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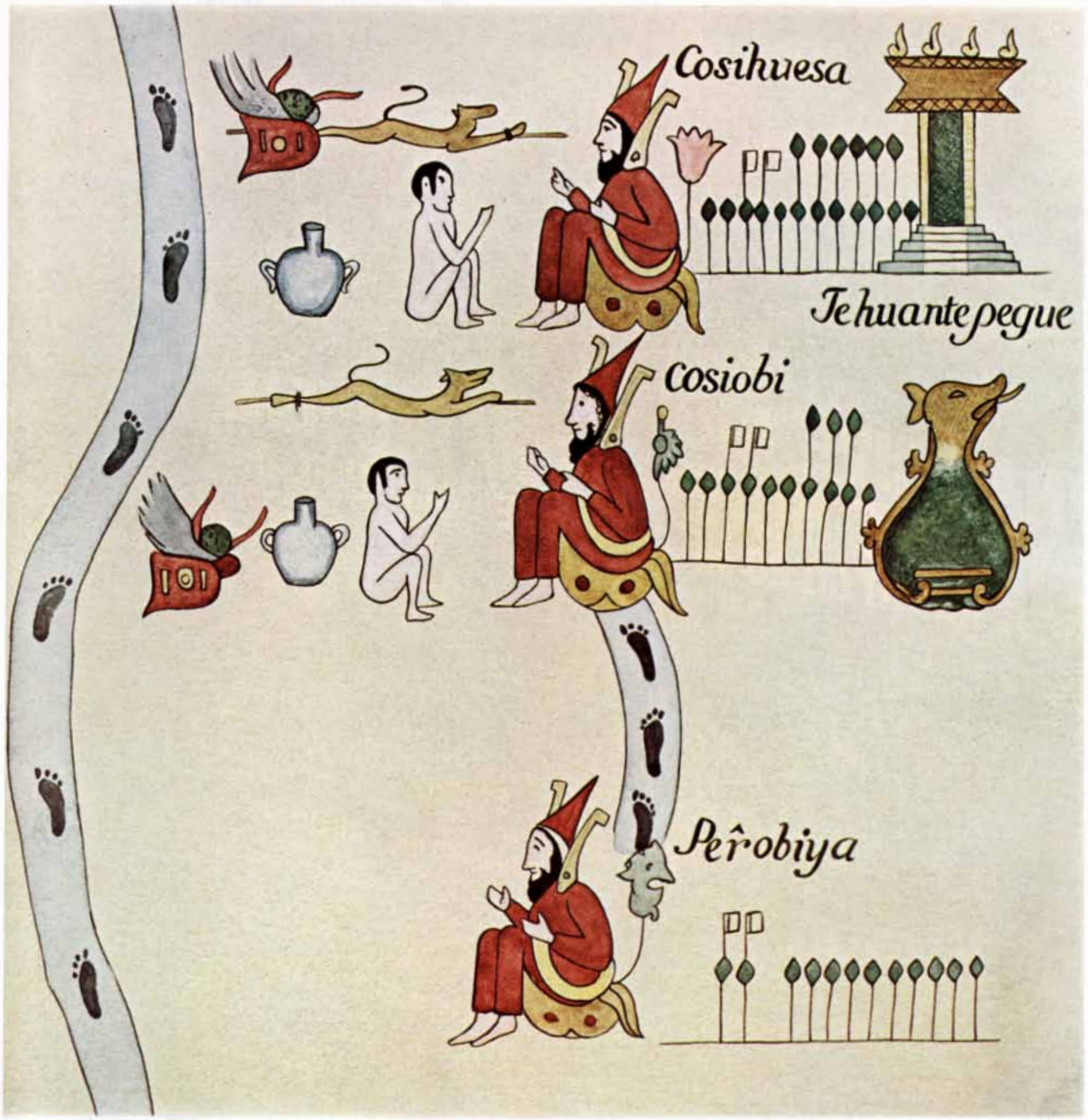

