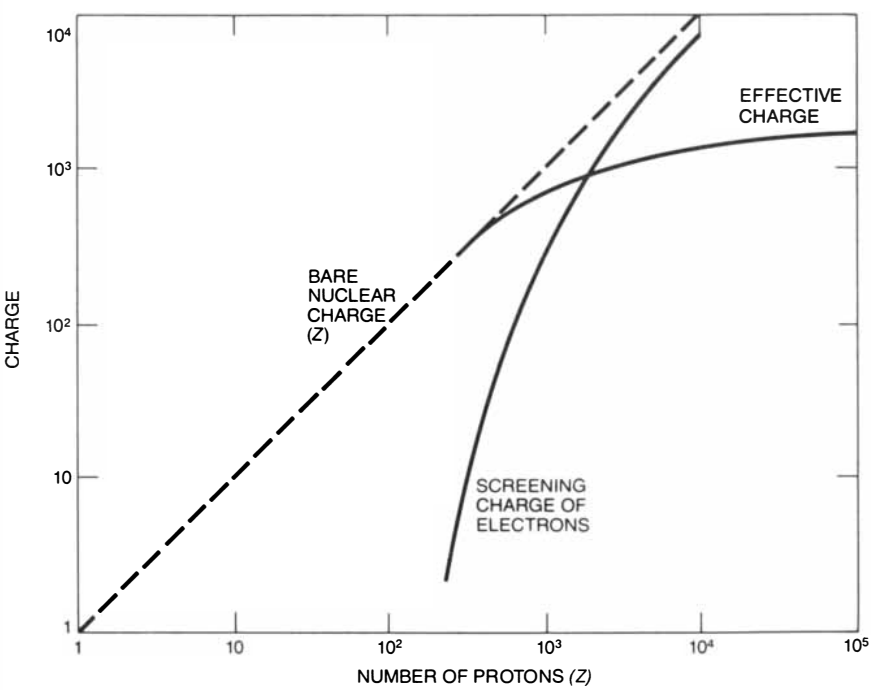
comes more complicated because the vacuum charge itself makes an important contribution to the potential that determines the motion of the electrons. The negative vacuum charge tends to screen a part of the nuclear charge, thereby reducing the effective potential. For strong fields, predicting the state of a single electron inevitably becomes a many-body problem.

For very high values of Z Müller and one of us (Rafelski) have shown that the vacuum charge increases roughly as fast as the nuclear charge. For example, if a nucleus with a charge of 10,000 could be assembled under suitable conditions, it would accumulate a vacuum charge of about $-9{,}000$. The 9,000 positrons would be emitted in an interval of less than 10^{-18} second. Most of the vacuum charge would be confined to a radius of about 100 fermis from the center of the nucleus. (One fermi is 10^{-13} centimeter.) Beyond that distance, therefore, 90 percent of the nuclear charge would be effectively neutralized. To a distant observer the nucleus would seem to have a charge of only 1,000.

It is unlikely that a nucleus with a charge of 10,000 could be held together for even 10^{-18} second, but a nucleus that is at least slightly overcritical might well be assembled. The essential tool for such an experiment is the heavy-ion accelerator, where the nuclei of elements as heavy as uranium ($Z = 92$) and californium ($Z = 98$) can be formed into an intense beam and given an energy of as much as 10 MeV per unit of atomic mass. Most particle accelerators generate beams of lighter projectiles, such as individual protons or electrons.

The technology of heavy-ion accelerators is comparatively new. At present only one machine is able to reach high energy and high beam intensity when accelerating the heaviest nuclei. It was built under the direction of Ch. Schmelzer at the Gesellschaft für Schwerionenforschung (GSI) at Darmstadt in West Germany. Several other laboratories may soon have this capability. One stimulus to the investigation of heavy-ion interactions has been the long-standing speculation that certain superheavy nuclei may be stable or at least long-lived. These "islands of stability" would be found near atomic numbers 126 and 164. It is not too large a step from there to overcritical nuclei.

The method for creating such large aggregations of nuclear matter is to accelerate the nuclei of a heavy element, such as uranium, and allow them to collide with equally heavy or even heavier nuclei in a stationary target. For collisions of uranium with uranium the largest nucleus that could conceivably be created would have an atomic number



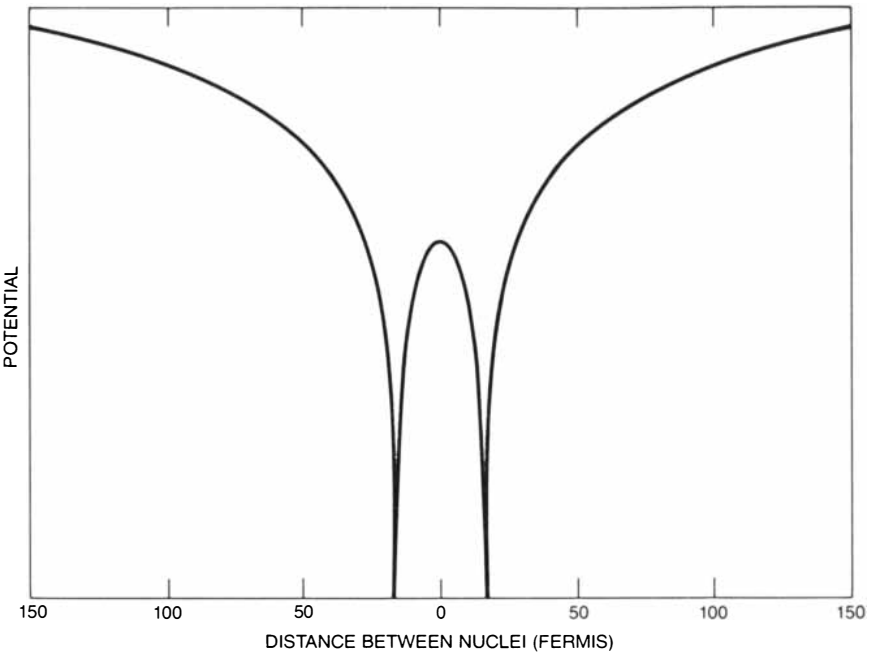
SCREENING OF THE NUCLEAR CHARGE would have a major influence on the observed properties of very large aggregates of nuclear matter. Initially the nuclear charge grows much faster than the compensating vacuum charge: some 60 protons must be added in order to fill the first three orbitals with spontaneously created electrons. Higher orbitals, however, are more closely spaced in energy and on the average hold more electrons, so that the vacuum charge rises faster. If a nucleus with 10,000 protons could be assembled, some 9,000 electron-positron pairs would be created, and the vacuum charge would screen 90 percent of the nuclear charge.

of 92 + 92, or 184. For collisions of californium with californium the upper limit is 196.

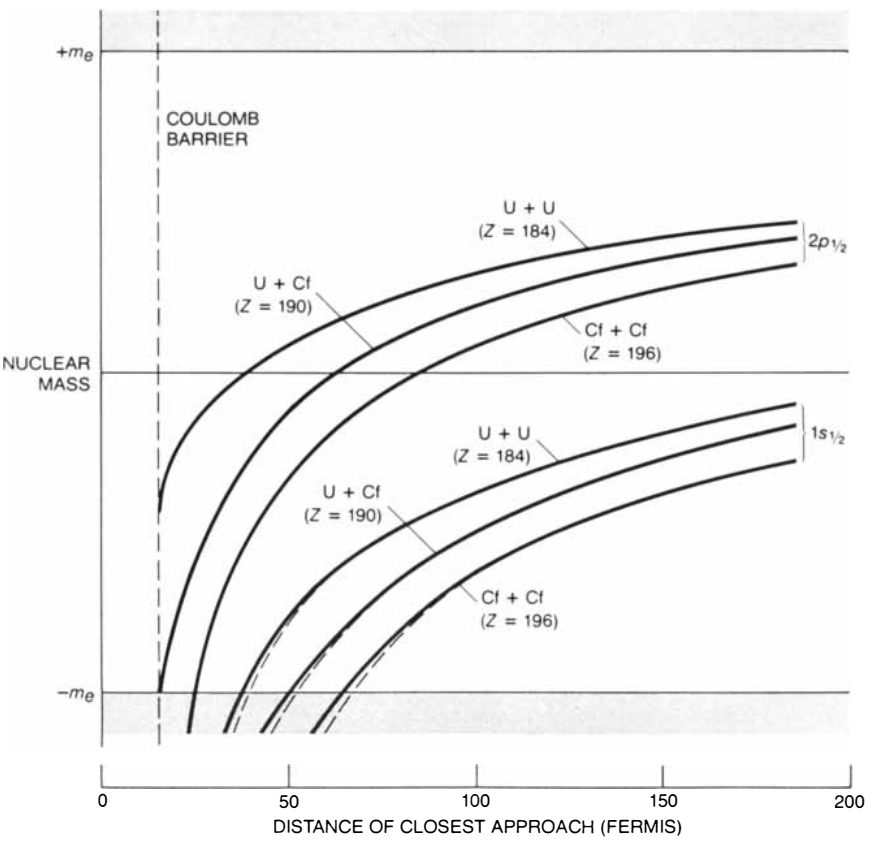
It is not expected that nuclei this massive and this highly charged would be stable or even that they would survive long enough to be detected as recognizable nuclei. In order to observe the decay of the neutral vacuum, however, it is not necessary that the two nuclei actually merge. They need merely approach each other to within a distance that is small compared with the radius of the atomic orbitals.

The repulsive force between two nuclei, which results from their electric charges, grows rapidly as their separation is reduced. In collisions between uranium atoms with a beam energy of 5 or 6 MeV per unit of atomic mass, much of the repulsion can be overcome. In a few percent of the collisions, in which the nuclei happen to meet almost head on, the distance of closest approach is comparable to the diameter of the nucleus. During such a collision the velocities of the nuclei are typically about 10 percent of the speed of light, whereas the electron velocities are much greater, approaching the speed of light. As a result it is reasonable to assume that the motions of the electrons adjust gradually to the changing electric fields of the moving nuclei. Moreover, each electron can be considered to be bound in the potential generated by both nuclei. The situation is much like that in a diatomic molecule, where the electrons are shared by two nuclei. The resulting structure is called a quasi-molecular state. This model has been verified experimentally through the detection of X rays emitted by electrons in the inner orbitals of quasi-molecular states. The X-ray studies were carried out by Walter E. Meyerhof of Stanford University and by K. H. Kaun of the Joint Institute for Nuclear Research at Dubna in the U.S.S.R.

During heavy-ion collisions the binding energy of the electrons in the innermost orbitals rises steadily as the distance of closest approach is reduced and the electric field becomes more like that of a single overcritical nucleus. For any given pair of beam and target nuclei there is a critical separation where the binding energy becomes equal to twice the electron mass. Müller, one of us (Rafelski) and Greiner have calculated that distance for a number of orbitals and nuclei. In uranium-uranium collisions the critical separation for the $1s_{1/2}$ orbital, where any vacancies in this state will be filled by electron-positron creation, is about 34 fermis. That is roughly twice the diameter of a uranium nucleus. None of the other quasi-molecular orbitals exceed the critical binding energy in uranium-uranium collisions. In collisions of californium with californium, on the other hand, the critical dis-



COLLISION OF TWO HEAVY IONS is the only practical means of creating an overcritical nuclear charge. The colliding nuclei need not actually merge, but they must approach each other closely enough for their joint electric potential to be greater than that of a single nucleus with a critical charge. The potential shown is that for two uranium nuclei at the critical separation distance of 34 fermis. (One fermi is 10^{-13} centimeter.) An electron subjected to this potential would act much like an electron in a molecule, and so the system is called a quasi-molecular state. For uranium nuclei at distances closer than this one the binding energy of an electron in the $1s_{1/2}$ orbital is greater than twice m_e, so that an electron-positron pair can be created.

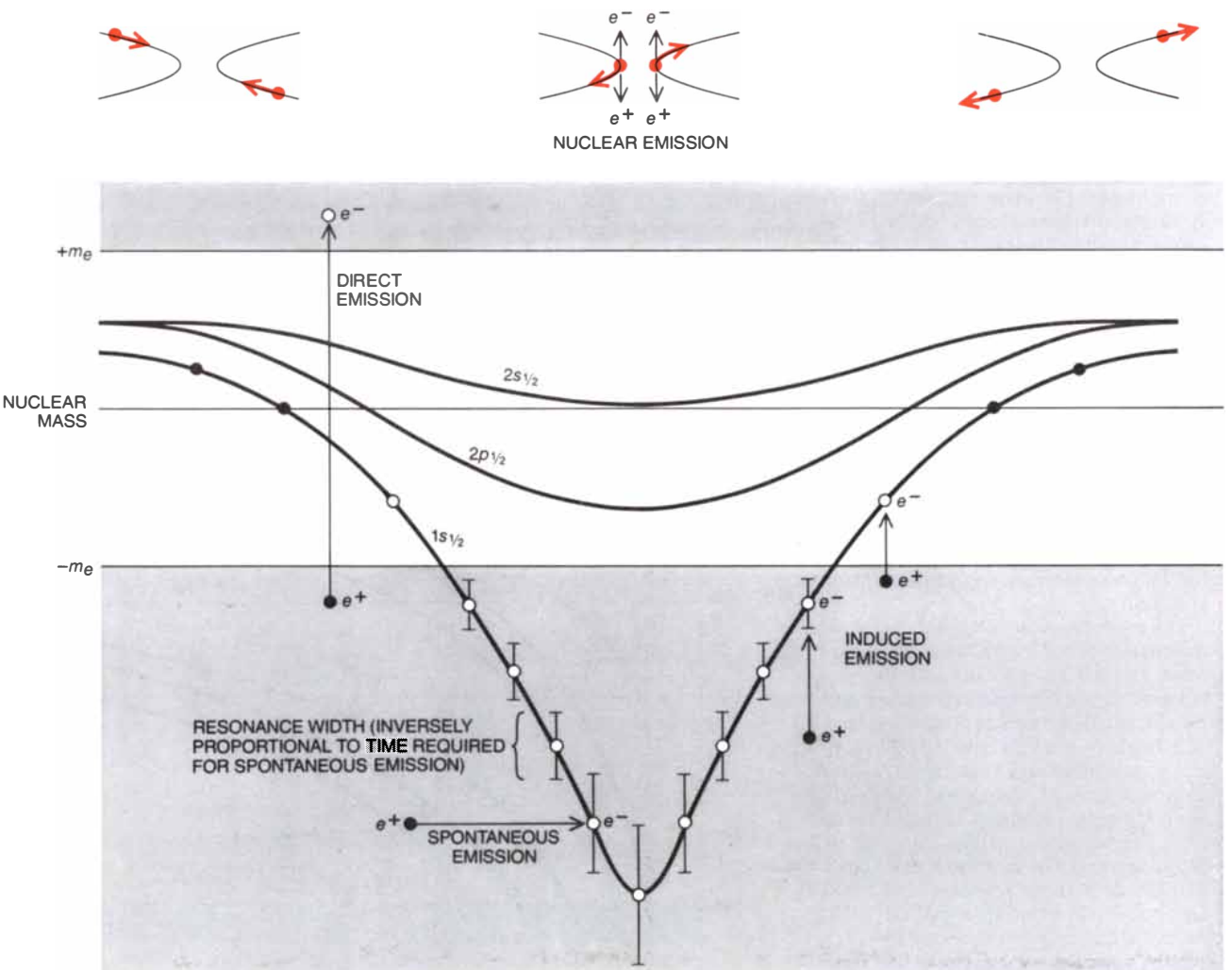


CRITICAL DISTANCE in heavy-ion collisions is the separation between nuclei at which the quasi-molecular potential first exceeds the critical charge for a particular orbital. In collisions between uranium nuclei ($Z = 92$) the decay of the neutral vacuum can be expected to fill only the $1s_{1/2}$ orbital. By employing californium ($Z = 98$) the $2p_{1/2}$ state might also be occupied spontaneously. The distance of closest approach depends mainly on the energy of the collision.

tance is about 60 fermis for the $1s_{1/2}$ state, and at a separation of about 20 fermis the $2p_{1/2}$ orbital also exceeds the critical binding energy. Precise knowledge of the critical distance is necessary in order to compare the rate of positron emission predicted by theory with the experimentally observed rate. The results given here have recently been confirmed by calculations done by V. S. Popov and his colleagues in the U.S.S.R.

For an electron-positron pair to be spontaneously created there must be vacancies in the appropriate quasi-molecular orbitals. If the orbitals are filled with their maximum of two electrons, the energy of the system will already be at its minimum and nothing will happen when the critical charge is exceeded. At the start of the interaction between the colliding nuclei the orbitals are ordinarily filled. The beam nucleus is part of an atom that is only slightly ionized; it is normally stripped of some of its electrons but not all of them, and the vacancies are not likely to be found in the inner orbitals. The target nucleus can be expected to have a full complement of electrons. If this condition were to remain unchanged, there would be no hope of observing the decay of the neutral vacuum in heavy-ion interactions. The collision itself, however, is a violent process, in which appreciable energy can sometimes be transferred to the electrons, raising them to excited states, so that the lower-lying orbitals are temporarily vacated. The probability of creating a vacancy in the $1s_{1/2}$ state in this way has been estimated by W. Betz, Müller and their colleagues at the University of Frankfurt to be 1 or 2 percent.

In uranium-uranium collisions the expected rate of pair creation is further reduced by another factor: the two nuclei remain within the critical range only for a period that is considerably shorter than the average decay time of the neutral vacuum. This does not mean the decay cannot take place at all. The time required for the decay is not a fixed interval but depends on a probability distribution. The nominal decay time is the most likely one, and only those comparatively rare events that happen to proceed very quickly can be observed in uranium-uranium collisions. Among the collisions in which the nuclei ap-



SPONTANEOUS EMISSION OF POSITRONS following the decay of the neutral vacuum is only one of several mechanisms that can give rise to positrons in heavy-ion collisions. The spontaneous emission is represented here by a horizontal arrow, signifying that no energy need be added to the system in order to create the electron-positron pair. The time required for the process is inversely proportional to a quantity called the resonance width, which is determined in part by the extent to which the binding energy exceeds twice m_e. Other mechanisms of positron production do require the input of energy. Excited states of the nuclei themselves can decay through the emission of an electron-positron pair. Moreover, rapid changes in the electric field of the moving nuclei can make energy available for the direct or the induced creation of an electron-positron pair (*vertical arrows*). These events, which can take place even when the critical charge has not been exceeded, represent an obscuring background to the spontaneous emission associated with the appearance of the charged vacuum.

proach to within the critical range and in which there is a vacancy in the $1s_{1/2}$ state about 5 percent should give rise to a spontaneous electron-positron pair. The time available for vacuum decay is more favorable in collisions of californium with californium, but for the present the difficulties of dealing with a radioactive target material outweigh the advantages of a higher event rate.