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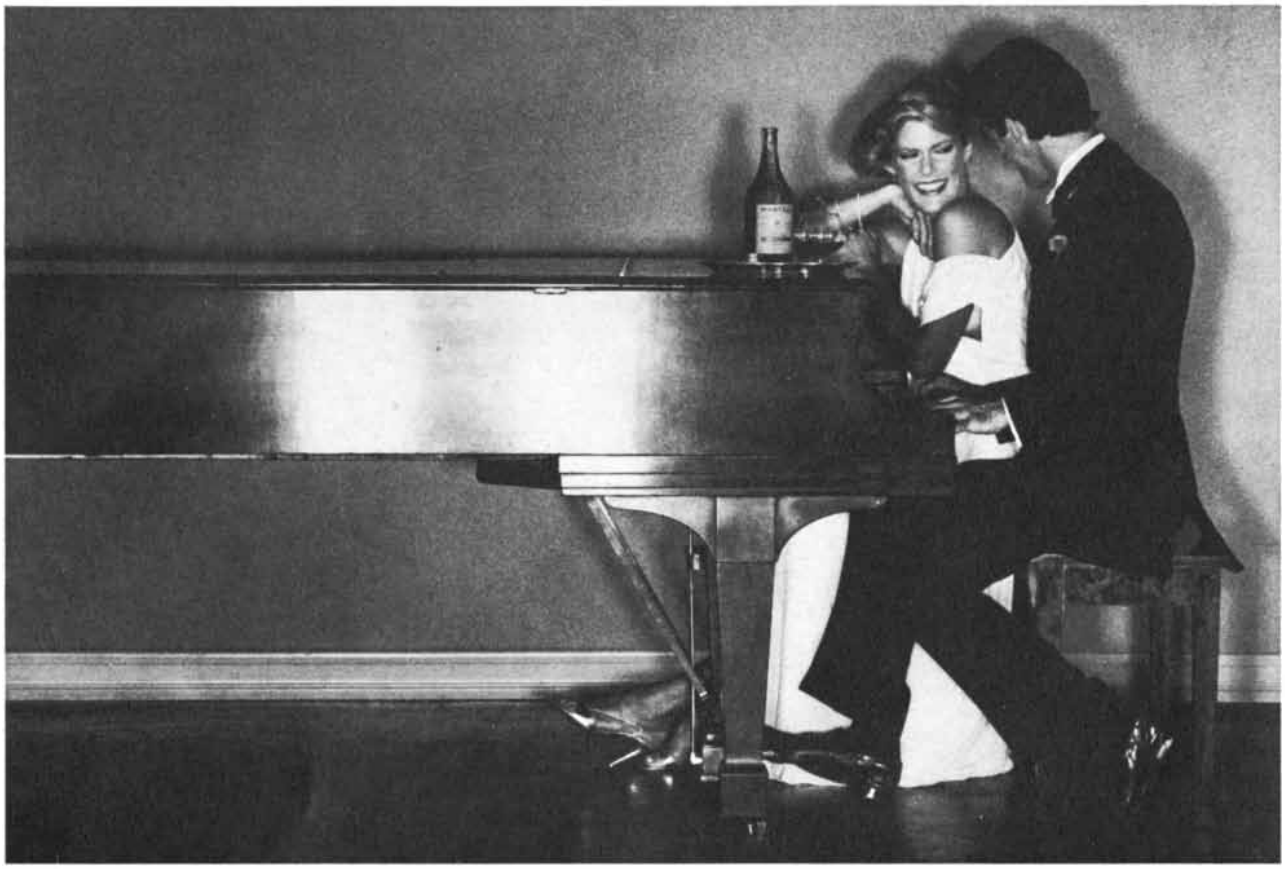

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MARTELL COGNAC

Established 1845 **SCIENTIFIC AMERICAN** February 1980 Volume 242 Number 2

ARTICLES

DEPARTMENTS

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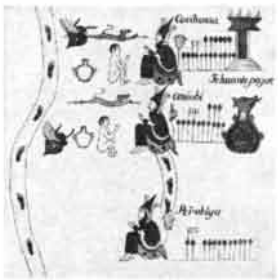

THE COVER

The painting on the cover reproduces a part of a document written for the Spanish colonial authorities in Mexico in A.D. 1540. Known as the Lienzo de Guevea, the document defined the genealogy of certain Zapotec rulers and the geographical bounds of Santiago de Guevea, a Zapotec town on the Isthmus of Tehuantepec (*see illustration on page 51*). At the top a Zapotec ruler identified as Cosihuesa (more properly Cocijoeza, or "Lightning Maker") is seen receiving tribute: an animal tied to a carrying pole, a bundle containing feathers and other items, a naked captive and a large container perhaps filled with pulque. The ruler seated below "Lightning Maker," who is receiving similar tribute, is his son Cosiobi (more properly Cocijopii, or "Lightning Wind"). Behind him is a "hill sign," identified as Tehuantepegue, the Tehuantepec of today. The identity of the third figure, shown without tribute, remains controversial. He is, however, almost certainly a member of the same royal family. Studies of inscribed Zapotec monuments, particularly at Monte Albán, indicate that colonial documents such as the Lienzo echo the Zapotec pre-Columbian system of writing (see "Zapotec Writing," by Joyce Marcus, page 50).

THE ILLUSTRATIONS

Cover painting by Enid Kotschnig

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LETTERS

Sirs:

"Constructive Mathematics," by Allan Calder [SCIENTIFIC AMERICAN, October, 1979], gives an interesting picture of questions gnawing at the foundations of mathematics, particularly questions about the validity of Aristotle's law of the excluded middle when it is applied to infinite sets....

Do not elementary quantum phenomena provide further examples of where Aristotle's law fails? The famous two-slit experiment, as it would work with electrons, provides a simple case. Electrons pass one by one through a system of two slits and form an interference pattern on a screen. A simple statement can be made for each electron that reaches the screen: "The electron passed through slit No. 1," which certainly appears meaningful because an experiment can be designed to test it. (The test, however, destroys the interference pattern.) Nevertheless, such statements can be neither true nor false when there is interference.

The two-slit experiment is a traditional starting point for studies of quantum mechanics. Could it hold a lesson in formal mathematics as well? It may caution against uncritical applications of the law of the excluded middle in complex situations, for example applications with infinite sets.

W. E. BAYLIS

University of Windsor
Windsor, Ont.

Sirs:

We wish to point out an error in "Constructive Mathematics," by Allan Calder, and then to comment on constructivism in general. Georg Cantor's existence proof for transcendental numbers is completely constructive, even though it may sometimes be disguised as a pure-existence proof in the language of reductio ad absurdum. Far from "giving not the slightest hint of how even a single transcendental number might be found," as Calder writes, Cantor's argument gives a specific and easy-to-understand algorithm that approximates a particular transcendental number arbitrarily closely by rational numbers. (Implementation may be cumbersome, but this is not at issue.)...

Calder's (and all constructivists') point is well taken that when it is feasible, classical mathematical proofs are more informative when they are presented so as to reveal their constructive content. We should like to have seen Cantor's proof presented in this light. It would have been much more instructive than the boxed example on page 154, where the distinctions between classical and "modern" are slight and so easily interchangeable as to be unrevealing.

One of the important features of contemporary mathematics is that of axiomatic theories formalized within first-order logic. Such theories have a certain perfection guaranteed by the incompleteness theorem of Kurt Gödel: they can be regarded as machines for producing theorems. Moreover, a good axiomatization (whether in first-order logic or not) often points the way for future developments. For example, axiomatizations played a paramount role in the building of geometries such as non-Euclidean ones. In addition mathematical studies of the foundations of mathematics were made possible only on the basis of axiomatizations found by Gottlob Frege, Ernst Zermelo and T. A. Skolem. And the present-day investigation of strong axioms of infinity and of their impact on set theory is growing on this same ground.

Constructivists by and large (Errett Bishop included) do not formalize their theories, even within intuitionistic logic (which does not have the law of the excluded middle). And so their work remains less appealing to those mathematicians who are intensely aware of the above-mentioned developments. One might say that constructive mathematics is still a remote country ruled more by authority than by law.

WALTER TAYLOR

Professor of Mathematics

JAN MYCIELSKI

Professor of Mathematics
University of Colorado
Boulder

Sirs:

Quantum theory does provide a very interesting example of where classical logic appears to break down. Such examples force us to reassess our dependence on classical reasoning and our notions of reality. This point was brought out in "The Quantum Theory and Reality," by Bernard d'Espagnat [SCIENTIFIC AMERICAN, November, 1979].

I thank Professors Taylor and Mycielski for pointing out an error in my article. In addition to the proof of the existence of transcendental numbers that I presented, Cantor gave a constructive proof in which he described a "counting" of the algebraic numbers and then produced transcendental numbers from it with his diagonal argument.

That this proof has been mainly forgotten by mathematicians (including me) in favor of the nonconstructive proof is a good example of the point I was making with the boxed example on page 154. I do not agree, however, with Taylor and Mycielski's contention regarding my example that the distinctions made were slight and interchangeable. It is of course true in the context of nonconstructive mathematics, where there is no distinction at all.

I most certainly agree that axiomatic formalization plays an important and productive role in modern mathematics. But constructivists, particularly those influenced by Bishop, try to avoid formalizing their theories, because once they are formalized it is possible to generate theorems without the need to understand what is going on. You do not have to understand a proof to know that it is formally correct. Without understanding it is difficult to be certain that your results still have constructive meaning.

Most of the mathematics that I do is highly nonconstructive, but I do feel strongly that formalism must be kept in a proper perspective and not used as a substitute for understanding. In my opinion formalism is the opium of the thinking classes.

ALLAN CALDER

Department of Mathematical Sciences
New Mexico State University
Las Cruces

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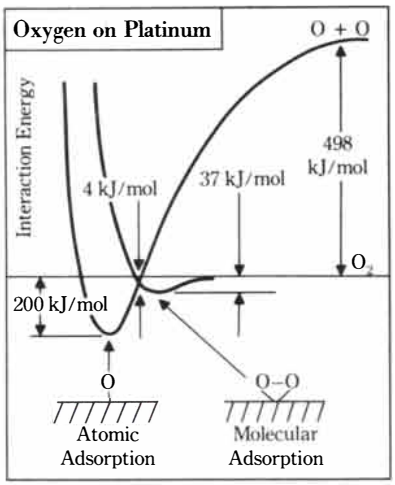
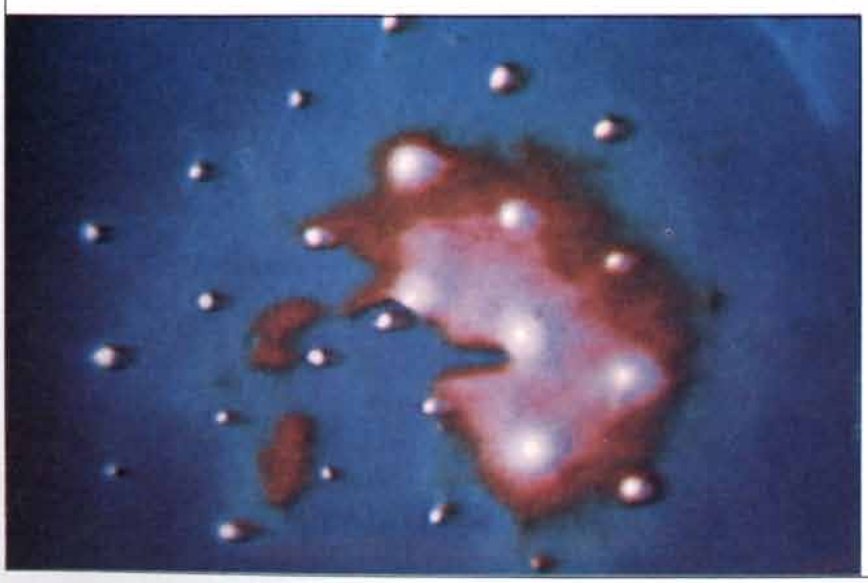
The Atomic Arrangement