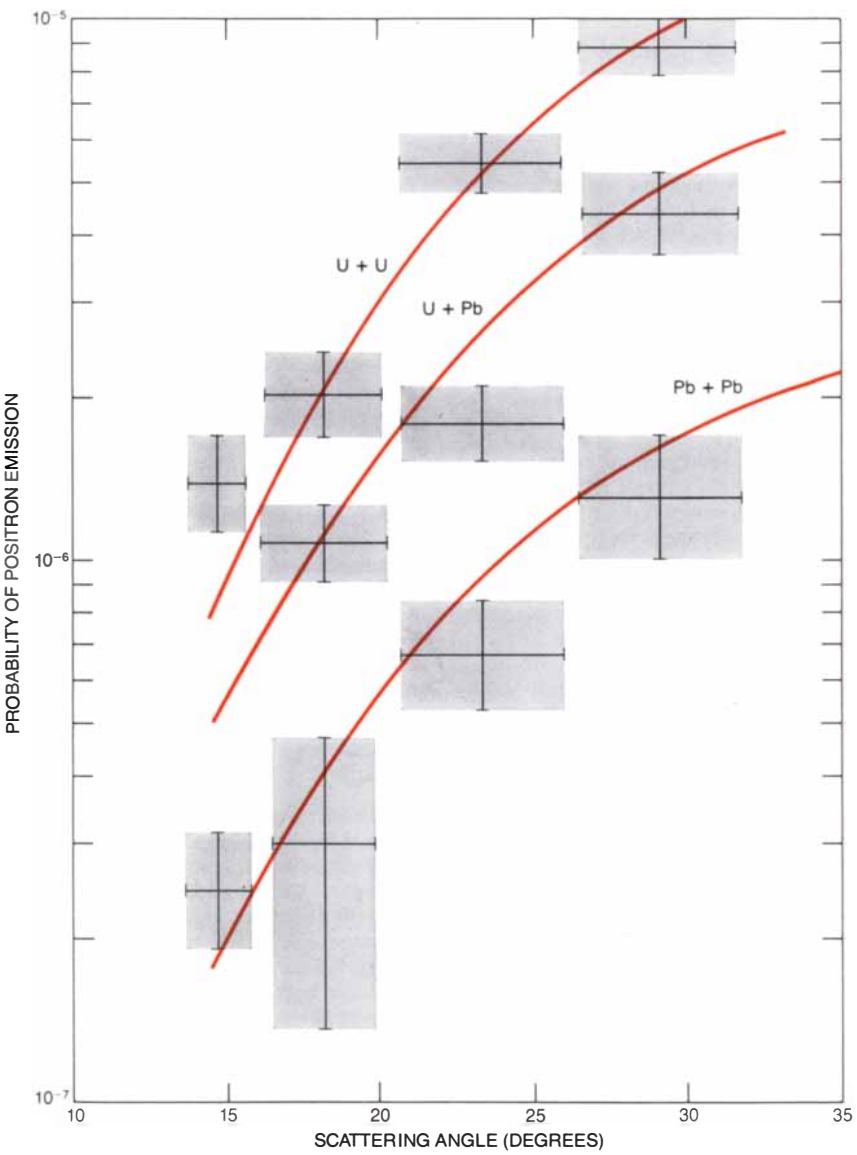
The decay of the neutral vacuum does issue a clear signal: the positron that is expelled from the vicinity of the nucleus can escape to macroscopic distances and can readily be detected. If the positron is allowed to come in contact with ordinary matter, it must eventually encounter an electron, with the result that both the positron and the electron are annihilated. The products of the annihilation are almost always a pair of photons, each photon with an energy roughly equivalent to the rest mass of one electron, or about .5 MeV. The photons can be detected by several kinds of instrument and can be distinguished from other photons by their narrow range of energies and by the fact that they appear simultaneously, moving in more or less opposite directions.

If there were no other source of positrons in heavy-ion interactions, the detection of correlated pairs of photons with energies near .5 MeV would provide unmistakable evidence for the decay of the neutral vacuum. Actually, however, several other processes also give rise to positrons. The nucleus itself is often promoted to an excited state and can return to the ground state by emitting a photon; if the photon has an energy greater than 1.02 MeV, which is not uncommon, it can decay to yield an electron-positron pair. Certain atomic processes other than vacuum decay can also lead to positron emission. In these events the appearance of the electron-positron pair is not spontaneous; rather, energy must be supplied to make up the mass. The energy is drawn from the rapidly changing electric field of the moving and distorting nuclei.

These extraneous positrons represent a distracting background to the events of interest. There is no way to suppress their emission or to discriminate between them and the spontaneous positrons, and so their number must be estimated and subtracted from the total number of positrons. If all pertinent factors have been taken into account, the difference should be the number of positrons associated with the decay of the vacuum.

An aid in these calculations is that the mechanisms responsible for the background positrons also operate in collisions between somewhat lighter nuclei, such as those of lead, where the critical charge is never exceeded. No spontaneous positrons should be emitted in such collisions, and so the background events can be counted reliably. The extrapolation to overcritical nuclear charges depends on a theoretical model, however, and the subtraction of the background remains a significant source of uncertainty in the results of any experiment.

Several experimental searches for spontaneous positrons have been carried out at GSI. The first results were reported by a large collaboration of experimenters led by Hartmut Backe, Jack S. Greenberg, Egbert Kankeleit, Paul Kienle and Christoph Kozhuharov. Although no unambiguous evidence for the decay of the neutral vacuum has yet been recognized, the results have confirmed the theoretical understanding of the background processes in the subcritical region. For example, the probability of positron emission in lead-lead and uranium-lead collisions has been measured, and the difference between the two probabilities agrees with the results of theoretical calculations done at Frankfurt by the group of theorists led by Greiner. Indeed, the agreement is close enough to inspire confidence that the decay of the neutral vacuum will soon be detected.



RECORD OF POSITRONS DETECTED in heavy-ion interactions shows that their number increases both with the charge of the colliding nuclei and with the violence of the collisions. The graph plots the probability of detecting a positron in the aftermath of a single collision as a function of the angle at which the two nuclei scatter. The scattering angle is an indicator of how closely the nuclei approached each other. In lead-lead and lead-uranium collisions all these events result from background processes. The number of background positrons must be subtracted from the total rate of positron emission in those collisions where the critical charge is exceeded, as it is when uranium nuclei collide. The remaining events represent the spontaneous emission resulting from the decay of the neutral vacuum. The data were recorded at GSI.

Tephra

Airborne fragments from an erupting volcano, known collectively as tephra, come in a wide variety of sizes, shapes and compositions. The study of tephra deposits assists in the dating of ancient events

by Laurence R. Kittleman

The word tephra, from the Greek τέφρα, meaning "ash," has come into use among geologists to describe the assortment of fragments, ranging from blocks of material to dust, that is ejected into the air during a volcanic eruption. It was first used in this modern sense a few decades ago by Sigurdur Thórarinsson, a volcanologist at the University of Iceland. Thórarinsson also coined the word tephrochronology, the dating of geological and other events by reference to their position in a sequence of tephra deposits. The two words express the essence of the current state of understanding of such matters: A volcano produces successive showers of tephra that fall throughout the surrounding countryside, forming layers that constitute a tephrochronological record of the volcano's activity.

Most tephra deposits result from volcanic eruptions in which molten rock containing dissolved gas rises in a conduit and suddenly separates into liquid and bubbles. The bubbles grow explosively, burst the surrounding liquid and give rise to a mixture of fragments and gas that is driven from the vent by the force of its own expansion and hurled far above the volcano. The fragments, which cool and solidify during their flight, are caught by winds blowing across the eruption cloud and are carried leeward, falling to the ground as much as thousands of kilometers away. The tephra falls into whatever environment happens to lie below the volcanic plume: hills, valleys, oceans, lakes, stream terraces, bogs or human settlements. There it is likely to form a persistent layer that has latent in its properties clues that can be deciphered long afterward to determine the nature of the eruption, the meteorological conditions prevailing at the time and perhaps the year or even the season of the event. Tephra influences the environments into which it falls, generating effects whose consequences often can be discerned in the stratigraphic record. Since tephra layers are formed quickly throughout a large area, they serve as handy time markers. The layers often contain or are closely associated with materials that can be dated by various means. Once a layer has been dated that date is applicable wherever the layer can be recognized, and it can be used to establish the time of any event that can be related to the tephra layer.

Tephra is found all over the world in deposits of every geological age. Its diverse properties, effects and scientific applications have attracted the attention of anthropologists, archaeologists, astronomers, botanists, chemists, climatologists, geographers, geologists, historians, oceanographers, sociologists, soil scientists and zoologists. To sample this diversity I shall summarize the current understanding of the production and dispersal of tephra and describe some ways to study the material and exploit its properties; I shall also give a few examples of eruptions that have been notable subjects of research. The discussion will mainly concern tephras of the last ice age and thereafter, for which the evidence is in some ways easiest to interpret, but it should be understood that the principles invoked apply also to older tephras.

Volcanism is the release at the earth's surface of magma, a complex molten mixture of silicon, metals, oxygen, hydrogen, sulfur and other elements, some of which are given off as gases as the magma comes near the surface. Although the nature and the origin of magmas have been studied for more than a century, several important matters remain unexplained. There is now, however, agreement on the main features.

The most likely source of the heat responsible for magma is the radioactive decay of elements dispersed in the earth's mantle, the thick layer of material that lies between the metallic core and the rocky crust. Magma probably forms in the uppermost few hundred kilometers of the mantle, but just how it is melted and mobilized is not understood. What is known is that the material of the mantle somehow melts and reaches the surface as magma at temperatures of approximately 1,100 degrees Celsius.

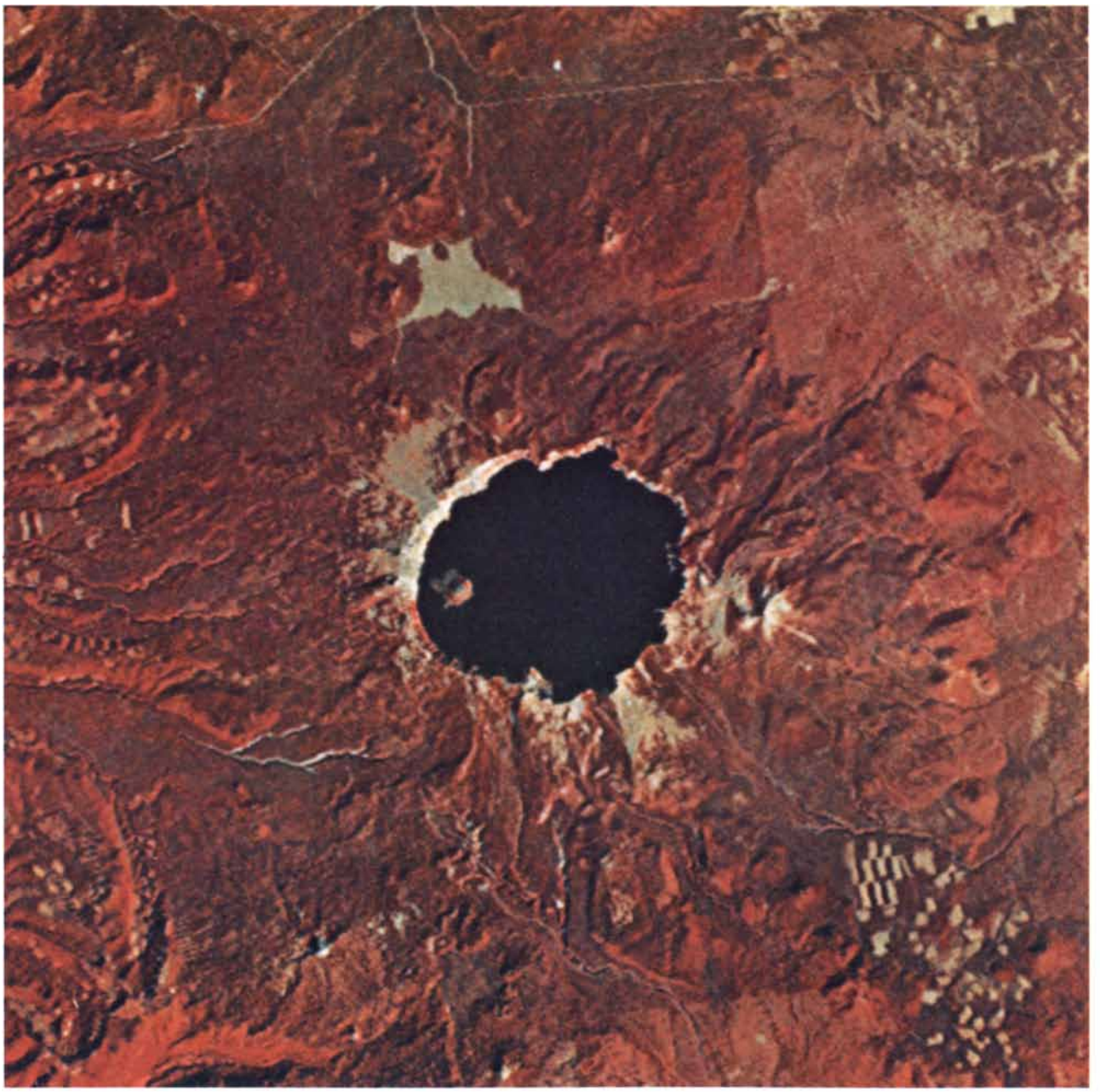
Magma that has spilled out onto the surface is called lava. It can have various compositions, ranging from mafic lava, which is rich in magnesium, iron and calcium and poor in silica (silicon dioxide), to silicic lava, which is rich in silica, sodium and potassium. This variability is responsible for the great variety evident in the products of volcanic activity.

Nearly every type of volcano produces some tephra. For example, comparatively quiet outpourings of very fluid lava are accompanied occasionally by fountains of molten material, whose spray solidifies into a kind of tephra. Tephra produced in this way is usually small in quantity and confined to the neighborhood of the vent. Some eruptions, called hydromagmatic, occur when water from an external source (ground water, a lake or an ocean) gains access to magma in a conduit, giving rise to violent explosions that are not necessarily accompanied by much new magma; almost all the tephra produced comes from the walls of the conduit or from shattered parts of the volcanic crater. The largest amount of tephra comes from eruptions that are accompanied by the rise of new magma. In an eruption of this type little or no lava flows out at the surface; instead the magma is converted into tephra.

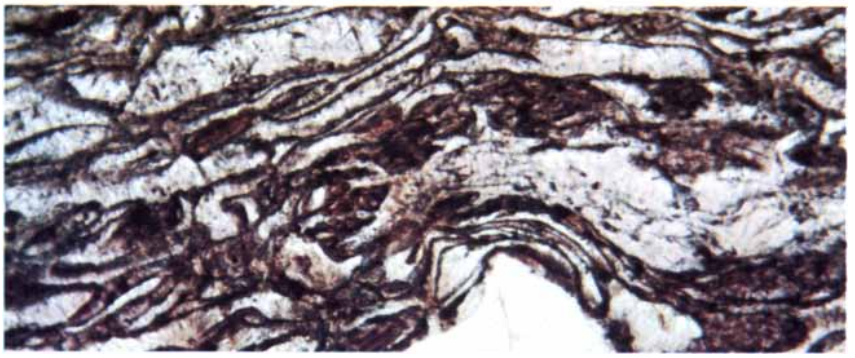
The amount and the character of the tephra ejected during a particular eruption are determined largely by the properties of the magma, the most important of which are the amount of dissolved gas and the viscosity. Gas-rich, viscous magmas tend to be associated with eruptions that produce much tephra, whereas gas-poor, fluid magmas are likely to yield flows accompanied by little tephra. The viscosity of magmas is governed largely by the chemical behavior of silicon, the second most abundant element in magma (after oxygen). Mafic basaltic magmas, for example, are about 45 percent silica, and their viscosity at 900 degrees C. is approximately 10,000 poises, some 100,000 times greater than the viscosity of motor oil at room temperature. Silicic rhyolitic magmas are about 72

percent silica, and their viscosity at 900 degrees C. is close to a trillion poises. A viscosity of such magnitude surpasses ordinary experience, but the viscous behavior of silicic magmas seems to be an important factor in tephra eruptions. After the destructive eruption of Mount Pelée on Martinique in 1902, for example, a stiff protrusion of lava grew from the crater to a height of 300 meters, like a gigantic squeeze of toothpaste.