The Atomic Arrangement

In a recent experiment, scientists at the General Motors Research Laboratories studied changes in chemical bonding during the dissociation of oxygen molecules on platinum. Preliminary surface work has explored an interesting new phenomenon: the mechanism of oxygen dissociation over a wide range of temperatures.



A simplified schematic illustrating the reaction potential energy surface for oxygen-adsorption on a close-packed platinum surface.



An electron diffraction pattern which shows diffraction patterns from an oxygen-covered hexagonally close-packed platinum surface at 0° C.

UNDER what conditions will oxygen molecules dissociate into single atoms on a platinum surface? What is the mechanism for oxygen dissociation? Those are the kinds of questions that Dr. John Gland and his colleagues at the General Motors Research Laboratories are investigating to get a better understanding of the chemistry behind catalysis.

Their work has valuable practical implications for the automotive field, where catalysis is used to remove harmful emissions from automobile exhaust. Most cars built in the U.S. use catalytic converters filled with beads containing platinum to chemically transform carbon monoxide and unburned hydrocarbons into harmless CO_2 and water.

While it has long been known that catalysts are an effective way to convert these gases, little is known about precisely why and in what order the basic atomic reactions occur.

In seeking answers to these questions, surface chemists study the elemental composition and geometric arrangement of atoms in the first few atomic layers of the surface and the means by which atoms and molecules from the gas phase bond to the surface.

In his most recent work, Dr. Gland has been studying the adsorption and desorption of oxygen on platinum single-crystal surfaces. This is important because oxygen is the agent that must be adsorbed on the surface to react with carbon monoxide and hydrocarbons to convert them to CO_2.

The experiments were conducted in a stainless steel ultrahigh vacuum system equipped with an electron energy analyzer and a mass spectrometer. The electron energy analyzer allows one to measure the concentration and character of the oxygen adsorbed on the platinum surface. The mass spectrometer is used to measure the desorption of O_2 as the platinum surface is heated. Mathematical analysis of the desorption process allows one to characterize the chemical bond between the oxygen and the platinum surface.

In these experiments, the platinum surface is covered with oxygen at the extremely low temperature of −179°C (almost the temperature of liquid nitrogen) by exposing it to gaseous O_2 molecules. The oxygen remaining in the gas phase is pumped away, and then the desorp-

tion of oxygen from the surface is observed as the platinum crystal is gradually heated to 1000°C.

The oxygen was found to desorb from the surface in two distinctly different temperature regimes—part at −125°C and the rest at about 425°C. By using the oxygen-18 isotope, it was established that the low temperature desorption represents oxygen that was adsorbed on the surface in a molecular form while the higher temperature desorption corresponds to oxygen adsorbed in the atomic form. From an analysis of the desorption process, it was possible to establish the complete energetics. Oxygen molecules from the gas phase strike the surface and are weakly bound (37 kJ/mol). The adsorbed oxygen molecule can either desorb into the gas phase (37 kJ/mol) or dissociate into atoms (33 kJ/mol). The atoms are bonded very strongly (200 kJ/mol) to the surface.

FROM the desorption analysis, it was also possible to deduce the mechanism for the dissociation process. The interesting conclusion that results is that the formation of O atoms on platinum is a two-step process—oxygen is adsorbed in a molecular state and then dissociates to form atoms.

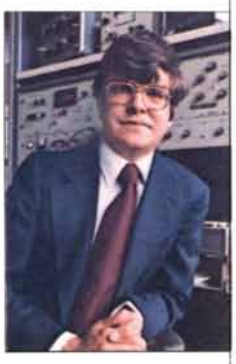
The GM scientists were most interested in learning how this adsorbed molecular species is bonded to the platinum surface. Fortunately, another technique was available to determine the bonding. The technique is called electron energy-loss spectroscopy and is quite new—there are only six or seven such instruments in the world. The measurements not only confirmed the existence of the adsorbed molecular oxygen but showed that it was bound by the transfer of two electrons from the platinum surface into the antibonding π_g orbitals of oxygen. "This was most exciting" said Dr. Gland, "because this is the first time that this type of oxygen bond has been observed on a metal surface.

"We're getting closer and closer to a more specific understanding of catalysis," says Dr. Gland. "The more we learn about simple chemical systems, the better we'll be able to control more complicated systems. That has excellent implications for protecting the environment."

THE MAN BEHIND THE WORK

Dr. John Gland, 32 years old, is a Senior Research Scientist in surface chemistry at the General Motors Research Laboratories. He heads a group of 7 investigators, 4 with Ph.D.s, all involved in work relating to the basic surface chemistry of catalysis.

A graduate of Whittenberg University in Ohio, Dr. Gland received his Ph.D. in physical chemistry at the University of California, Berkeley, in 1973 and joined the General Motors staff that year.



Dr. Gland comments: "I came to GM Labs because I wanted to get in on the ground floor of an exciting new field. The atmosphere here is very open, with lots of cross-pollination among departments. With several hundred people with Ph.D.s here, we've got a lot of human resources to draw on in all the basic sciences.

"Typically, management defines a broad problem, then we're free to tackle the solution in any way we choose. They give us the freedom, equipment and support to get the job done correctly."

In addition to his research, Dr. Gland enjoys backpacking in Wyoming and in the Sierra Nevada Mountains in California.

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

FEBRUARY, 1930: "The use of a cathode-ray tube as a television receiver has many advantages over the well-known scanning-disk method of visual broadcasting, according to Dr. Vladimir K. Zworykin, research engineer of the Westinghouse Electric and Manufacturing Company. Dr. Zworykin has developed for his receiving apparatus an entirely new type of cathode-ray tube that he calls a kinescope. In this tube a pencil of electrons bombards a screen of fluorescent material. The pencil follows the movement of the scanning light beam in the television transmitter, and its movement is so rapid that the eye receives a perfect impression of a continuous miniature motion picture. The cathode-ray television receiver has no moving parts. Another advantage is that the fluorescent screen aids the persistence of the vision, so that it is possible to reduce the number of pictures shown each second without noticeable flickering. This in turn allows a greater number of scanning lines and results in the picture's being reproduced in greater detail without increasing the width of the radio channel. The pictures formed by the receiver are four by five inches in size."

"Commander Richard E. Byrd's notable flight to the South Pole from Little America is expected to have many valuable results. Data gathered by the Byrd expedition will fill in many blank spots in the Antarctic continent. To aeronautics the expedition has added much needed data in regard to the operation of airplanes and the behavior of metals and lubricants under conditions of extreme natural cold. In the radio field Commander Byrd has made history. He is the only man to have sent radio messages from both the North Pole and the South Pole. Since the flight Byrd has been made a Rear Admiral."

"The complexities of the situation the London Naval Conference will face are becoming more and more evident. On the other hand, President Hoover and Prime Minister MacDonald have skillfully avoided many pitfalls in handling the preliminary measures. They are supported by an overwhelming public opinion in favor of reducing armaments, and it only remains for conciliatory statesmanship to find the solution. The country approves the President's action in surrounding our civilian members of the conference with experienced naval advisers, and the previous records of rear admirals Jones, Pratt, Moffett, Pringle, Yarnell and Hepburn ensure that the civilian members will be furnished the necessary technical assistance. We feel sure that the presence of these flag officers in London assures the safeguarding of American interests, and we fondly hope the collective wisdom of the assembled delegates will find a solution that will further world peace. Now is the time to limit armaments, for many of the hatreds of the World War have evaporated, while the memory of the suffering it caused is still fresh."

FEBRUARY, 1880: "We have been surprised that the volume published a few months since by the Government on the state of labor in Europe has not received more general attention. The statistics, furnished by the various United States consuls, purport to cover the rates paid for labor in all the leading countries, together with the cost of living in Great Britain and nearly every country on the continent of Europe. Elaborate tables are also given comparing the averages thus obtained with the rates of wages paid and the cost of living in this country. William M. Evarts, our accomplished Secretary of State, gives us a synoptical résumé of its contents, together with some general conclusions of his own. The tenor of his discourse is to point out that our workingmen must accept lower wages in the future. The principal ground on which this reasoning is based lies in the much higher rates per day now paid to American workingmen, which, the Secretary argues, cannot be permanently maintained when we are exporting largely of domestic manufactures in competition with the products of the cheap labor of Europe."

"Dr. Alcée Chastant of New Orleans takes strong ground against the germ theory of the origin of yellow fever. The germ theory he regards as not only unproved but also highly improbable. On several occasions Dr. Chervin swallowed the matter of black vomit and suffered no harm. Neither did Dr. Guyon at Martinique from similar experiments. Dr. Firth inoculated dogs with the fresh matter and subjected himself to the same operation. He applied the fluid to the surface of a cut made on his arm, securing it there for two days by means of sticking plaster, and repeated the experiment more than 20 times in various parts of his body. He inserted the matter in his eyes and swallowed a large quantity of black vomit, pure and dilute, and no injurious effects ensued. Cats, dogs and fowl were fed it without sensible effects, and the fumes obtained by evaporating black vomit did not harm those who inhaled them. Such heroic experiments may not disprove the germ theory, but they certainly tell very strongly against it."

"The vast cavities in the sun we call sunspots are not solid things, and they are not properly to be compared to masses of slag or scoria swimming on a molten surface. They are, rather, rents in that bright cloud surface of the sun we call the photosphere, and through which we look down to lower regions. Their shape may be very rudely likened to a funnel with sides at first slowly sloping (the penumbra) and then suddenly going down into the central darkness (the umbra). This central darkness has itself gradations of shade, and cloud forms may be seen there obscurely glowing with a reddish tinge far down into its depths, but we never see to any solid bottom. We are able now to explain in part that mysterious feature in the sun's rotation, for if the sun be not a solid or a liquid but a mass of glowing vapor, it is evidently possible that one part of it may turn faster than another. Why it so turns no one knows, but the fact that it does is now seen to bear the strongest testimony to the probably gaseous form of the sun throughout its mass."