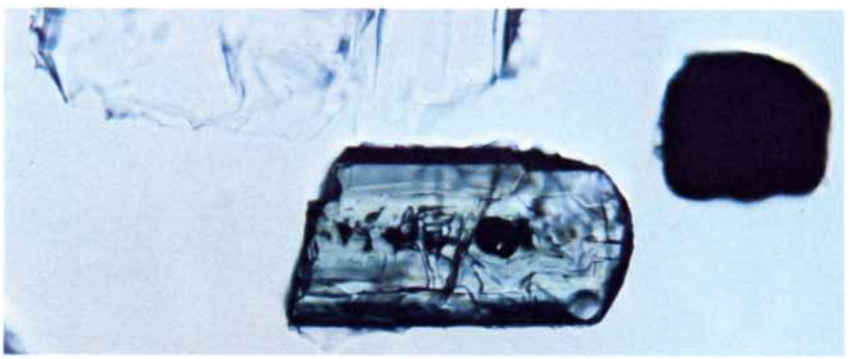
The investigation of the products of volcanic eruptions has yielded ideas that explain generally how tephra is made, although many details remain to be explored. As silicic magma rises in its conduit it cools and the pressure on it decreases. These changes cause the viscosity to increase and enable dissolved gases, mainly steam, to form bubbles. The two effects act together progressively, so that bubbles are growing most rapidly and forcefully at the same time that the enclosing liquid is becoming more viscous. Eventually the gas pressure ruptures the films of liquid between adjacent bubbles, and the froth disintegrates into a cloud of fragments and gas. If the final events happen near the orifice of the eruption, a mass of disrupted froth may spill out and flow down the slopes of the volcano. If the final events happen some distance below the orifice, the mixture, confined in the conduit as though it were in the barrel of a gun, is propelled upward by the steadily expanding gas and is ejected from the vent, often with enormous violence. The cloud of tephra and gas rises high above



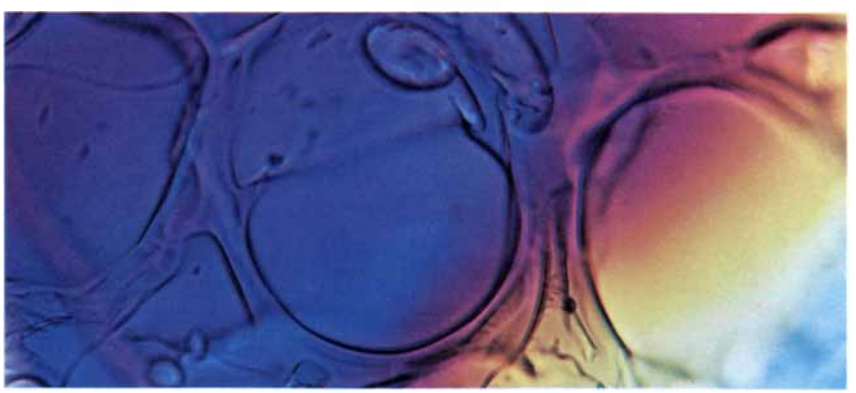
CRATER LAKE, at the crest of the Cascade Range in southwestern Oregon, is seen from an altitude of more than 900 kilometers in this false-color composite image made with data recorded by the Landsat II satellite. The lake, which is nine kilometers across and 600 meters deep, occupies a basin where the top of a volcano, Mount Mazama, once stood. The volcano erupted violently some 7,000 years ago, scattering about 30 cubic kilometers of tephra fragments over an area of nearly a million square kilometers. The withdrawal of so much magma left the volcano's summit unsupported and it collapsed, creating the basin (known as a caldera) that now contains the lake. The island visible near the western edge of the lake is Wizard Island, a basaltic cinder cone that rose long after the formation of the caldera.



COMPRESSED, DEFORMED TEPHRA FRAGMENTS are viewed by transmitted light in this color micrograph of a thin section of welded ash-flow tuff, a variety of ignimbrite. Deposits of ignimbrite are produced by a particular kind of volcanic eruption called a pyroclastic flow, in which coherent streams of tephra and gas travel close to the ground. In the micrograph the individual tephra fragments are delineated by dark lines that were probably formed by the oxidation of iron at their surfaces. The shards were compressed in the vertical direction by the force of gravity after the pyroclastic flow came to rest but before the tephra layer cooled and hardened. The shards are bent around the edge of a large colorless grain of feldspar near the bottom. The sample, from the Dinner Creek tuff in southeastern Oregon, dates from the Miocene epoch (between five and 22 million years ago). Field of view is about a millimeter across.



MINERAL GRAINS from the tephra mantle of ancient Mount Mazama were recovered in the Blue Mountains of Oregon some 300 kilometers northeast of Crater Lake. The gray oblong object near the center of this transmitted-light micrograph is a grain of hypersthene, an iron-magnesium silicate whose orthorhombic crystal form is evident in the shape of the grain. The smaller black grain at the right is magnetite, an iron oxide, and the colorless grains at the upper left are the feldspar mineral plagioclase, a sodium-calcium aluminosilicate. All the grains have patches of glass clinging to them, remnants of the molten material in which they were suspended just before the eruption. The hypersthene grain is about 350 micrometers long.



BUBBLE-WALL TEXTURE characteristic of tephra particles is revealed in this micrograph, made in transmitted polarized light, of the surface of a mineral grain from the Mount Mazama tephra. The surface retains the impressions of tiny gas bubbles present in the molten glass in which the grain was suspended prior to the volcanic eruption. Most of the glassy jacket surrounding the grain was torn away in the course of the eruption, leaving the grain covered with a thin film of glass bearing the marks of the bubbles. Bubble imprint at center is approximately 70 micrometers wide. All three of the micrographs on this page were made by the author.

the volcano, and particles in it are carried downwind, producing a rain of tephra that forms a deposit called a tephra mantle. To be sure, there are modes of eruption intermediate between these extremes, and there may be a continuous range of modes consistent with this general scheme. Almost innumerable variations on the process, representing intricate interactions among the amount and the composition of the magma, the rate of ascent and the rates of change of the viscosity and the pressure, account for the diversity of tephra; it is this diversity that makes it possible to distinguish the deposits of one eruption from those of another and to learn the nature of eruptions long past.

The mechanism described above accounts at least for the two main kinds of tephra eruption customarily recognized by geologists: pyroclastic flows and tephra falls. Pyroclastic flows are coherent, mobile streams of tephra and gas that usually travel along or close to the ground and may follow existing stream valleys. Such flows can extend for tens of kilometers and can travel at more than 100 kilometers per hour. The deposits formed from them are called ignimbrites. Deposits of this type are common and may cover thousands of square kilometers. In the past few decades geologists have characterized a particular kind of ignimbrite, called welded ash-flow tuff, among rocks of Cenozoic age (from 65 million years ago to the present). These deposits are the result of pyroclastic flows in which the tephra fragments have been welded together by retained heat after the flow came to rest, producing a dense rock made of compressed, deformed tephra fragments.

There have been a number of pyroclastic flows in historic times. They are dangerous, owing to their sudden onset, speed and extent. The 1902 eruption of Mount Pelée was a pyroclastic flow: a horizontal jet of tephra, gas and scalding mud that destroyed St. Pierre, a city of 30,000.

A tephra fall, the second kind of tephra eruption, is a shower of fragments borne by winds from the eruption cloud above the volcano. It is tephra of this kind that is commonly called "volcanic ash" and that forms the widespread, voluminous tephra deposits of great eruptions, some of which extend over hundreds of thousands of square kilometers. These tephra mantles will be the main subject of the rest of this article, although in general the description of their composition and mineralogical properties is applicable to other kinds of tephra as well.

Up to now I have written in general terms of the creation of tephra fragments. What are these fragments? To answer the question I must return briefly to the subject of magma. If mag-

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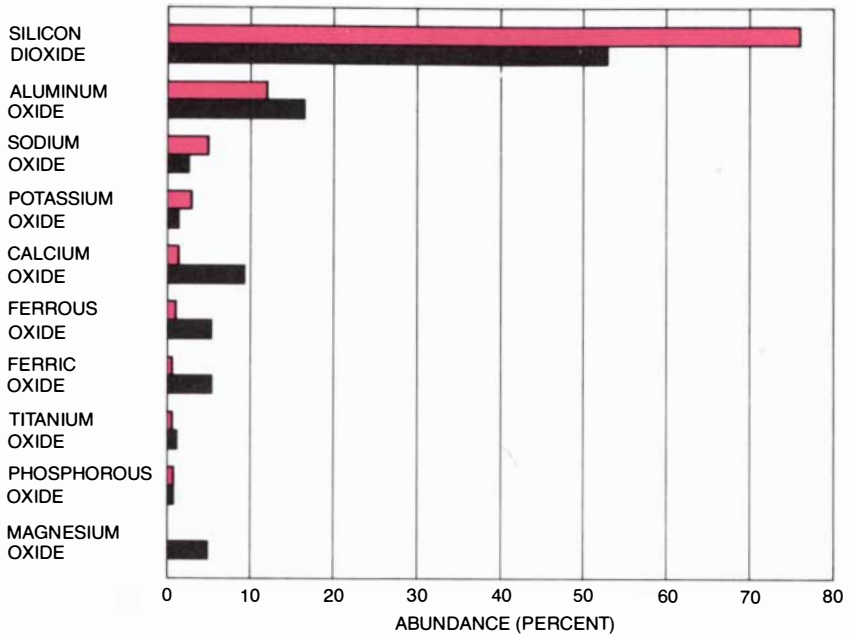
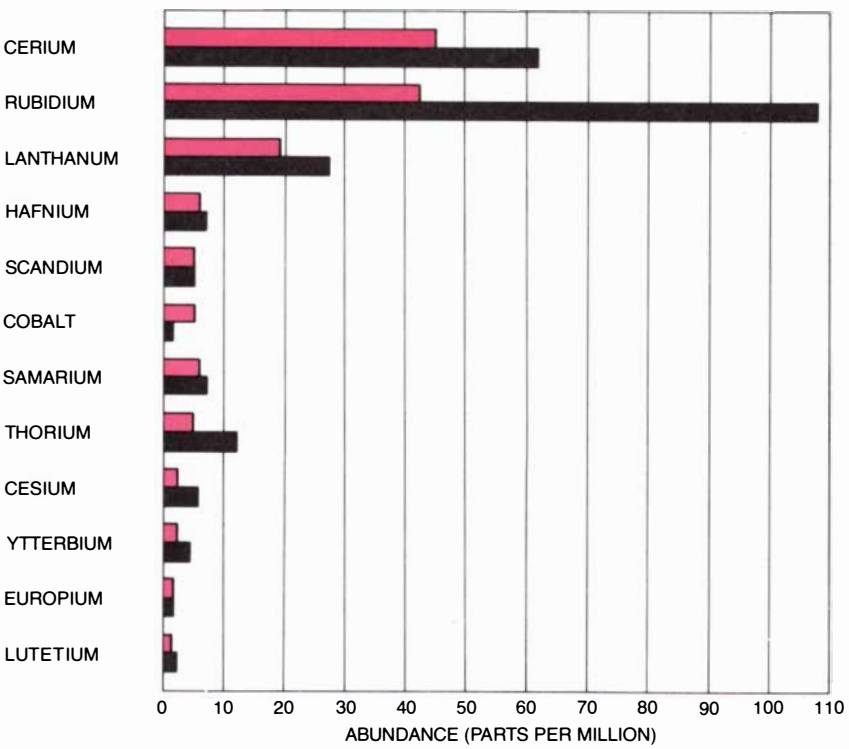


MAJOR ELEMENTS IN TEPHRAS, expressed here as oxides, exhibit a reciprocal relation between the amount of silica (silicon dioxide) present and the abundances of oxides of other elements. For example, the silicic tephra of Mount Katmai in Alaska (*colored bars*) is rich in silica but comparatively poor in oxides of calcium, iron (both ferrous and ferric forms) and magnesium. In contrast, the mafic tephra of the volcano Semeru in Indonesia (*black bars*) is poorer in silica but comparatively rich in oxides of aluminum, sodium and calcium. In general volcanic rocks exhibit broad chemical similarities among specimens with the same silica content; hence distinguishing features must sometimes be sought among the details (*see illustration below*).



TRACE ELEMENTS IN TEPHRAS are usually present in parts per million, but their importance transcends their small abundance. They supply clues to the origin and evolution of magmas, they can often be used to date geological events and they facilitate the identification of individual tephras. Shown here are trace-element abundances found in tephras from two ancient volcanoes in Oregon: Mount Mazama (*colored bars*) and Newberry Crater (*black bars*).

ma is allowed to cool slowly, crystalline chemical compounds—minerals—grow in the liquid, drawing their substance from elements in the magma. If the growth continues to completion, the result is rock consisting entirely of an assemblage of minerals whose aggregate composition is the same as that of the magma, excluding any substances that may have escaped as gas. For most tephras, however, the process of crystallization does not go to completion. Usually magma rising in a conduit already contains some mineral grains that have grown during the ascent. The frothy liquid in which these grains are suspended is quenched suddenly when the mixture erupts. The product is a glass mixed with mineral grains and with fragments of lava or other kinds of rock broken off the walls of the conduit or the crater. In short, tephra is a mixture of glassy, mineralic and rocky fragments combined in various proportions, depending on the characteristics of the eruption that produced them. The material is called respectively vitric, crystal or lithic tephra, depending on which component is predominant. Glassy fragments are usually the main product (and sometimes the only product), but in certain tephras mineral grains or rock fragments are most abundant.

Glassy fragments are often broken walls of burst bubbles, called bubble-wall shards. These microscopic particles can be filmy plates without ornamentation, ribbed fragments, multipoint forms, crescent-shaped slivers, threads, bundles of minute tubes, strings or clusters of bubbles and so on almost without limit. Often they consist of clear, colorless glass whose curves, angles and facets sparkle brilliantly when they are suitably illuminated under the microscope, and usually they are accompanied by brightly colored mineral grains, some with a crystalline form.

Glassy fragments larger than a few millimeters are usually present in the form of pumice, a frothy rock crowded with tiny cavities that once were gas bubbles. The cavities may be roughly spherical, irregularly shaped or drawn out into long, thin tubes like the bubbles in taffy. Often the material has a distinctive silky appearance, and usually it is light enough to float on water.

There are other kinds of glassy fragments. Grant H. Heiken, a geologist at the Los Alamos Scientific Laboratory, has classified the shapes of tephra particles, relying on both transmitted-light microscopy and scanning electron microscopy. He examined both glassy and rocky particles, since there is no definite distinction between them but rather a gradation from entirely glassy fragments at one extreme to entirely rocky ones at the other. Besides bubble-wall shards he identified forms that include fragments of droplets, angular particles

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with or without tiny bubbles and fragments of froth that might be called micropumice. Heiken found a relation between the style of the eruption and the forms of the fragments. For example, tephra eruptions that arise from mafic magmas of low viscosity are likely to produce droplets and fragments of droplets composed of the basaltic glass sideromelane, whereas hydromagmatic eruptions tend to produce angular, chunky rock fragments with curved faces. It is possible from such observations to learn the mode of an ancient eruption by examining the forms of the tephra particles it produced.

Tephras may contain any of the many minerals that are found in volcanic rocks, but the number of common minerals is small. A single tephra ordinarily will contain only a few minerals, and it is usual for three or four kinds to constitute 80 or 90 percent of those present. Particular assemblages of minerals tend to be regional in occurrence, so that volcanoes of a chain or a province characteristically produce certain assemblages and rarely produce others.

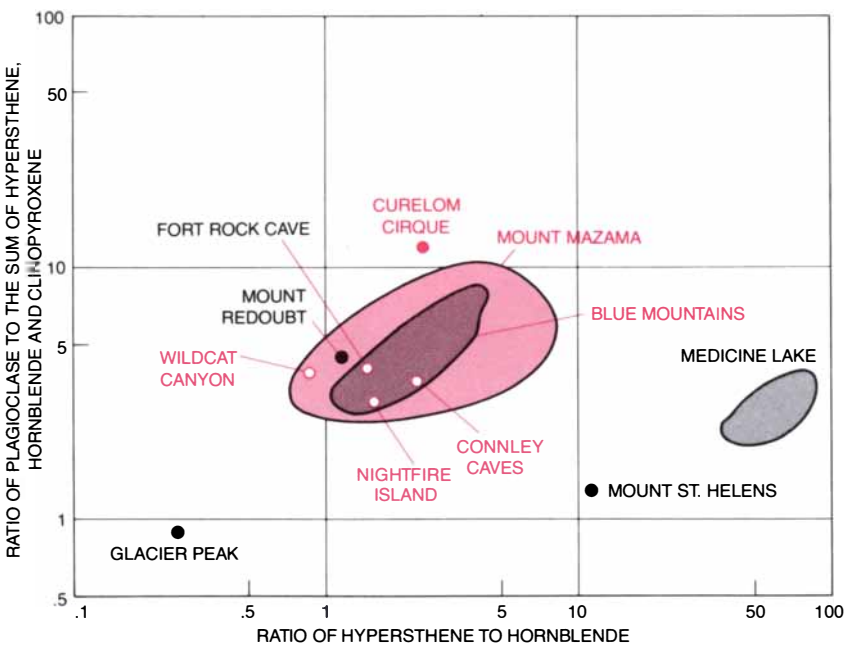
Minerals of the feldspar group are common, often predominant. Included are the plagioclase feldspars (sodium-calcium aluminosilicates) and the alkali feldspars (potassium-sodium aluminosilicates). Among the ferromagnesian minerals, those with important amounts of iron and magnesium, are the pyroxenes (iron-magnesium silicates and aluminosilicates), the amphiboles (hydrous iron-magnesium aluminosilicates) and various opaque minerals (principally iron-titanium oxides). Olivine (iron-magnesium silicate), zircon (zirconium silicate) and the mica mineral biotite (hydrous potassium-magnesium-iron aluminosilicate) are sometimes present too. The proportions of the minerals and their individual optical properties vary, and it is this variation that helps to distinguish one tephra from another.

Since the mineral grains in tephra were once suspended in molten material, films of liquid have clung to them, later becoming jackets of glass that bear the impressions of tiny adjacent bubbles. These impressions create a pattern on the surface of the grain that has been named bubble-wall texture by Richard V. Fisher of the University of California at Santa Barbara. Bubble-wall texture clearly marks tephra particles that have found their way into other kinds of sediment. The glassy jackets quickly wear off during fluvial transportation, however, and so their preservation indicates that the particles have not traveled far.

Volcanic rocks generally contain about 75 chemical elements in significant quantities, of which some 10 major elements have abundances of .1 percent or more. The remainder are trace elements. Some elements not represented in analyses of rocks are erupted in important quantities as gases, chiefly hydrogen and oxygen in the form of steam, carbon in the form of carbon dioxide, sulfur in the form of hydrogen sulfide and sulfur dioxide, and chlorine and fluorine as atomic gases. The major elements, expressed as oxides, account for more than 99 percent of the material analyzed, and four of them, silicon, aluminum, calcium and sodium, account for more than 80 percent. The abundances of these elements vary reciprocally, so that rocks rich in silica are also fairly rich in sodium and potassium, whereas those poor in silica are richer in magnesium, calcium and iron. Such relations impart a broad uniformity to volcanic rocks of similar silica content, and so distinctions must be sought among the details.