"The arrival of the *Orient* at Adelaide in Australia has been telegraphed, the passage from Plymouth in England, including all stoppages, having been made in 37 days 22 hours. The distance being about 12,000 nautical miles, the *Orient* must have retained an average speed for the entire voyage of more than 14 knots, a performance unequaled in the annals of steam navigation."

"Man labors with his hands and with his wits for mutual support and protection. Woman rears her children, tends the sick and conducts domestic affairs. Such, if the most primitive, is probably the healthiest and happiest condition for the female. Her sympathetic and susceptible nature has here every scope for action without being shaken by rude and oft-repeated shocks. Medical philosophers have declaimed, and will long continue to do so, in vain against the whole system of education in bringing up women, which is directed solely to the purpose of making them personally attractive and subsequently securing for them brilliant settlements for life, at the expense of their health. Thus women from their earliest days are constantly subjected to the yoke of prejudices, are under the necessity of a perpetual state of acting and deception, of dissembling their desires and real inclinations for the sake of propriety, of keeping to themselves the most powerful passions and the strongest propensities, and of feigning a calmness and indifference when they are devoured by a burning fire."

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THE AUTHORS

CHARLES LEE JACKSON ("The Allocation of the Radio Spectrum") is an electrical engineer with a special interest in the public-policy aspects of communications technology; he currently serves as staff engineer to the Committee on Communications of the U.S. House of Representatives. A graduate of Harvard College, he received his Ph.D. in 1977 from the Massachusetts Institute of Technology, where he majored in communications and operations research and minored in computer science. Before taking his present job Jackson worked as an engineering assistant to a Federal Communications Commissioner and as special assistant to the chief of the Common Carrier Bureau.

STANLEY N. COHEN and JAMES A. SHAPIRO ("Transposable Genetic Elements") are molecular geneticists. Cohen is professor and chairman of the department of genetics at the Stanford University School of Medicine, where he is also professor of medicine. His degrees are from Rutgers University and the University of Pennsylvania School of Medicine. Since joining the faculty at Stanford in 1968 he has concentrated on the investigation of plasmids: extrachromosomal DNA segments found in certain bacteria. In 1973 he and his colleagues demonstrated that plasmids could be made to serve as carrier molecules for foreign DNA in what were the first successful gene-transplantation experiments. Shapiro is associate professor of microbiology at the University of Chicago. As an undergraduate at Harvard College he majored in English literature; he then went to England to study genetics, obtaining his Ph.D. in that field from the University of Cambridge in 1968. Shapiro has worked at the Pasteur Institute, the Harvard Medical School and the University of Havana.

JOYCE MARCUS ("Zapotec Writing") is assistant curator of Latin-American archaeology at the Museum of Anthropology of the University of Michigan. She did her undergraduate work at the University of California at Berkeley and her graduate work at Harvard University, where she received her doctorate in anthropology in 1974. She spent a year as Robert Woods Bliss Fellow at Dumbarton Oaks, where her book *Emblem and State in the Classic Maya Lowlands: An Epigraphic Approach to Territorial Organization* was published in 1976. Since joining the Michigan faculty in 1973, she has yet to miss a Wolverine football game, basketball game or wrestling match. "With time," Marcus says, "I hope to match the record of my idol, the late Hazel M. Losh, a professor of astronomy whose half century of unfailing support for Michigan's teams earned her the title of 'Homecoming Queen for Life.'"

RICCARDO GIACCONI ("The Einstein X-Ray Observatory") is professor of astronomy at Harvard University, where he also serves as associate director of the high-energy astrophysics division of the Center for Astrophysics. He was born and educated in Italy, obtaining his Ph.D. in physics from the University of Milan in 1954. He taught at Milan until 1956, when he came to the U.S. as a Fulbright Fellow to do research at Indiana University. Before Giacconi took his present jobs in 1973 he was executive vice-president of American Science & Engineering, Inc.

ROBERT B. SMITH and ROBERT L. CHRISTIANSEN ("Yellowstone Park as a Window on the Earth's Interior") share a professional interest in the Yellowstone area. Smith is professor of geophysics at the University of Utah. He received his B.S. and M.S. degrees at Utah State University and his Ph.D. in 1967 from the University of Utah. From 1961 to 1964 he was a geodetic officer with the Air Force, serving as the U.S. exchange scientist with the British Antarctic Survey. Smith was a visiting scientist at the Lamont-Doherty Geological Observatory of Columbia University in 1969 and a visiting professor at the Swiss Federal Institute of Technology in 1976 and 1977. Christiansen has been associated with the U.S. Geological Survey since 1961, when he obtained his Ph.D. in geology from Stanford University. A specialist in volcanology, he recently returned to full-time research in this field after having been coordinator of the Geological Survey's Geothermal Research Program. Smith and Christiansen would like to acknowledge the support of their work by the National Park Service.