The trace elements are usually present in amounts conveniently expressed as parts per million, but their importance exceeds that expressed by abundance figures alone, because they furnish clues to the origin and evolution of magmas. Some, for example, are nuclides of radioactive-decay series whose abundances can be exploited to measure the time elapsed since the tephra was formed. Relative abundances of trace elements can distinguish one tephra from another, probably with greater confidence than that provided by the major elements.

The gradation of grain sizes in tephras is large, extending from more than a meter to a few micrometers, a range of more than a millionfold. A single sample might contain fragments whose size ranges roughly from 10 centimeters to 10 micrometers, although some tephras are predominantly coarse-grained and others are fine. In 1961 Fisher proposed a grain-size classification that is now widely adopted: particles up to two millimeters in diameter are called ash, those between two and 64 millimeters lapilli and those more than 64 millimeters blocks or bombs. Blocks are fragments that were solid when they were erupted, whereas bombs were molten.



RELATIVE ABUNDANCES OF MINERALS can be analyzed in order to distinguish individual tephra deposits from one another. In this diagram, for example, the ratio of the abundance of plagioclase to the sum of the abundances of hypersthene, hornblende and clinopyroxene is plotted with respect to the abundance ratio of hypersthene to hornblende for a variety of tephra samples. The dots and the open circles designate single analyses of tephra samples; the shaded areas encompass the results of a number of analyses of the same tephra layer. The samples represented by the black dots were obtained from Mount Redoubt in Alaska and from Glacier Peak and Mount St. Helens in Washington; those represented by the light shaded areas were obtained from Mount Mazama in Oregon (*light colored area*) and Medicine Lake Highlands in California (*light gray area*). The open circles stand for analyses of tephra layers at archaeological sites at Wildcat Canyon, Fort Rock Cave and Connley Caves in Oregon and at Nightfire Island in California, all of which can be shown on the basis of this and other evidence to be tephra deposits from Mount Mazama. A tephra layer in Curelom Cirque bog in northwestern Utah (*colored dot*) is also recognizable as originating from the Mount Mazama eruption, as is a tephra layer in the Blue Mountains (*dark colored area*). Although tephras from Mount Redoubt and Mount Mazama resemble each other mineralogically, their only connection is that they come from volcanoes of the same chain. The possibility that they could be confused is ruled out because they are far apart and show different abundances of trace elements.

Volcanic bombs are still soft enough to change shape during their flight and to flatten or spatter when they land. The various types of volcanic bomb are named, for example, cannonball, spindle, bread crust, cow dung, ribbon or fusiform, depending on their shape or the appearance of their surface. Occasionally they will explode after landing, owing to the expansion of gas in a molten interior under a solid crust.

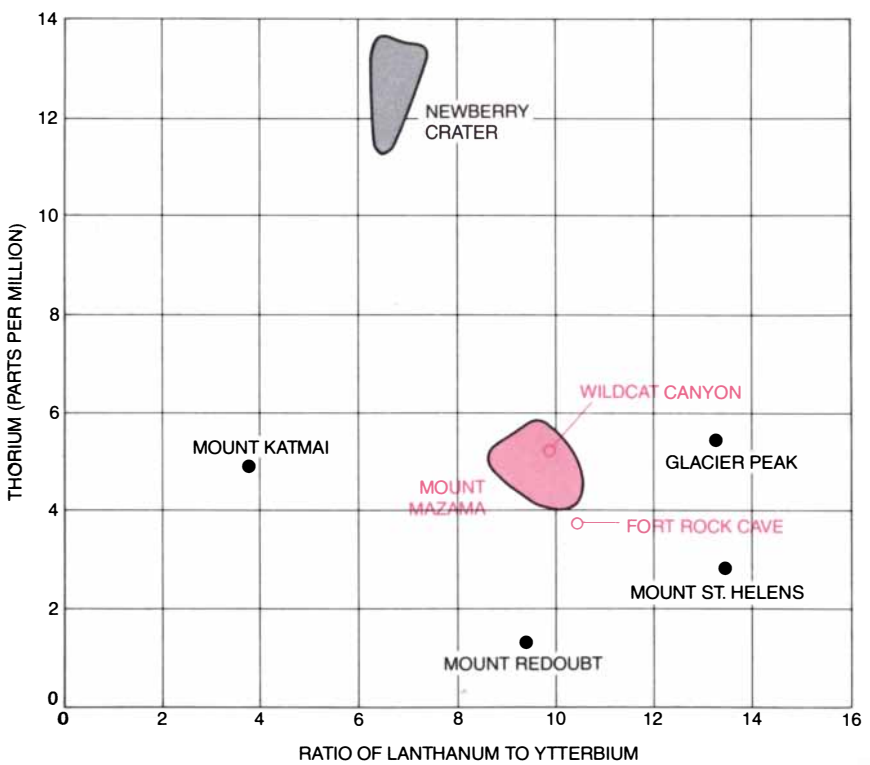
It is important to realize that technically the term volcanic ash means tephra of a particular grain size, a definition that may conflict with ordinary usage. The generic word tephra applies to fragments of any grain size.

Tephra fragments created near the orifice of a volcano are driven upward by the escaping gases. Observations at the beginnings of eruptions show that the eruption cloud rises rapidly. Thórarinsson noted during the eruption of Mount Hekla in Iceland in 1947 that the cloud rose at an average rate of about 70 meters per second during the earliest stages. The eruption cloud above Mount Asama in Japan in 1936 was observed by Takeshi Minakami of the Earthquake Research Institute in Tokyo to rise at a rate of more than 100 meters per second. Clearly the individual particles in such clouds must also rise rapidly. The velocity at which the particles are ejected (their muzzle velocity, so to speak) is not necessarily the same as that of the fluid propellant, however, because solids in the stream of gas tend to sink gravitationally. The ejection velocities of the fragments can be estimated by measuring the distance they were tossed. For example, Minakami calculated that during the eruption of Mount Asama in 1783 particles five centimeters in diameter were carried to an altitude of nearly 15 kilometers, implying an ejection velocity of at least 500 meters per second.

C. A. Wood and F. M. Dakin of the University of Addis Ababa, studying a hydromagmatic crater in Ethiopia named Ara Shatan, calculated that pieces about 40 centimeters in diameter had an ejection velocity of 90 meters per second and those about a meter across an ejection velocity of nearly 70 meters per second. They estimated that the stream of gas had a velocity of almost 125 meters per second, which would have called for a pressure of perhaps 200 atmospheres. William G. Melson of the Smithsonian Institution and his associates concluded from studies of the eruption of the Central American volcano Arenal in 1968 that the ejection velocity was as much as 600 meters per second under a pressure of about 4,700 atmospheres.

Tephra-laden eruption clouds rise as high as 80 kilometers, smaller fragments being carried to the highest altitudes owing to their greater ejection velocity and their greater susceptibility to the lift of the rising gas. Wind catches the particles, which are carried leeward at the velocity of the wind. Then they begin to fall, ultimately reaching a terminal velocity. The path followed by each particle is governed by the resultant of the wind velocity and the terminal velocity; a particle will strike the surface at whatever distance it can travel with the wind in the time needed for it to fall to the ground from its starting altitude at the terminal velocity. The smallest particles of course fall farthest from the volcano.

The terminal velocity is that steady speed reached by a solid particle falling freely in a fluid at which the force of gravity, acting downward, equals the force of fluid drag, acting upward. The idea, long a fundamental of fluid mechanics, is essential to studies of grain size in tephra and other sediments. The terminal velocity can be calculated with the aid of a formula that takes into account the gravitational constant, the coefficient of fluid drag, the density of the solid particle, the density of the fluid (in this case air) and the diameter of the particle. The numerical solution of this seemingly simple formula is difficult, however, because the coefficient of drag itself depends on the velocity, the shape of the particle and the viscosity of the fluid. Fluid properties such as temperature, density and viscosity, all of which affect the terminal velocity, vary with altitude, so that the terminal velocity will actually change during a particle's fall. G. P. L. Walker and his colleagues at the Imperial College of Science and Technology in London analyzed the matter in detail and also found experimentally that better results can be obtained if the particles are treated mathematically as though they were cylinders rather than spheres. (The particles do in fact have irregular shapes.) The wind velocity also may vary with altitude, influencing the path of the falling particle independently of its rate of fall.



RELATIVE ABUNDANCES OF TRACE ELEMENTS can also serve to characterize individual tephra deposits. In this case the abundance of thorium is plotted with respect to the abundance ratio of lanthanum to ytterbium for a variety of tephra samples. As in the diagram on page 166, the dots and the open circles designate single analyses of tephra samples, whereas the shaded areas encompass the results of a number of analyses of the same tephra layer. The tephras of Newberry Crater and Mount Mazama in Oregon, Mount Katmai and Mount Redoubt in Alaska and Glacier Peak and Mount St. Helens in Washington are clearly distinguished. The locations of open circles, representing tephra layers at archaeological sites at Fort Rock Cave and Wildcat Canyon in Oregon, show that both samples are from Mount Mazama.

Surveys of tephra deposits reveal the relations between grain size and distance of transport. My own work with the tephra of Mount Mazama in southern Oregon (the present site of Crater Lake) confirms the underlying dependence on terminal velocity. The average grain size of tephra deposits measured at sites arrayed along a line radial to the source decreases systematically with in-

creasing distance. Work on Mount Mazama tephra by Howel Williams of the University of California at Berkeley and Gordon G. Goles of the University of Oregon and on the tephra of Mount Hekla by Thórarinsson shows also that the thickness of the deposits decreases regularly outward, depending on the distance from the source and other factors peculiar to each deposit.

Tephra dispersed according to these processes forms around the volcano a tephra mantle whose shape, volume and variations in grain size are governed not only by the characteristics of the eruption but also by the factors described above. Typically the mantle has a teardrop shape, with the volcano near the narrow end. The mantle will be longer for strong winds than for weak ones, and variable winds or different wind directions at different altitudes may give rise to a multilobed form. It is significant that some characteristics of the mantle have little or nothing to do with happenings at the volcano but express only variable meteorological conditions.

Tephra can be carried for great distances. Tephra from the 1947 eruption of Mount Hekla, for example, fell in Helsinki, 3,800 kilometers away, carried there at an average speed of about 75 kilometers per hour. Tephra from the eruption of Mount Mazama some 7,000 years ago can be recognized in western Saskatchewan, nearly 2,000 kilometers from the volcano. The finest tephra reaches into the stratosphere, where it can be carried around the world by strong global winds.

Tephra eruptions are brief. The greatest production of tephra is usually confined to a short, acute event, although a period of intermittent lesser activity may last for months or years from the first signs to the waning episodes. Nearly all the tephra from the eruption of the Indonesian volcano Krakatoa in 1883 fell in two days, although the eruption lasted for 90 days. The 1947 eruption of Mount Hekla lasted for 180 days, but 86 percent of the tephra fell on the first day. Prehistoric eruptions were doubtless similar. Peter J. Mehringer, Jr., and his associates at Washington State University studied pollen associated with a layer of tephra believed to have come from Mount Mazama in a bog in western Montana. They deduced from the estimated rates of the influx of pollen and from the indications of seasons in the relative abundances of the different kinds of pollen that the Mount Mazama eruption began in the fall and may have lasted for three years. Michael T. Ledbetter of the University of Rhode Island, working with a technique based on the terminal velocities of tephra particles in the ocean, estimated that a prehistoric tephra layer he studied was deposited within 21 days.

Samples from long sequences of tephra layers can be obtained in some geological settings, particularly deep-sea sediments, which can be sampled by modern submarine-drilling techniques. For example, Ken F. Scheidegger and Laverne D. Kulm of Oregon State University studied tephra layers interbedded with other sediments in the Gulf of Alaska, the oldest of which were deposited about eight million years ago. The tephras almost certainly came from the Aleutian Islands, a chain of volcanoes believed to lie above a subduction zone, where according to the modern theory of plate tectonics oceanic crust is plunging into the mantle and being consumed. Chemical analyses show cyclical variations in silica content: silicic eruptions are manifested in samples of tephra originating in modern times, 2.5 million years ago and five million years ago; less silicic ones are manifested about a million years ago, 3.5 million years ago and eight million years ago. The causes of this cyclicity are not known, but Scheidegger and Kulm surmise that the variation may reflect changes in the rate of the subduction of crust into the Aleutian Trench.

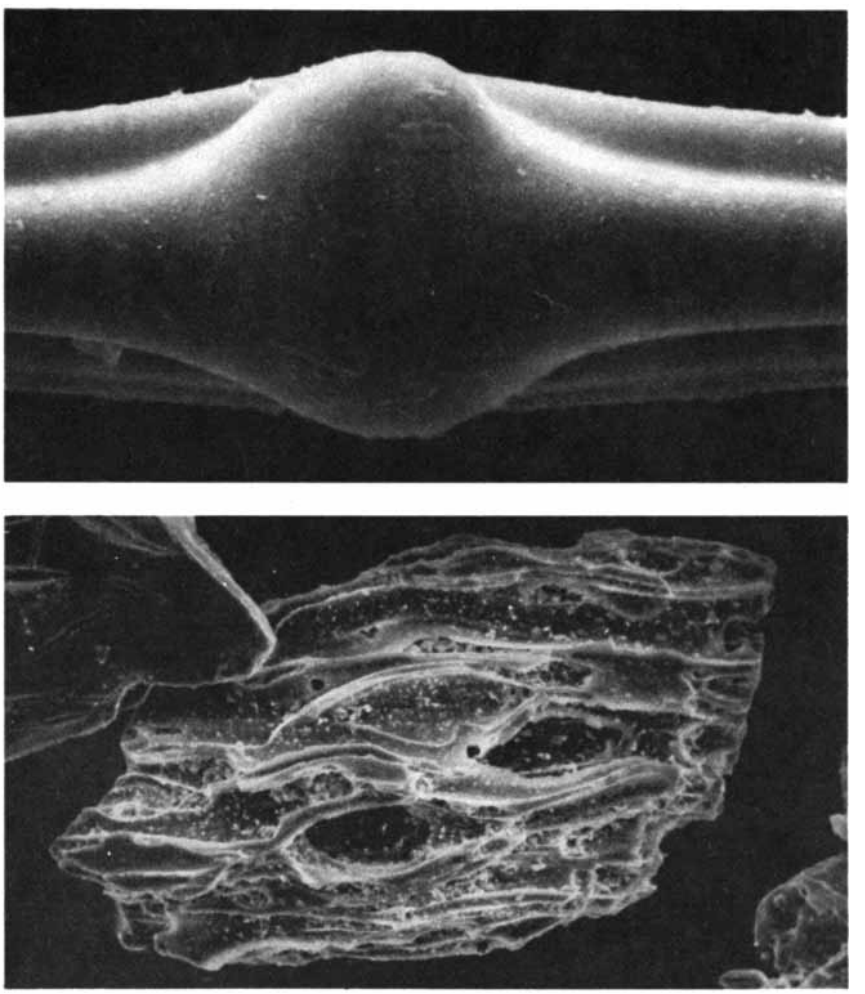
The theory of plate tectonics holds that most volcanism arises at the active margins of plates, either along subduction zones or along the lines where new ocean floor is created by the upward flow of material from the mantle and plates move away from each other. Volcanoes are regarded as indicators of tectonic activity, not only at present but also throughout the past; the geological record of volcanism is considered to be a record of the motions of plates. The ideas of plate tectonics influence the interpretation of geological data in surprising ways. For example, Dragoslav Ninkovich and William L. Donn of the Lamont-Doherty Geological Observatory argue that the motions of the plates must be taken into account in interpreting sequences of tephra layers in deep-sea sediments. They propose that the motion of a plate would over a period of time carry a sampling site from beyond the fallout range of a tephra source into that range, so that earlier parts of the record would lack tephra layers. If the site were assumed to have been stationary with respect to the source, then the record would be interpreted, in this view erroneously, to show no evidence of early volcanism when in fact that evidence would be lacking only because the site would have been beyond the fallout range at those earlier times.

A tephra mantle forms quickly everywhere throughout its extent. It represents the time of the eruption that created it wherever it is found, and this remains the case even if parts of the mantle later are removed by erosion or buried by younger deposits. In applying the principles of tephrochronology two things are essential. First, a tephra layer must be recognized and distinguished

from all other layers with which it might be confused; second, the age of the layer must be determined. If these tasks are accomplished, then any deposit or object that can be associated with the tephra layer is thereby dated. Some such associations may only establish that an event happened before or after the tephra fall, but others are more exact, as when an object is enclosed within a tephra layer or between two layers. It is helpful to know the identity of the volcano that produced the layer, but it is not strictly necessary.

Relative dating based on established sequences of geological strata, assemblages of fossils, pottery types, historical events and the like has long been an important part of geological research and remains so. In recent years, however, physical and chemical means of dating also have become essential; they depend little on judgment, and their results can be expressed in years rather than in less precise relative terms. All these dating methods are based on the measurement of properties that change regularly and predictably with the passage of time. The main ones are carbon-14 dating, potassium-argon dating, fission-track dating, obsidian-hydration dating and amino acid–racemization analysis. These techniques are costly and are dependent on the analysis of materials that are not always available; tephrochronology can extend the significance of the few analyses needed to date a tephra layer.

Tephras can be recognized individually by comparing their properties. Techniques for this purpose have been developed by, among others, Ray E.



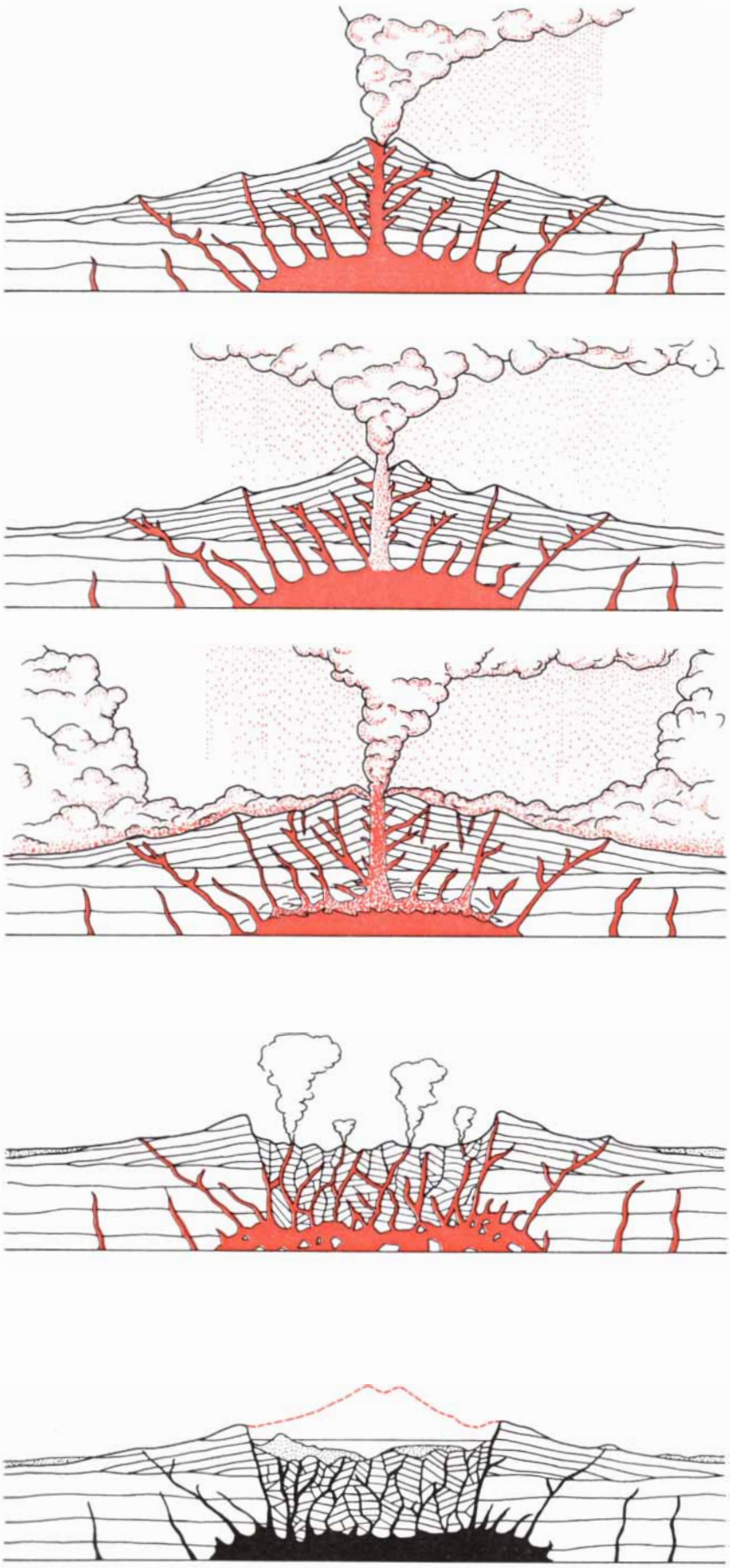
TWO UNUSUAL TEPHRA PARTICLES appear in these scanning electron micrographs made by Grant H. Heiken of the Los Alamos Scientific Laboratory. The glassy threadlike particle extending across the upper micrograph was recovered from the vicinity of Mauna Ulu volcano in Hawaii. Tephra particles of this kind, called Pele's hair, are characteristically produced in lava fountains consisting of low-viscosity basaltic magma. The prominent bulge in the glass envelope, which measures about 35 micrometers in diameter, contains an olivine crystal. The fragment of pumice in the lower micrograph is from the 1883 eruption of Krakatoa in Indonesia. This blocky particle of silica-rich glass had many small gas bubbles in it when it was ejected from the volcano, as can be seen from the characteristic array of elongated hollow structures that make up much of the bulk of this kind of tephra particle. The pumice fragment is about 250 micrometers long. The dustlike specks that adhere to it are smaller fragments of glass.

Wilcox of the U.S. Geological Survey and by Virginia C. Steen-McIntyre of Colorado State University. In such studies it is assumed that samples of tephra from one mantle resemble one another more closely than samples from different mantles do. Among the properties that can be examined are the mineralogical composition, the physical properties of the individual minerals, the grain size, the thickness, the color and the chemical composition of the entire tephra or any of its constituents. In general, characterizations based on more than one property are more reliable. A typical chemical study might include the analysis of as many as 30 trace elements, although comparisons among three or four elements might be adequate, particularly in combination with tests of other properties.

Collaborating with me, Keith Randle and Goles conducted a neutron-activation analysis of trace elements to characterize some tephras in the Pacific Northwest. The measured abundance of thorium and the abundance ratios of lanthanum to ytterbium served to distinguish among the tephras we examined. The tests showed that tephra layers found at certain archaeological sites came from Mount Mazama. Mineral abundances that I studied in the same tephras also varied from layer to layer and confirmed the source of the tephra layers at the archaeological sites. These findings were consistent with archaeological evidence of the antiquity of artifacts under the tephra. One of the archaeological sites was Fort Rock Cave, which was excavated by Luther S. Cressman and later by Steven F. Bedwell, both of the University of Oregon. Under the tephra Cressman found sandals made of sagebrush bark, one of which was dated by carbon-14 analysis and found to be some 9,000 years old.

An earlier tephrochronological study by Thórarinsson revealed 15 tephra layers from the eruptions of Mount Hekla, which he dated on the basis of archaeological and historical evidence. The earliest layer fell in A.D. 1104, two centuries after the settlement of Iceland; the latest fell in 1970. The eruptions of Mount Hekla have come at intervals that average 61 years; the shortest interval was 15 years and the longest was 120 years. The longer the volcano is in repose, the more silicic the tephra of the ensuing eruption is, so that long quiet intervals are likely to be followed by a large eruption.

Dwight R. Crandell, Donald R. Mullineaux, Wilcox and their associates at the U.S. Geological Survey have documented more than 25 tephra layers from Mount Rainier, Mount St. Helens and Mount Mazama in deposits in and near Mount Rainier National Park in Washington; all were shown by carbon-14 dating to have been deposited within the past 20,000 years. The layers have been



useful in correlating and dating the glacial deposits with which they are interbedded. One layer is interbedded with the deposits of a great flood in the Columbia River basin resulting from the sudden release of a glacial lake through the failure of an ice dam. The carbon-14 date of 13,000 years ago, previously obtained for the tephra layer, also dates the flood.

Deposits dating from the last ice age and earlier in the Great Plains region of the U.S. have been correlated with the help of tephra-layer evidence by John D. Boellstorff of the University of Nebraska. He recognized some 20 tephra layers that range in age from about 11 million years to 400,000 years. The tephra layers are interbedded among fluvial, windblown and glacial deposits. They were dated mainly by the fission-track method, and they can be distinguished from one another by their chemical characteristics, particularly their abundances of manganese, iron and samarium. Some of the tephras came from as far away as northeastern California and Yellowstone National Park in Wyoming.

William F. Ruddiman and L. K. Glover of the U.S. Naval Oceanographic Office found tephra particles dispersed in submarine sediments about 9,300 years old in the North Atlantic. The tephra particles are too coarse to have been carried by wind from the volcanoes nearest the sampling sites. Ruddiman and Glover believe the tephra was blown westward from volcanoes in Iceland and fell on pack ice drifting through the Denmark Strait. From thence the ice was carried southeastward by ocean currents into the North Atlantic, where it melted and dropped its burden of tephra on the ocean floor. The data are believed to indicate the existence of ocean currents flowing southward between Greenland and Iceland about 9,300 years ago. Such a deduction can serve in turn to aid in the reconstruction of the climatic patterns that may have prevailed at the time.

When tephra is dispersed over a large area, its effects spread with it. Consequences propagate through ecosystems, alter landscapes, nurture

FORMATION OF CRATER LAKE following the great tephra eruption of Mount Mazama in about 5000 B.C. is shown in this series of drawings, based on the work of Howel Williams of the University of California at Berkeley. An estimated 30 cubic kilometers of volcanic material was ejected from the volcano in the course of the eruption, depleting the magma chamber under it. The summit then collapsed into the empty chamber, creating the vast caldera, which subsequently filled with rainwater and melted snow to form the present lake. A smaller eruption in about the 10th century A.D. led to the emergence of Wizard Island from the floor of the caldera.

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VOLKSWAGEN DOES IT AGAIN

soils and influence climate. They are brief, prolonged or delayed, subtle or conspicuous. Some aspects are as yet poorly understood, and research is only beginning on means of recognizing consequences in the historical record.

In the case of large eruptions the effects near the volcano are anything but subtle. The land is buried under tens of meters of tephra, and the vegetation is destroyed. Farther away, however, the tephra is not hot enough when it falls to start fires, and at the margin of the tephra mantle the accumulation may be only a few millimeters thick.

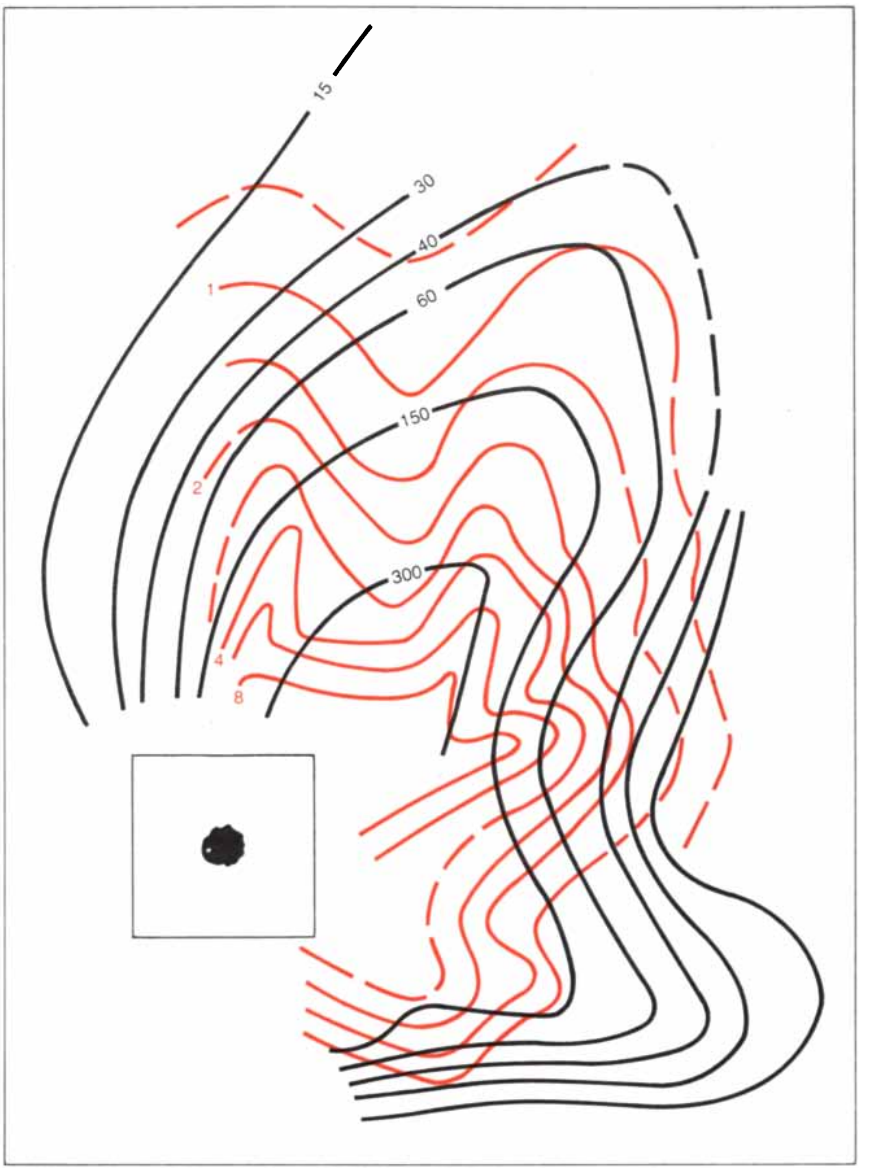
The responses of plants are varied. Trees may be damaged by the weight of clinging tephra, and shorter vegetation is often smothered. The larger and more mobile animals may not be harmed, but they may move out when their food is gone. The response of animals is not easy to predict. A geologist watching the eruption of Paricutín in Mexico in 1943 told of his group's dismay when an unexpected burst of activity caught them near the crater; the dog that was with them, however, was curled up asleep in the warm tephra on the ground.

Freshly fallen tephra can give off substances that are poisonous in sufficient concentration, mainly carbon dioxide, fluorine, chlorine and compounds of sulfur. After the eruption of Laki in Iceland in 1783 nearly 80 percent of the sheep in the country died of fluorine poisoning, which they got from eating contaminated grass. Measurements made after the 1970 eruption of Mount Hekla showed as much as 4,000 parts per million of fluorine in dry grass; 250 parts per million would kill livestock in a few days.

Studies by William I. Rose, Jr., of the National Center for Atmospheric Research and by Paul S. Taylor and Richard E. Stoiber of Dartmouth College indicate that tephra particles may scavenge substances from the eruption cloud. These investigators leached freshly fallen tephra in water and analyzed the solutions they obtained. Apparently sulfur, chlorine and fluorine in the eruption cloud quickly form acidic aerosols that adhere to tephra particles and react with them to form salts that are dissolved by rain. The tephra fall from the volcano Cerro Negro in Nicaragua in 1968, for example, had a volume of about 13 million cubic meters, from which there may have been released into the environment, among other elements, some 8,900 tons of chlorine, 140 tons of fluorine and 2.1 tons of copper.

In spite of the apparent devastation caused by tephra falls, recovery can be rapid. After the initial prolonged eruption of Paricutín oak trees survived where the tephra was less than 1.5 meters deep, and grass lived to send out new shoots where it was buried by as much as 25 centimeters of tephra. The eruption of Mount Katmai in Alaska in 1912 deposited 25 centimeters of tephra on Kodiak Island, where low vegetation was smothered and the branches of trees were weighted down. By September plants sprouted from crevices in the compacted tephra. Most of the trees survived and replaced their damaged foliage, and by 1915 grasses and other low vegetation were thriving. Icelanders have traditionally resumed their normal routine after a volcanic eruption by clearing tephra from fields and around buildings; today they are aided by machines.

Not all the effects of tephra are harmful. Repeated tephra falls in the Tropics probably renew the fertility of the soil, which otherwise would be quickly leached of nutrients in the prevailing climate. Generally tephra seems to have a mulching effect, improving moisture-holding capacity and enhancing fertility. Studies of Mount Mazama tephra by Frederick W. Chichester of Oregon State and by Ronald R. Tidball of the



CONTOUR MAPS of the tephra mantle resulting from the eruption of Mount Mazama trace lines of equal thickness in centimeters (*black*) and lines of equal median grain size in millimeters (*color*). The different shapes of the two sets of contours demonstrate the general rule in volcanology that the direction in which the greatest volume of tephra is carried need not be the same as the direction of travel of the largest particles. In this case, for example, the absence of a detectable eastern lobe in the grain-size contour map suggests (among other possible explanations) that a westerly wind at a high altitude might have carried a large volume of comparatively fine-grained tephra particles eastward, dispersing them over a much larger area. The overall shape of the mantle in both maps indicates that the main winds during the tephra fall were from the southwest. The map of equal-thickness contours was originally drawn by Williams; the map of equal-grain-size contours was prepared by Richard V. Fisher of the University of California at Santa Barbara. The square outline at lower left shows the extent of the Landsat image reproduced on page 161; Crater Lake is drawn to scale at the center of the square.

University of California at Berkeley indicate that intricately shaped glassy particles hold water through capillarity, thereby prolonging storage and keeping moisture in contact with the glass, which easily decomposes chemically, releasing nutrients. The Mount Mazama tephra, in which there are few obvious signs of soil formation, supports forests of ponderosa pine and lodgepole pine.

After prolonged weathering and burial glassy fragments change to clay minerals, mainly montmorillonite, and most of the glassy tephras of Miocene age (between five and 22 million years old) or older have been partly or entirely transformed into clays. One of the most conspicuous properties of montmorillonite is its stickiness when wet. This property is familiar to anyone who has tried to drive on a wet unpaved road in terrain underlain by altered tephra, a common experience in the Western states.

Tephra the size of dust that reaches very high altitudes is carried around the world by stratospheric winds as a kind of haze, dubbed the volcanic dust veil by Hubert H. Lamb of the University of East Anglia. The dust may remain suspended for years in the stratosphere, where one of its effects is the attenuation of the solar radiation that reaches the ground. Lamb developed a method of quantitatively assessing the intensity of the dust veils produced by eruptions in historic times in a way that is uniformly applicable to modern eruptions and to earlier ones for which accurate instrumental observations are not available. Recently Bernard G. Mendonca and his colleagues at the National Oceanic and Atmospheric Administration reported daily observations of the transparency of the atmosphere in Hawaii between 1957 and 1977. Their measurements showed a significant decline in transparency during the upsurge of explosive volcanism between 1962 and 1966. Some investigators believe such changes, if they are protracted, can influence climate by lowering the average global temperature and can perhaps even contribute to the initiation of glaciation.

The mere mention of volcanoes is likely to evoke images of rivers of lava and fountains of incandescent molten rock. Nevertheless, volcanic eruptions that produced mainly tephra are among the most notorious, as the following examples will convey.