J. J. REILLY and GARY D. SANDROCK ("Hydrogen Storage in Metal Hydrides") are respectively a chemist in the Basic Energy Sciences Division of the Brookhaven National Laboratory's Department of Energy and Environment and a metallurgist in the Energy Systems Section of the International Nickel Company's Inco Research and Development Center. Reilly, who received his B.S. at Fordham University in 1952, was employed for several years as an industrial chemist before he joined the staff at Brookhaven in 1956. In collaboration with R. H. Wiswall, Jr., Reilly began in 1965 "a search for new metal hydrides that could be used as cheap and convenient hydrogen-storage compounds." Sandrock, who was graduated with a B.S. in metallurgical engineering from the Illinois Institute of Technology in 1962, worked for a number of years as a research metallurgist at the National Aeronautics and Space Administration's Lewis Research Center in Cleveland before he returned to graduate school; he obtained his Ph.D. in metallurgy in 1971 from Case Western Reserve University and joined the staff of the Inco Research and Development Center soon afterward. For the past four or five years, Sandrock writes, "my overwhelming professional passion has been hydrides, and I have worked almost exclusively on that subject."

JAMES T. TODD, LEONARD S. MARK, ROBERT E. SHAW and JOHN B. PITTENGER ("The Perception of Human Growth") are experimental psychologists with a common interest in the role of perception in human behavior. Todd, Mark and Shaw are at the University of Connecticut, Todd and Mark as research associates and Shaw as professor of psychology. Todd, who received his Ph.D. in experimental psychology from the University of Connecticut in 1977, has worked as a computer-programming consultant for the University of Connecticut Health Center and the New York University Medical Center; he describes his main research topic as "mathematical modeling of the optical stimulation that supports complex activities such as catching baseballs or driving a car." Mark, who also holds a Ph.D. in experimental psychology from Connecticut (1979), wrote his dissertation on "A Transformational Approach toward Understanding the Perception of Craniofacial Growth" (the subject of the present article). Shaw, the senior member of the group, obtained his Ph.D. in psychology from Vanderbilt University in 1965. He taught at the University of Minnesota and at Cornell University before joining the Connecticut faculty in 1976. Pittenger is a member of the psychology department at the University of Arkansas at Little Rock. His Ph.D. is from the University of Minnesota (1971).

MARY K. WICKSTEN ("Decorator Crabs") is a research fellow at the Crustacea Laboratory of the Allan Hancock Foundation at the University of Southern California. A graduate of Humboldt State College, she did much of her work on decorator crabs as part of her dissertation at the University of Southern California, where she received a Ph.D. in 1977. She has worked as a marine biologist for the Bureau of Land Management, participating in a variety of projects in the ocean off southern California and in the Gulf of Alaska. Her investigation of decorator crabs, Wicksten reports, "combines laboratory studies with my two favorite pastimes, underwater photography and scuba diving."

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MATHEMATICAL GAMES

The coloring of unusual maps leads into uncharted territory

by Martin Gardner

"'I know by the color. We're right over Illinois yet. [Huckleberry Finn is speaking to Tom; they are on a balloon trip.] And you can see for yourself that Indiana ain't in sight....'

'What's the color got to do with it?'

'It's got everything to do with it. Illinois is green, Indiana is pink.... I've seen it on the map, and it's pink.'"

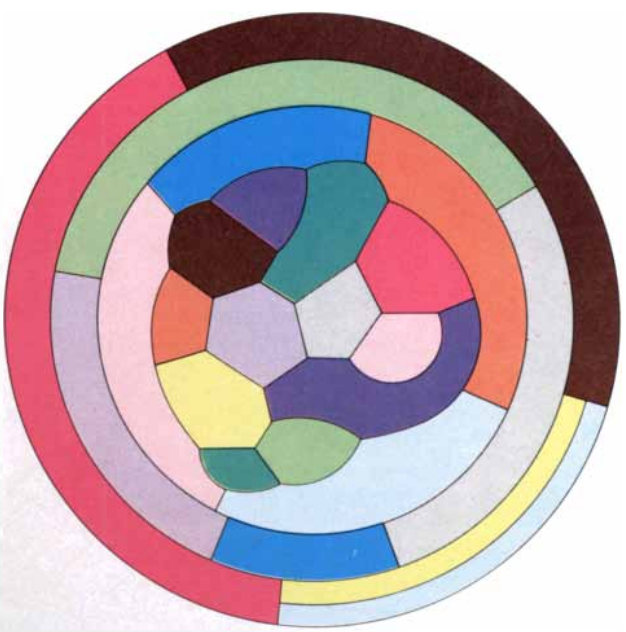
—MARK TWAIN, *Tom Sawyer Abroad*

In 1976 Wolfgang Haken and Kenneth Appel of the University of Illinois at Urbana-Champaign announced they had finally laid to rest the famous four-color-map problem. As the reader surely knows, the renowned conjecture in topology asserts that four colors are both sufficient and necessary for coloring all maps drawn on a plane or sphere so that no two regions that "touch" (share a segment of a boundary) are the same color. Haken and Appel, with the assistance of John Koch, proved that the conjecture is true by a method that made unprecedented use of computers. Their proof is an extraordinary achievement, and when their account of it was published in 1977, the Urbana post office proudly added to its postmark "Four colors suffice." To most mathematicians, however, the proof of the four-color conjecture is deeply unsatisfying.