In about 5000 B.C. a volcano on the crest of the Cascade Range in southern Oregon erupted cataclysmically, spreading tephra over an area of almost a million square kilometers. The volcano was Mount Mazama, which during the last ice age grew to a height of perhaps 3,700 meters. The mountain supported glaciers from time to time, and eruptions of glassy lavas from vents on its upper slopes sometimes filled and overflowed *U*-shaped glacial valleys. Then came the tephra eruption, first a tephra fall and then a lesser pyroclastic flow, together more than 30 cubic kilometers of volcanic material. The summit of the mountain, left without the support of the magma that had been inside it, collapsed. That it collapsed rather than blew up is indicated by the absence of rocky fragments in the tephra. The collapse occurred along steep, curved fractures girdling the top of the volcano, so that today an unbroken circle of great cliffs faces a central basin that contains a lake: the centerpiece of Crater Lake National Park. In about the 10th century a small basaltic cone, Wizard Island, grew up from the floor of the depression and then stopped growing. Is the volcano now dead? I believe few volcanologists would say so.

It is known that people lived around the mountain when it erupted, because artifacts have been found both above and below the tephra layer, but research in progress has yielded only a little evidence of the effects of the tephra fall on human populations and the plants and animals that sustained them. What did witnesses to the eruption think of it? Some evidence may have survived. Ella Clark of Washington State University, a compiler of native American traditions from the Pacific Northwest, has reported a legend attributed to the Klamath people, who call the mountain Lao Yaina. The story relates that the Chief of the Below World, who lived within the mountain, was angered by the refusal of a young woman to become his wife, and he vowed to destroy her people with the Curse of Fire. He stood raging at the summit, fire spewing from his mouth, and the mountain shook and rumbled. Red-hot rocks hurtled through the sky, burning ashes fell like rain and flame devoured the forests. The people prayed to the Chief of the Above World, who caused the Chief of the Below World to be driven back inside the mountain, and the top of the mountain fell in on him. In the morning the high peak was gone. The essence of the modern interpretation is all there, in a spoken tradition that may have endured for 7,000 years, although perhaps some allowance should be made for the possibility of embellishment by later translators with some knowledge of modern geology.

In the eastern Mediterranean the volcano Thera, on an island in the Aegean Sea, erupted in about the middle of the 15th century B.C., spreading tephra southeastward over an area that includes Crete. At that time Crete was the center of the Minoan civilization, a society of maritime traders who dominated the Aegean and extended their influence throughout the eastern Mediterranean. The people had houses with several stories, courtyards and sewers. Their arts are magnificent, particularly their frescoes depicting the sport of bull vault-

ing. Archaeological excavations have revealed that the Minoan culture declined and disappeared suddenly after about 1450 B.C. Archaeologists have been puzzled by the unusual suddenness of the collapse, and when the approximate date of the Thera eruption became known, it was proposed that the tephra fall was the cause. The matter has been investigated by Dorothy B. Vitaliano of the U.S. Geological Survey. Data from submarine core samples analyzed by Norman D. Watkins and his associates at the University of Rhode Island indicate that as much as 10 centimeters of tephra may have fallen on eastern Crete, perhaps not enough to destroy a flourishing civilization but enough to be harmful. One carbon-14 date shows that the volcano probably erupted between 1499 and 1413 B.C., but Vitaliano found tephra from Thera in Minoan buildings that had been abandoned and covered by about 1500 B.C., according to the dating of artifacts in the area. The mystery will not be solved until more accurate dates are available, but for now it appears that the Minoan society remained vigorous for some decades after the eruption of Thera. Vitaliano believes the tephra fall could have contributed to the decline, together with later natural and political events.

Perhaps the most famous volcanic eruption in Western history is that of Mount Vesuvius on August 24, A.D. 79. It is famous because of a tephra fall that buried the Roman city of Pompeii, preserving it intact until modern times, along with the many articles of daily life abandoned when their owners fled. Most of the 20,000 residents seem to have escaped, but 2,000 skeletons have been found, along with cavities in the tephra that are the molds of bodies. Plaster poured into the cavities makes a cast, the surface of which preserves details of the body, including hair and clothing. The victims often had their hands over their face, as though to ward off suffocating gases, and it is likely that the tephra did give off gases such as carbon dioxide and sulfur dioxide. Some of the dead had been carrying bags of coins. A number of the skeletons were found well above the bottom of the tephra layer, an indication that people survived the early part of the tephra fall only to die later.

The study of tephra for its own sake and for what it can tell about the past is rewarding enough, but there is a further reason for such an undertaking, if one is needed: people living today are not immune to events such as those that overtook the people of the Pacific Northwest, Crete and Pompeii. Tephra falls cannot be prevented, but knowledge of their characteristics can help scientists, public officials and citizens in general to forestall chaos, prevent loss of life and limit damage.

THE AMATEUR SCIENTIST

The physics and chemistry of a failed sauce béarnaise

by Jearl Walker

One of the most difficult sauces to prepare is sauce béarnaise, a warm emulsified concoction consisting primarily of dilute vinegar, wine, egg yolks and butter. For many cooks the blending of this sauce verges on alchemy. The difficulty is not only that the preparation is demanding but also that even when the preparer seemingly does everything right, the sauce can still go bad, coagulating into a repellent mess.

Two recent scientific papers have discussed how to salvage a coagulated sauce béarnaise. C. M. Perram, C. Nicolau and J. W. Perram argued in *Nature* that a coagulated sauce can be resurrected by adding a small amount of dilute acetic acid (vinegar) and then stirring the sauce vigorously. (The word coagulated may be incorrect. The authors probably meant to describe a reversible aggregation of the droplets of butter in the sauce; true coagulation is irreversible.) The stratagem of adding an acid appears to have been known earlier; Julia Child, the popular cooking expert, has recommended adding lemon juice (citric acid) to rejuvenate the sauce.

The second paper was published in *The New England Journal of Medicine* by D. M. Small, a biochemist in Boston, and Michael Bernstein, a chef at a French restaurant in Rochester. They point out that the *p*H of the solution (the measure of its acidity or alkalinity) appears to have no effect on the temperature at which the sauce goes bad and hence that the addition of an acid to prevent coagulation is unnecessary. Instead they recommend that the sauce be briskly stirred into a clean container with a small amount of water. Some of my own cookbooks make a similar recommendation.

Which technique is correct? Does the acid level matter? Why is sauce béarnaise so hard to make? Why does it go bad? To answer these questions one must first understand the physics and the chemistry of the sauce, both of which are fairly complex and not yet fully understood in fundamental terms. Here I shall describe what I understand of the sauce in terms of emulsions and colloidal suspensions. If you pursue the subject, you can correct and expand my picture. Recipes for preparing the sauce vary slightly, differing primarily in the method of mixing in the egg yolks and of heating the sauce. I shall follow the recipe outlined as the "professional method" in *The Making of a Cook,* by Madeleine Kamman. (This fine cookbook actually explains some of the science involved in cooking.) Kamman's list of the ingredients for the sauce appears in the illustration on page 184.

The first task is to make an infusion of wine, vinegar, shallots, 1½ teaspoons of tarragon, one teaspoon of chervil, three teaspoons of fresh parsley, a bay leaf, salt and white pepper. The infusion is cooked over low heat until only five teaspoons of liquid remain when you press the herbs with the back of a spoon. The egg yolks are added and the mixture is stirred with a wire whisk over low heat until it is thick. Kamman warns that if the pot is thin, a pad of asbestos or metal should be put under it to protect the mixture from hot spots and rapid heating. If the mixture is overheated at this stage, the product will amount to scrambled eggs (actually denatured egg yolk) floating on an infusion of herbs.

The mixture is removed from the heat and the warm butter is dribbled into it. The butter must be added in a slow stream to facilitate the making of an emulsion. If it is added too quickly, it will separate into a layer. Once the butter is added the emulsion is drained through a coarse strainer into a warm bowl. The strainer should be sufficiently fine to remove the herbs but not the butter droplets.

After preparing the basic emulsion you make a mixture of the remaining herbs. Mix one teaspoon of tarragon and one teaspoon of chervil into a tablespoon of boiling water. Add the rest of the parsley and a good pinch of cayenne pepper. (Kamman defines a good pinch as the amount "you can pick up on the tip of a paring knife.") Everything is added to the strained sauce. The sauce is to be served warm to accompany broiled red meats, chicken, fish and even poached eggs.

The sauce can be described as a colloidal suspension of solid or semisolid particles, mostly the fat of the butter, in a liquid medium of water, acetic acid, salt and various other ingredients. Colloidal suspensions are characterized by having particles with diameters of between one micrometer and 100 micrometers. The term colloidal is usually reserved for a suspension of solid particles in a liquid, but it is also employed loosely for the sauce in spite of the semiliquid nature of the particles. The term emulsion also describes the sauce, since sauce béarnaise is a dispersion of two immiscible liquids (butterfat and water), with one of them forming droplets in the other.

Regardless of terminology, the stability of the sauce depends on the correct interplay of the forces holding the particles or droplets in suspension. A failure of the sauce to turn out right arises because the delicate balance of those forces can be broken by variations in the ingredients or by careless overheating of the sauce. Both papers agree that attractive forces operate to aggregate the suspended particles or droplets, but they disagree on the nature of the repulsive forces countering the attraction. Each paper may be partly correct.

According to Perram, Nicolau and Perram the colloidal particles are micelles (electrically charged aggregates of large molecules) consisting of phospholipids, fats, proteins, cholesterol and several long-chain fatty acids. The particles are hydrophobic, so that they do not bond to water, and globular. (These descriptions may not reflect the usual terminology employed for colloids. The contention of these authors that the particles are lyophobic, that is, do not bond to the liquid medium, is an important concept to question later on.) The authors do not consider the possible role of the wine in the sauce, instead regarding the liquid medium as consisting of water, acetic acid, sodium chloride and dissolved molecules from the herbs. For the sake of simplicity I shall disregard both the wine and the herbs. Although these ingredients may be important to the science of the sauce, most of the interesting features of emulsions and colloidal suspensions can be displayed without them.

Perram, Nicolau and Perram think the key to the stability of the sauce lies in two electrical interactions of the colloidal particles, a repulsive Coulomb force and an attractive van der Waals force. The van der Waals force is a relatively weak one attributable primarily to the attraction between electric dipoles

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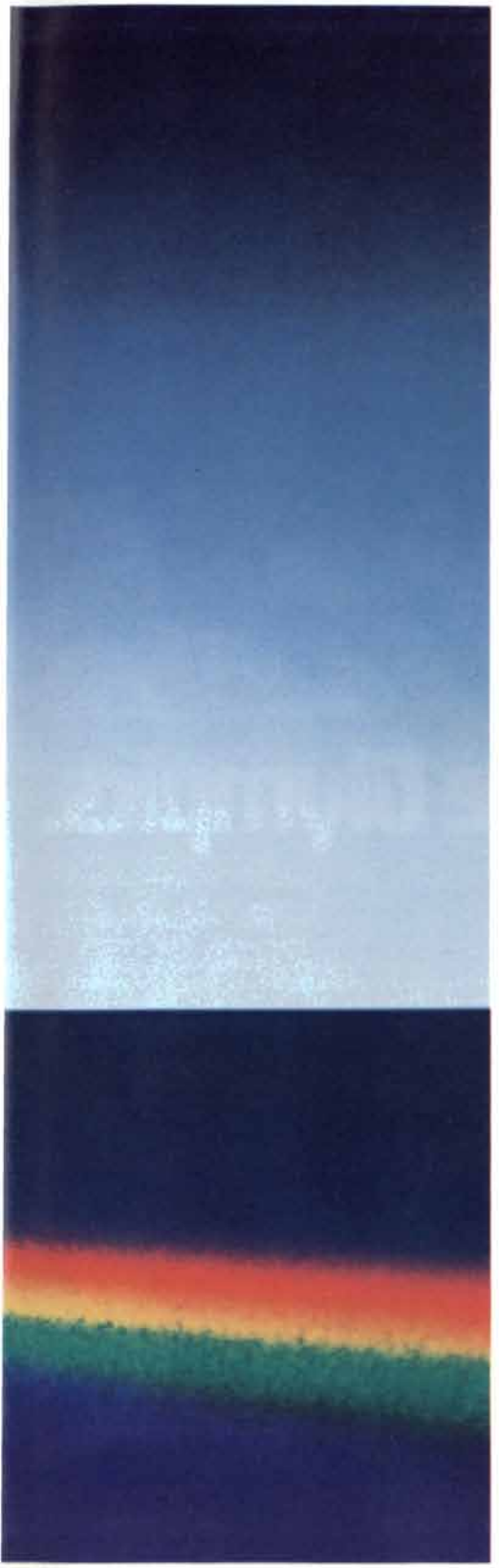

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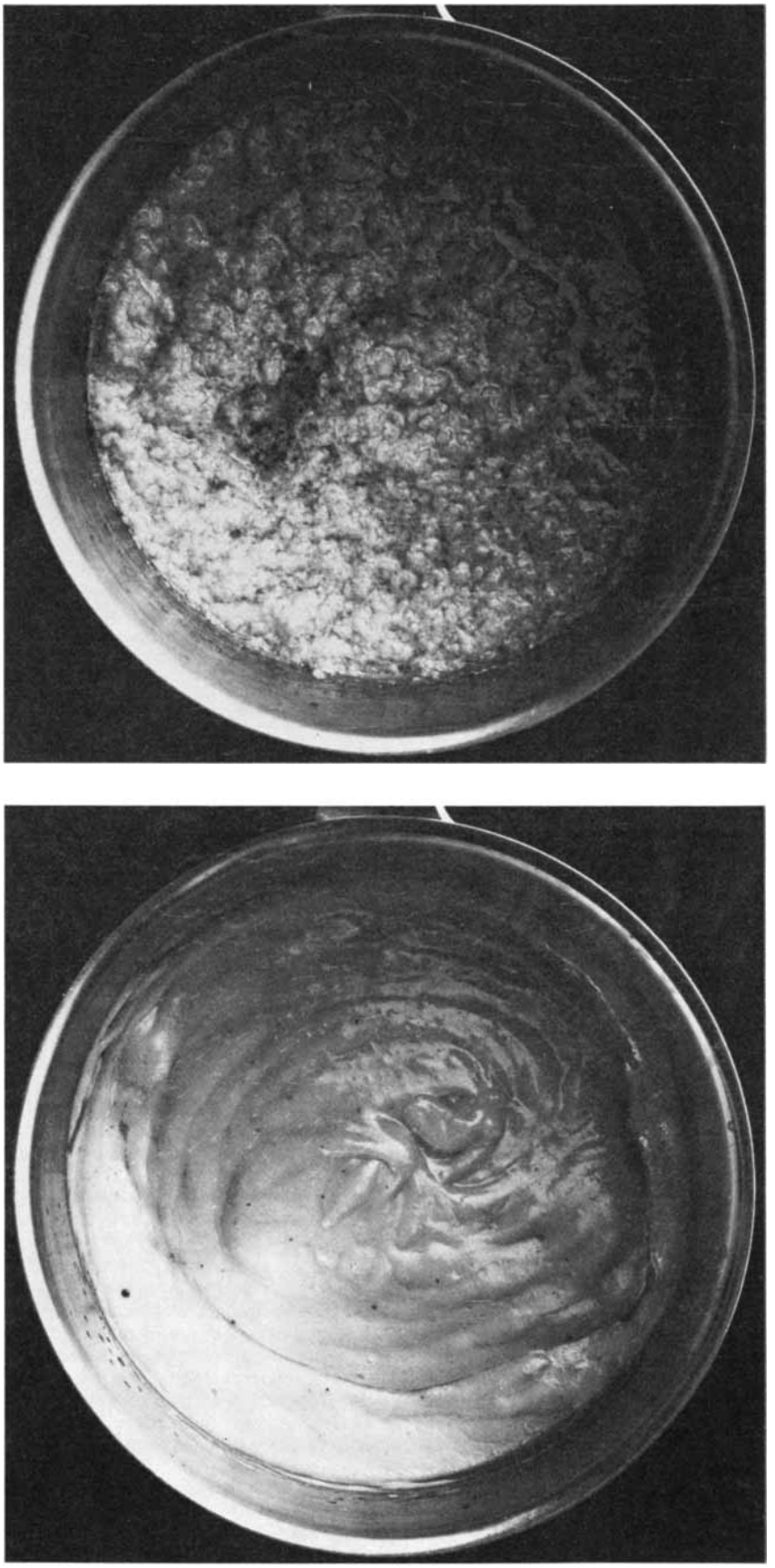
in two neighboring colloidal particles. Consider an electrically neutral molecule. If the centers of positive and negative charge in the molecule coincide, the molecule would display no external electric field. If the centers are separated, they constitute an electric dipole. An external electric field would arise even though the molecule itself is electrically neutral. Two such neighboring molecules can arrange themselves so that their electric dipoles attract each other, creating an attractive force between the molecules.

A molecule can have an electric dipole for three possible reasons. First, the charge distribution may be such that a dipole is always present. Second, a nonspherical molecule may have a dipole induced by a neighboring molecule that has a dipole. Third, quantum-mechanical fluctuations in the charge distributions may give rise to induced dipoles in two neighboring molecules.

The molecules of a colloidal particle will tend to align themselves so that they give the particle a net dipole. Hence neighboring colloidal particles will be attracted to one another by the van der Waals force between them. Specialists in colloids often call this force a dispersion force. I find the term misleading, since the force is attractive.

The van der Waals forces between the particles in sauce béarnaise are relatively weak and so do not come into play unless the particles are quite close. With a microscope one sees that the particles are normally close enough for this force to be important. If the sauce is kept cool, the colloidal particles are unlikely to touch one another with a frequency that would allow the van der Waals forces to make them coalesce into pools of butter. The sauce is heated during its preparation, however, and is served warm. The thermal motion of the molecules of the sauce sets the colloidal particles in Brownian motion. A warm sauce is likelier to coalesce because the Brownian motion makes collisions between particles more frequent.

The authors of the two papers differ primarily in their description of what prevents coalescence. Perram, Nicolau and Perram contend that a second electric interaction between neighboring particles counters the van der Waals force. Adhering to the surface of each particle is a layer of charge derived from the ionized molecules fixed to the droplet or from ions collected out of the liquid. These authors believe the colloidal particles in the sauce have a negative surface charge. Outside the surface is more negative charge, but its concentration decreases with distance. In the fluid layer adjacent to the surface is a positive charge distributed so that the net electric potential is increased from its value on the surface of the particle to the value of



Failure* (top) *and success* (bottom)*: a lumpy sauce béarnaise and a smooth one

the liquid at a distance from the surface. This arrangement of charges is called a diffuse double layer because of the intermixing of opposite charges. When two colloidal particles attempt to collide (because of the thermal motion and the van der Waals force), repulsion develops as their atmospheres of charge begin to overlap. The nature of the repulsion is the same as that of any electrostatic (or Coulomb) repulsion between charges of the same sign. The particles can aggregate only if the repulsion cannot prevent them from touching.

When warm (not overheated) sauce béarnaise fails, the reason may be an insufficient surface charge on the colloidal particles. With less surface charge the diffuse double layer is less charged and the particles can collide and adhere. Perram, Nicolau and Perram maintain that the negative charge on the butter droplets is due to the adsorption of ionized acetic acid provided by the vinegar. This argument is open to question, since the volatile acetic acid may be partly lost as the infusion is heated before the egg yolks are added.

Although the role ascribed to the attractive van der Waals force is likely to be correct, the one ascribed to the acetic acid may be wrong. Another way to view the sauce is as an emulsion of butterfat and water, which become emulsified because of an ingredient of the egg yolk. Whereas the acetic acid is responsible for the stability of the lyophobic suspension of micelles in Perram, Nicolau and Perram's model, it is the yolk to which I shall now turn as the source of the stabilization in a lyophilic suspension that involves bonding between the particles and the water.

½ cup white wine
⅓ cup vinegar (wine or cider)
2 tablespoons minced shallots
2½ teaspoons dried tarragon (or 2½ tablespoons if fresh)
2 teaspoons dried chervil (or 2 tablespoons if fresh)
4 teaspoons finely chopped fresh parsley
¼ bay leaf
⅓ teaspoon salt
½ teaspoon cracked white pepper
3 egg yolks
½ pound unsalted butter, melted
1 tablespoon boiling water
Cayenne pepper

1 teaspoon is approximately 5 milliliters
1 tablespoon is approximately 15 milliliters
1 cup is approximately 237 milliliters

The ingredients of the sauce

Unfortunately no one overall explanation of emulsions is available, but the major theories are grouped into two classes. One set of theories emphasizes the geometrical arrangement of the molecules on the surface of the droplets and the strength of the film of molecules at the interface of the two liquids. The other set, which is quite similar to the theories involving true colloidal suspensions, argues for an electric interaction between the particles. The connection between these two approaches to emulsions is hazy. The stability of sauce béarnaise may involve components of both theories. I think the difference between the two papers on the sauce reflects this difference in the theoretical explanations of emulsions.

To create the emulsion of water and butterfat in the sauce one adds egg yolks to provide the emulsifying agent for the two immiscible liquids. Generally such emulsifying agents have two purposes. One purpose is to lower the surface tension at the interface of the two liquids so that droplets of one of them can form. The other is to stabilize the droplets, preventing them from aggregating and coalescing and thereby separating into layers. In an emulsion of oil and water the molecules of the emulsifying agent will usually have on one end a lipophilic group, which is attracted to the butterfat. Normally the other end has a polar group, which is attracted to the water. (A polar molecule has its negative charge permanently separated from its positive charge. Because water is polar a molecule of water and another polar molecule can orient themselves so that they electrically attract each other.) In the sauce the butter droplets are covered with the emulsifying agent lecithin, which is provided by the lipoproteins in the egg yolks. The lecithin orients itself to present its polar end, called livetin, to the water and its lipophilic end to the butterfat droplet. In the conventional terminology of colloidal suspensions this arrangement is termed lyophilic because the particles (droplets) bind the liquid medium (in this case water) to their surface.

The layer of water molecules surrounding each droplet helps to prevent it from coalescing with other droplets. Although the water molecules are held in place by an electric interaction between polar molecules, this preventive effect is not due to the electric interactions between colliding particles I described above. In that instance the two particles were repelled from each other because of the electrostatic repulsion between the diffuse double layers on each particle. This time the preventive effect comes from the strength of the film of water molecules held in place on the drops, preventing the drops from touching and coalescing.

If the lecithin carried a charge, it could also create a diffuse double layer around each particle. Presumably two colliding particles would then be kept from coalescing by the electrostatic repulsion from their diffuse double layers and by the protective coating of bound water molecules. Small and Bernstein point out that lecithin is uncharged in a medium with a *p*H of 6, which is the *p*H of sauce béarnaise. Without a charge it would appear that the lecithin from the egg yolk protects the sauce against aggregation because of the layer of water it binds rather than because of an electrostatic repulsion.

An example of an emulsion involving an electrostatic interaction is oil and water emulsified with soap. A molecule of soap on the surface of an oil droplet orients itself so that its lipophilic component is toward the oil and its polar component, which is a negatively charged carboxyl group, is toward the water. Part of the strength of the emulsion may lie in the strength of the film of water molecules held in place around the oil droplet. Part is also due to the particular arrangement of charge at the surface. The negative carboxyl group, which is fixed to the surface of the droplet, attracts positive ions (such as potassium in a potassium soap) that lie in the liquid layer just outside the surface. The double layer of negative and positive charges therefore provides an electric repulsion between two colliding drops, and in this way it prevents them from coalescing.

Mayonnaise is another common emulsion (although the medium is semisolid rather than liquid), consisting of vegetable oils in dilute vinegar or lemon juice. Its emulsifying agents are egg yolks, extra lecithin and other additives. Mayonnaise is an oil-in-water emulsion. So is sauce béarnaise, although Small and Bernstein describe it more adequately as an oil-and-air-in-water emulsion because of the air whipped into the mixture to lighten the sauce.

Recipes for sauce béarnaise have traditionally called for the use of fresh eggs. Although this requirement may be partly based on personal preference, it could have some basis in the aging of the emulsifying molecules. If a yolk is to function well as an emulsifying agent in an oil-in-water emulsion, it must have a fairly high ratio of lecithin to cholesterol. Whereas the lecithin serves as an emulsifying agent for oil-in-water emulsions, cholesterol is an emulsifying agent for the opposite, a water-in-oil emulsion. When an egg is stored for any length of time, its lecithin apparently breaks down but its cholesterol does not. The ratio of the two is therefore reduced and the yolk does not serve as well in oil-

SCIENCE/SCOPE

A new ring and moon around Saturn were among the discoveries made by NASA's Pioneer 11 spacecraft during the historic first flyby of the giant planet in September. The spacecraft's electronic camera, an imaging photopolarimeter, also supplied close-up pictures of Saturn's banded cloud structure. Another instrument, an infrared radiometer, found atmospheric temperatures from -279° to -288°F on Saturn and its largest moon, Titan. The readings for Titan reduced the possibility of biologic activity in the organic gases of the moon's reddish smoglike atmosphere. The polarimeter and radiometer were built for NASA's Ames Research Center by the Santa Barbara Research Center, a Hughes subsidiary.

Two obstacles to the advent of phased array radars -- high cost and weight -- are being overcome at Hughes with innovations in technology and manufacturing. Tiny diode phase shifters now generate the same power as their bulkier ferrite counterparts. The many wires that required individual connections and testing are giving way to thick-film fabrication, in which circuits are "silkscreened" onto aluminum wafers. In fact, it's now possible to place radiators, phase shifters, and power dividers onto single substrates -- building blocks that can be assembled into larger sections before undergoing initial tests.

A gyroscope based on integrated optics technology promises to find important uses in missiles, aircraft, and the Space Shuttle. The new fiber-optic rotation sensor is less expensive, more compact, and longer lasting than conventional devices. It consists of a coil of fiber-optic cable and a one-inch-square chip containing a laser, beam splitters, a modulator, detectors, and data-processing circuits. The sensor detects motion by sensing changes in the path of light going in and out of the fiber-optic coil. Hughes is developing chips for NASA's Jet Propulsion Laboratory.

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Weapons equipped with electro-optical sensors can be guided with pinpoint accuracy from an aircraft by a specialized communications system. The new AN/AXQ-14 data-link weapon control system, developed by Hughes for the U.S. Air Force, performs two functions. First, it receives pictures from the electro-optical seeker in the nose of a GBU-15 guided weapon so the operator can guide the weapon to a target. Second, it transmits guidance signals from the aircraft to the weapon. Tests have been made in launchings from F-14, F-111, and B-52 aircraft.

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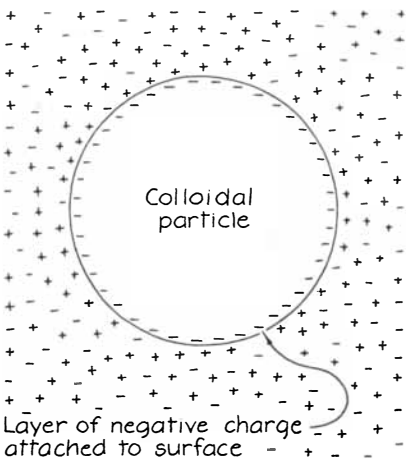


The charges on a colloidal particle

in-water emulsions such as sauce béarnaise and mayonnaise.

Two types of aggregation can be seen in sauce béarnaise. If the aggregation is reversible, it is called flocculation. If it is irreversible, it is called coagulation. The physical differences between the two are not well understood, and I am not certain that coagulation in the sauce involves anything more than the denaturing of the proteins from the egg yolks.

Small and Bernstein tested the temperatures at which the sauce will flocculate and coagulate. When they prepared a sauce with water instead of vinegar, the sauce flocculated at about 70 degrees Celsius (158 degrees Fahrenheit) and appeared to coagulate at temperatures between 70 and 80 degrees C. On coagulation the cooked egg floated to the surface. When the investigators tested a sauce prepared with the normal amount of vinegar, flocculation developed at about the same temperature, but coagulation was not observed even at 90 degrees.

Since the addition of vinegar did not alter the temperature of flocculation, Small and Bernstein concluded that the vinegar plays no role in preventing flocculation at lower temperatures. This conclusion could be wrong, however, if one argues (as is done in theories of colloidal suspensions) that when the sauce is heated, the impact of molecules on a particle eliminates the net charge on its surface, thereby compressing its diffuse double layer and making flocculation more likely. Hence one expects about the same temperature for flocculation regardless of the role of acetic acid at temperatures below the flocculation temperature.

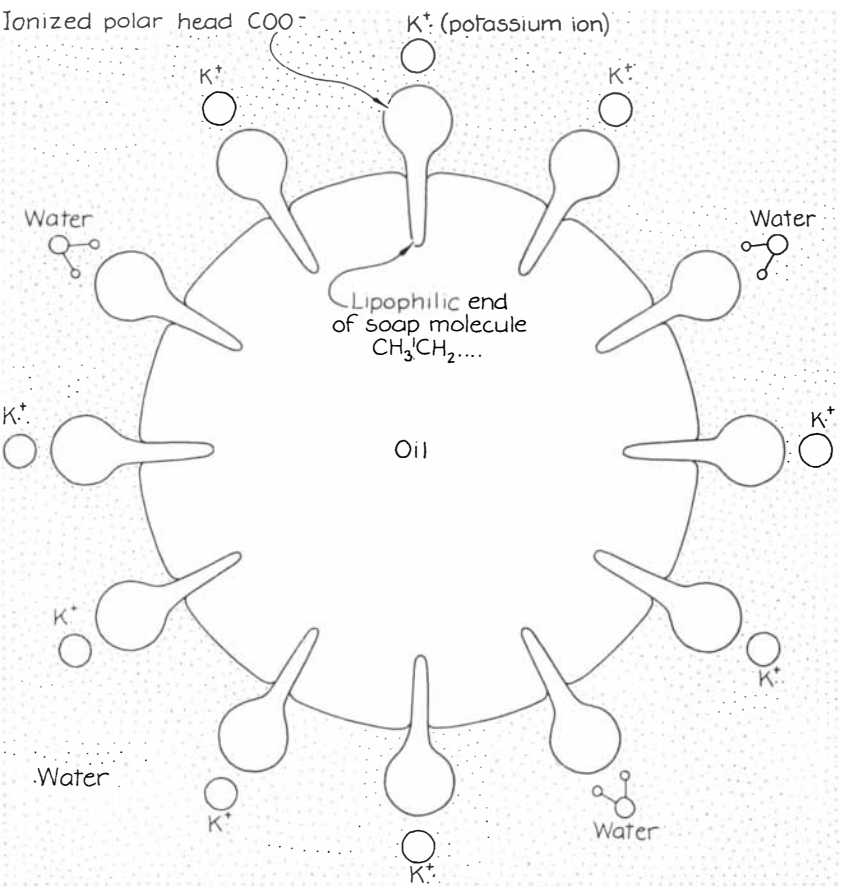
The thickness of the diffuse double layer surrounding the particles depends on the inverse of the square root of the concentration of ions in the electrolyte (an ionic solution). If the ion concentration is increased, the layer is compressed. At first flocculation would seem to be likelier, but the situation is probably not that simple. If an electrolyte is added to a lyophobic colloidal suspension (one that does not involve binding the liquid), one of three things can happen: (1) more charge can be adsorbed onto the surface of the particles, thereby increasing the surface charge and thickening the diffuse layer; (2) the electrolyte can neutralize the particles, eliminating the diffuse layer and thus causing flocculation, and (3) the added electrolyte can change the sign of the charge adhering to the particles, re-creating a diffuse double layer but with interchanged positive and negative charges.

Generally positive colloidal particles in lyophobic suspensions are neutralized by alkalis. If the colloidal particles are negative, they should be neutralized by the addition of acids. I do not know if this general rule holds for the sauce.

Electrolytes that release multivalent ions (ions with more than a single unit of charge) can have much stronger effects than those releasing univalent ions. For example, the bivalent ions released by Epsom salt (magnesium sulfate) should have a stronger effect than the univalent ions released by table salt (sodium chloride). If colloidal particles are negatively charged, they should be readily neutralized and then flocculated by multivalent positive ions released by the added electrolyte.

For some reason the negative ions released by the electrolyte play a minor role. With positively charged colloidal particles the effect is the opposite. The multivalent negative ions should readily neutralize the particles and so cause flocculation. For some equally mysterious reason the positive ions released by the electrolyte also play only a minor role. All the possible conditions of lyophobic suspensions come under what is called the Schulze-Hardy rule, which has three parts. First, flocculation of the particles is caused by ions opposite in electric charge from the charge of the particles. Second, the ions with charges of the same sign as that of the particles participate little. Third, the ability of an electrolyte to neutralize the particles and so flocculate the suspension increases dramatically with the valence of the ions it releases. Because of the Schulze-Hardy rule ingredients that release multivalent ions should be avoided in recipes for sauce béarnaise.

At the risk of discouraging you with



The emulsifying effect of a soap molecule on oil and water

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the complexity of the sauce, let me cautiously point out that the suspension may not be lyophobic at all, in which case all the above arguments would not be applicable. If the particles are charged and the mechanism that prevents them from flocculating is the diffuse double layer, the arguments are valid. If the particles are uncharged and the antiflocculation property stems from the layer of bound water, the arguments are not valid.

In a lyophilic suspension the addition of an electrolyte can have results that are much different from those in a lyophobic suspension. Salts may lead to flocculation, but only if they are added in relatively large concentrations, perhaps so large that this possibility is meaningless where sauce béarnaise is concerned. In nearly all lyophilic suspensions it is the negative ions released by the added electrolyte that figure in flocculation. The Schulze-Hardy rule therefore does not apply, and no significant difference in the flocculation of the suspension results from the valence of the ions that are released. When one compiles a list of the ability of certain salts to flocculate a lyophilic suspension, however, one finds that sulfates generally work better than chlorides, a fact I tested with my own sauce.

Before I try to resolve some of the arguments about sauce béarnaise let me summarize the ways the sauce can fail. It may be that not enough egg yolk or water is added or that the butter is put in too fast. The effect in each instance is to prevent the full emulsification of the mixture. The sauce can be carelessly overheated to the point of flocculation, which can be remedied, or coagulation, which cannot. The vaporization of the acetic acid during the initial heating of the infusion could diminish it as a source of the negative charge required by the colloidal particles later on. The interfacial film of water molecules protecting the particles may somehow be broken. Finally, the ions in the liquid may neutralize the particles.

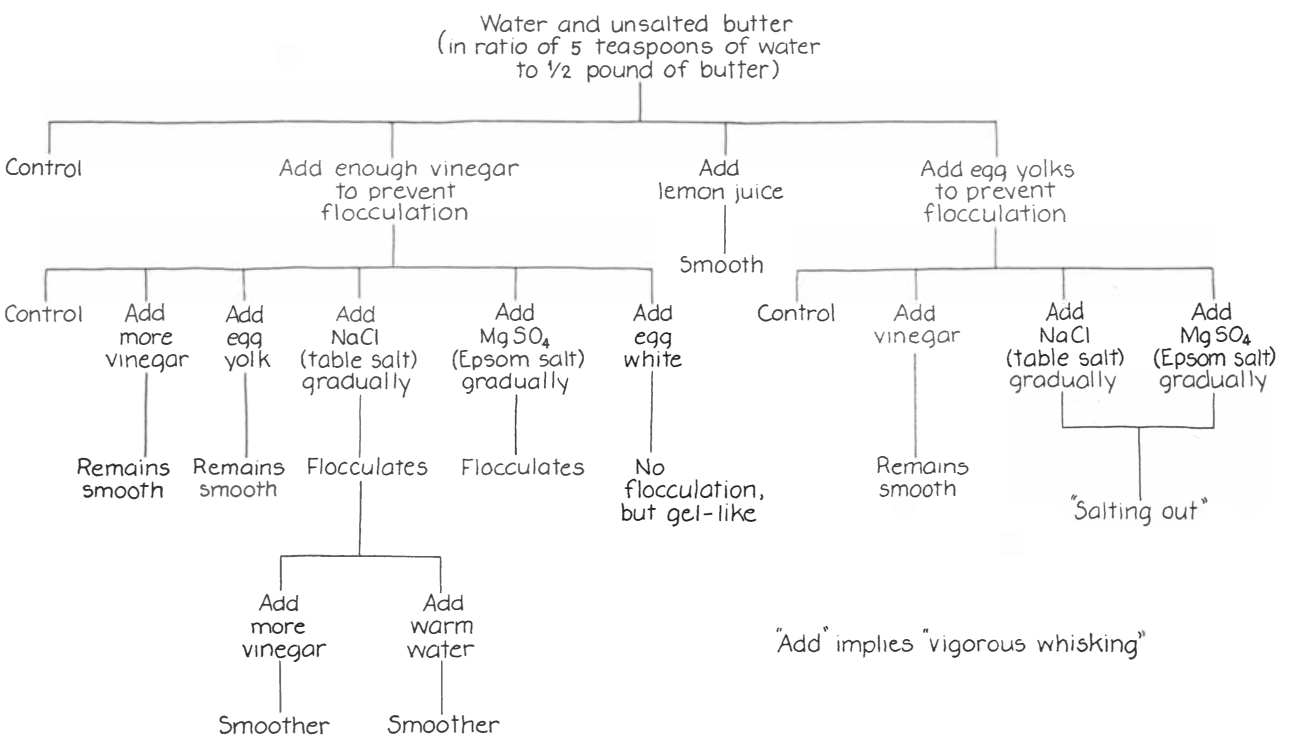
How might a flocculated sauce be remedied? Perram, Nicolau and Perram (along with Julia Child) suggest beating in additional acid. Small and Bernstein and some of my cookbooks imply that additional acid has no effect and instead recommend beating in water. Which technique is correct? I think either one may work, but the best choice is likely to be governed by the flavor of the resulting sauce.

If one adds vinegar or lemon juice, some of the acid molecules can be adsorbed onto the particles, as Perram, Nicolau and Perram believe. If the particles already have a surface charge, this addition of charge will thicken the diffuse double layer. If little acid remains from the original infusion, the addition of charge to the particles will help to create the double layer. The whisking by the cook breaks up the flocculation, and the diffuse double layers then aid in preventing or delaying reflocculation. (Of course, if the cook were to rely entirely on the acid for protection against reflocculation, the sauce would be much too acid for serving at table.)

Adding water to the sauce, either as tap water or as a component of vinegar or lemon juice, can have several possible effects. If the particles in the sauce are preventing flocculation by means of their surface charge, the medium may neutralize the particles and initiate flocculation. The addition of water decreases the ion concentration of the medium. Once the sauce is whisked and the flocculation is undone the medium will not neutralize the particles as fast, and reflocculation will be prevented or at least delayed.

A second effect from the addition of water may be that it and the whisking redissolve the flocculated particles. This result would be important if the sauce were primarily a lyophilic suspension that depended on the egg yolk for its protection against flocculation. The additional water may also be required if the ratio of water to butter is too low for adequate emulsification. Regardless of what the water does, an excess of it will certainly make the sauce too runny.

If the flocculation is due to insufficient yolk in the sauce, the best remedy is to whisk in more yolk. The step would also add water, since much of the yolk is water. If too much yolk is added, however,



The steps that yield good and bad sauce béarnaise

the sauce will lose its lightness and will sit heavily in the belly of the diner.

Which remedy is best? Any of the remedies will probably work in general, although some of them may not work in special cases and each one will lead to an unacceptable sauce if it is overdone. Since preparing the sauce involves rather inexact measurements of ingredients that can vary considerably in their composition, I cannot be more definite about what is responsible for the stability of the sauce or about which remedy is best every time. I cannot even say with certainty that the sauce is either a lyophobic or a lyophilic suspension or whether its stability is due to electric repulsions between diffuse layers or to protective coatings of bound water. In short, the preparation of sauce béarnaise remains more an art than a science.

My experiments with sauce béarnaise followed Kamman's basic procedure but did not include the herbs and (except for my first trial) the wine. The sauce was prepared on my electric stove (with asbestos pads on the burners) and with my usual kitchen utensils. The first trial was a mess because as soon as I added the butter the sauce flocculated heavily and rapidly. I followed Child's standing directive for decisive action in the face of a cooking disaster and immediately poured the sauce into two bowls. I vigorously whisked additional vinegar into one and soon had a smooth, unflocculated sauce. To the other I added a small amount of water and again was rewarded with a smooth sauce. Why did the first batch go bad? Because I had unwisely added the butter when the temperature of the infusion was slightly above 60 degrees C.

In my second attempt I kept the temperature of the melted butter and the infusion below 60 degrees. The wine and the salt were eliminated and the egg content was reduced so that the infusion consisted of only one egg yolk and five teaspoons of warm water. The resulting sauce was smooth, displaying no flocculation.

Some of the other trials I ran are summarized in the chart on the preceding page. Drawing on a "mother batch" of butter and water, I added vinegar, lemon juice, sodium chloride, Epsom salt, water, egg whites and egg yolks. The salts were included to check the possibility that they induced flocculation of the suspension, presumably by neutralizing the colloidal particles. To a portion of the mother batch I first added just enough vinegar to prevent the sauce from flocculating within five minutes after whisking. Then I added a salt, whisked the sauce and added more of the salt. Flocculation eventually resulted. I could see no difference between the salts in causing flocculation, notwithstanding the Schulze-Hardy prediction that the bivalent ions released by Epsom salt should promote flocculation more strongly in a lyophobic suspension. The fact that salt can lead to flocculation may be one reason unsalted butter is required in the recipe for the sauce. (Flavor must also be a factor.)

When I added egg yolk to the mixture of butter and water, the emulsification was much more difficult than it was when I followed the standard procedure of putting the yolk in before the butter. Vigorous whisking usually yielded a good sauce even with this reversal of procedure. To flocculate the sauce with salt required a relatively large amount of salt and resulted in a slurry that had a high viscosity. This result is called "salting out" and comes about because the salt competes with the lyophilic particles for the water in the mixture. Again the results with the two types of salt seemed to be approximately the same, although the sulfate should have led to flocculation more readily than the chloride did.

In another experiment I tested the effects of adding lemon juice and egg whites to the sauce. Lemon juice had the same rejuvenating effect as vinegar when the sauce was flocculated. The addition of a small amount of egg white helped to stabilize the sauce but made it look more like a gel than a table-ready mixture.

To summarize, a flocculated sauce béarnaise can be emulsified and held in a stable suspension if one vigorously whisks in either water or acid or if one includes additional egg yolks. The salt concentration may play a role in making the sauce unstable against the aggregation of the suspended butter droplets but probably only if the sauce depends on the electric repulsion between the particles for its stability.

If you would like to investigate sauce béarnaise further, much can be done. I was impressed by how little quantitative control I had over the experiments. For example, the eggs were nonuniform and all measurements were unnervingly imprecise for a physicist. A thorough quantitative, controlled experiment is needed. The comparison of the two salts should be investigated further. The role of the herbs and the wine needs to be clarified. Perhaps they are just for flavor. Finally, the question of whether the eggs need to be fresh could be pursued. All the experiments should monitor the state of the sauce for a reasonable period of time, because a stabilized sauce should remain stable for at least 30 minutes. I should be particularly pleased if someone could prove that my dual model of the sauce is incorrect and that the sauce is always either lyophilic or lyophobic. If the experiments make you tire of sauce béarnaise, you can turn to hollandaise sauce, another warm emulsified mixture, and start over with all my questions.

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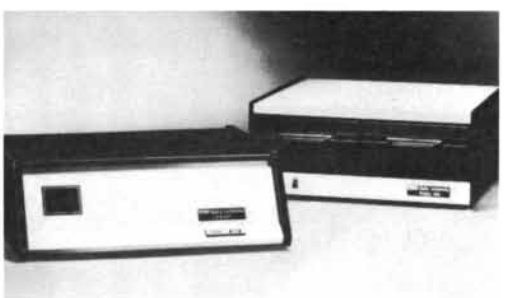

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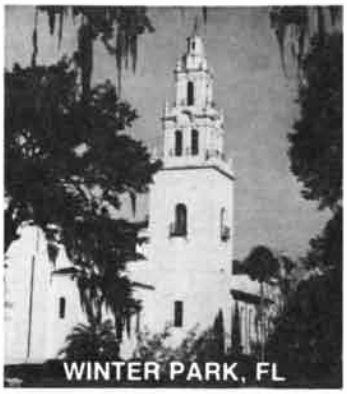

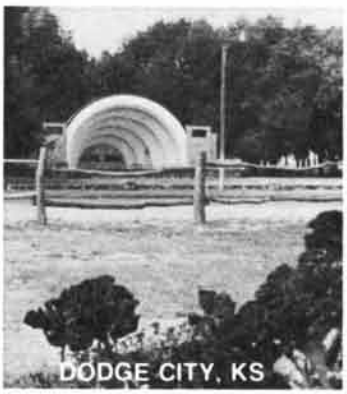

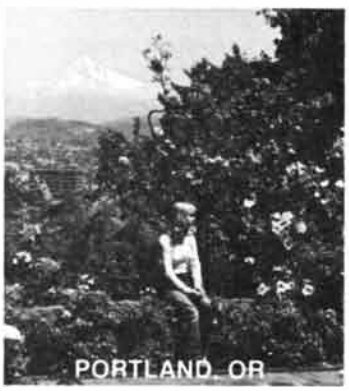

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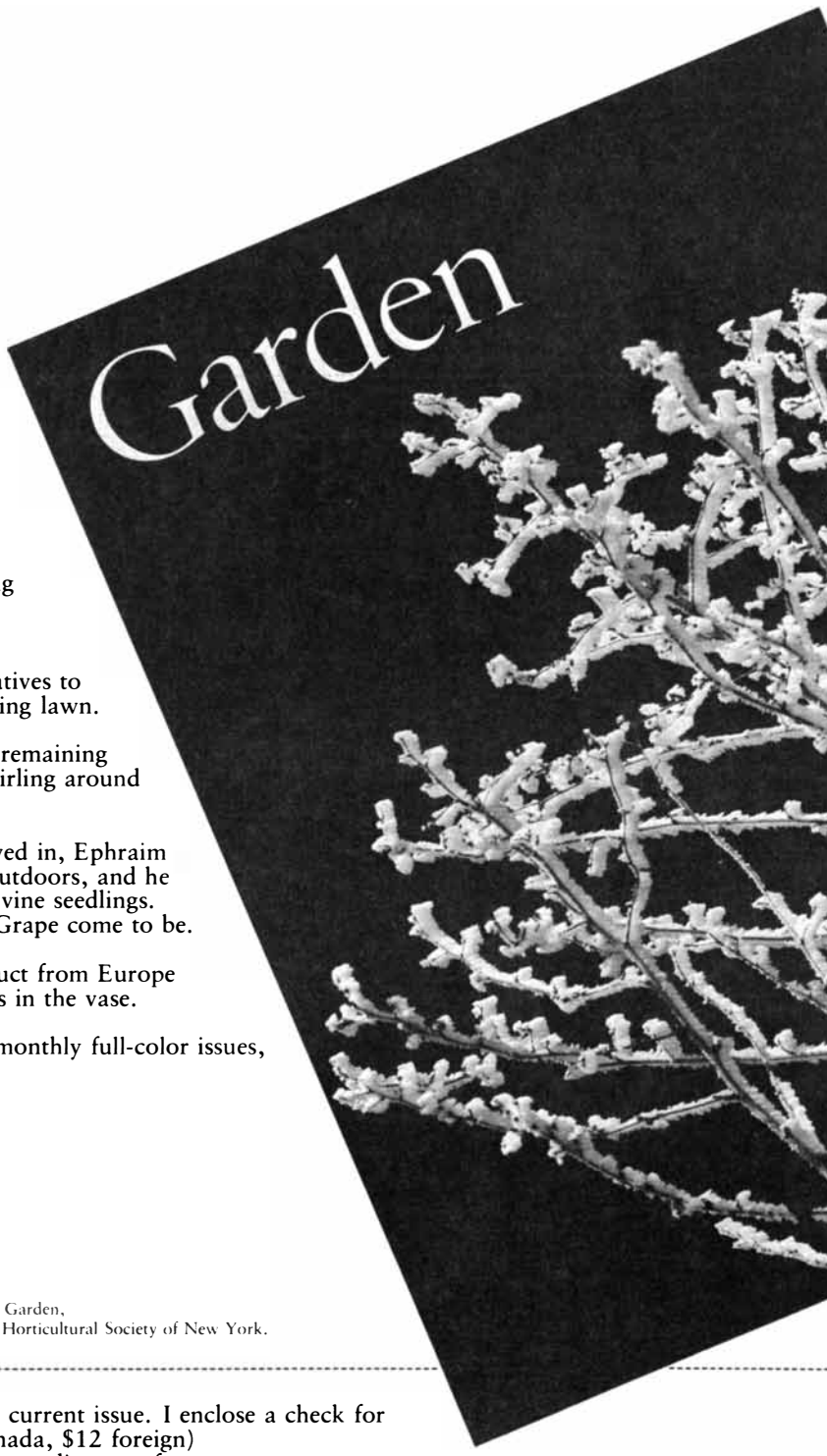

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The first color photographs from the surface of Mars, in 1976, came to Earth from the Viking orbiter via Motorola equipment.

IMAGINATIVE ELECTRONICS.

And now, the Voyager spacecraft, pursuing their boomerang trajectories around Jupiter and on toward Saturn. A long way indeed from the time when Motorola put radios into cars fifty years ago, and TV sets in America's living rooms. We no longer make home TV here at all, but we do make hundreds of models of two-way radios.

We have become one of the world's largest manufacturers devoted exclusively to electronics. We are one of the foremost designers of custom and standard semiconductors. Indeed we are one of the world's greatest innovators in electronic problem-solving.

A microcomputer, drawn larger than life.

We have developed systems that cut automobile fuel consumption; systems that help keep ships from colliding; systems that allow telephones without wires; systems that help keep computers from giving up their secrets to the wrong people—and, of course, systems that bring home to Earth the true face of other worlds.

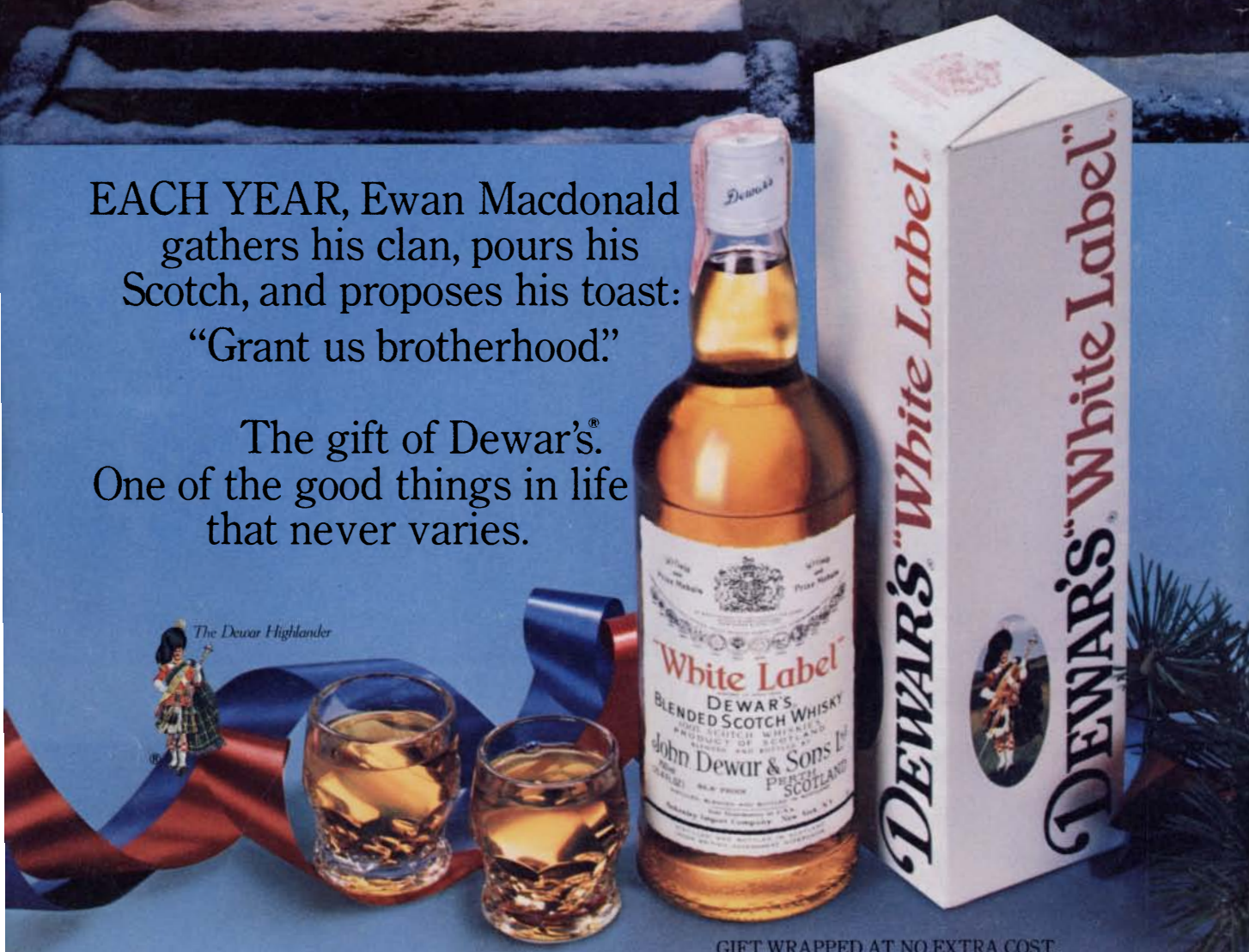
For further information, write Public Affairs Office, Corporate Offices, Motorola, Inc., 1303 E. Algonquin Road, Schaumburg, Illinois 60196.

MOTOROLA

Making electronics history since 1928.

EACH YEAR, Ewan Macdonald gathers his clan, pours his Scotch, and proposes his toast: "Grant us brotherhood."

The gift of Dewar's®.
One of the good things in life that never varies.



GIFT WRAPPED AT NO EXTRA COST.

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