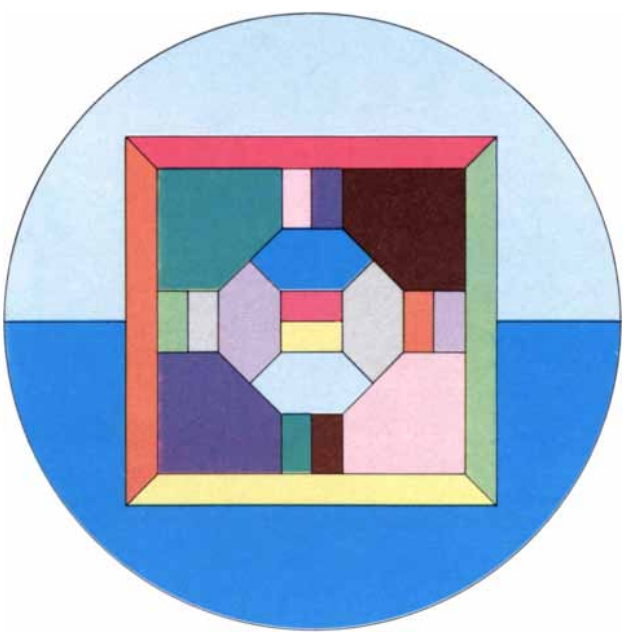
For more than a century topologists either suspected that a counterexample to the four-color conjecture (that is, a complex map requiring five colors) could be devised or trusted that a simple, elegant proof of the conjecture could be found. Although the conjecture is now known to be true, its proof is buried in printouts that resulted from 1,200 hours of computer time. The task of verifying the accuracy of these results is so horrendous that only a small number of experts have had the time, fortitude and skill to even attempt it. So far, however, all who have done so have attested to the proof's validity.

In an article titled "The Four-Color Problem and Its Philosophical Significance," published in *The Journal of Philosophy* (Vol. 76, No. 2, pages 57–83; February, 1979), Thomas Tymoczko argues that this kind of lengthy computer proof injects an empirical element into mathematics. No mathematician, he writes, has seen a proof of the four-color theorem, nor has anyone seen a proof that the work of Haken and Appel is, in fact, a proof. What mathematicians have seen instead is a program for attacking the problem by computer along with the results of an "experiment" performed on a computer. Tymoczko believes such a "proof" blurs the distinction between mathematics and natural science and lends credibility to the opinions of those contemporary philosophers of science such as Hilary Putnam who see mathematics as a "quasi-empirical" activity.

There is, of course, something to this viewpoint. All mathematical proofs are the work of human beings, and when proofs are extremely complex, human error is always a possibility. The validity of a difficult proof rests on a consensus among experts, who may, after all, be mistaken. There is a striking instance of this in the early history of the four-color theorem. Alfred Bray Kempe, an English mathematician, published what he said was a proof of the theorem in 1879, and for about a decade mathematicians assumed that the problem had been solved. Then in 1890 Percy John Heawood, another English mathematician, pointed out a fatal flaw in Kempe's reasoning.



Percy John Heawood's 12-color "2-pire" map



Scott Kim's symmetrical variant of Heawood's map

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If one accepts the dismal prophecies emanating from the automotive community, it appears we are destined to suffer a generation of thoroughly boring automobiles.

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My purpose here is not to argue the question of whether there is a sharp line separating "analytic" truth from "synthetic" truth. I shall say only that I think Tymoczko greatly overestimates the relevance of modern computers to this old controversy. All calculations are empirical in the trivial sense that they involve the carrying out of an experiment with symbols, either in the head, with pencil and paper or with the aid of a machine. The fact that with electronic computers, which are now essential for difficult calculations, mistakes can be made by both hardware and software differs in no essential way from the fact that mistakes can be made by a person multiplying two large numbers on an abacus. It seems to me a misuse of language to say that the possibility of such errors makes the truth of the multiplication table empirical and therefore a mistake to take this kind of inescapable error as an example of the fallibility of natural science.

Still, the Haken-Appel proof of the four-color theorem is certainly unsatisfying in that no one can call it simple, beautiful or elegant. Haken and Appel both think it unlikely that a proof can be found that does not require an equally intensive application of computers, but of course there is no way to be sure. If there is no simpler proof, the Haken-Appel proof is indeed something new in the degree to which it relies on computer technology.

This situation is ably discussed by Benjamin L. Schwartz in a book he edited titled *Mathematical Games and Solitaires.* Published last year by the Baywood Publishing Company of Farmingdale, N.Y., the book (which I enthusiastically recommend) is a choice selection of articles from *Journal of Recreational Mathematics.* In Schwartz's introduction to a section on the four-color problem he writes: "So one may ask, have Haken and Appel really proved what they claim?.... Personally I believe they have.... But the trial period is still not over. Others will have to check every step. And since [most] of the steps were carried out in hundreds of hours of high-speed computer operation, that checking will be a big job. At this writing no one had done it. New computer code will have to be written, perhaps for another computer.... Will a whole set of other stubborn mathematical problems... begin to yield to the new method of massive computational support? Or is this a fluke case that will have no lasting impact? This proof of the four-color theorem introduces a new era in mathematics, and no one knows where it will lead."

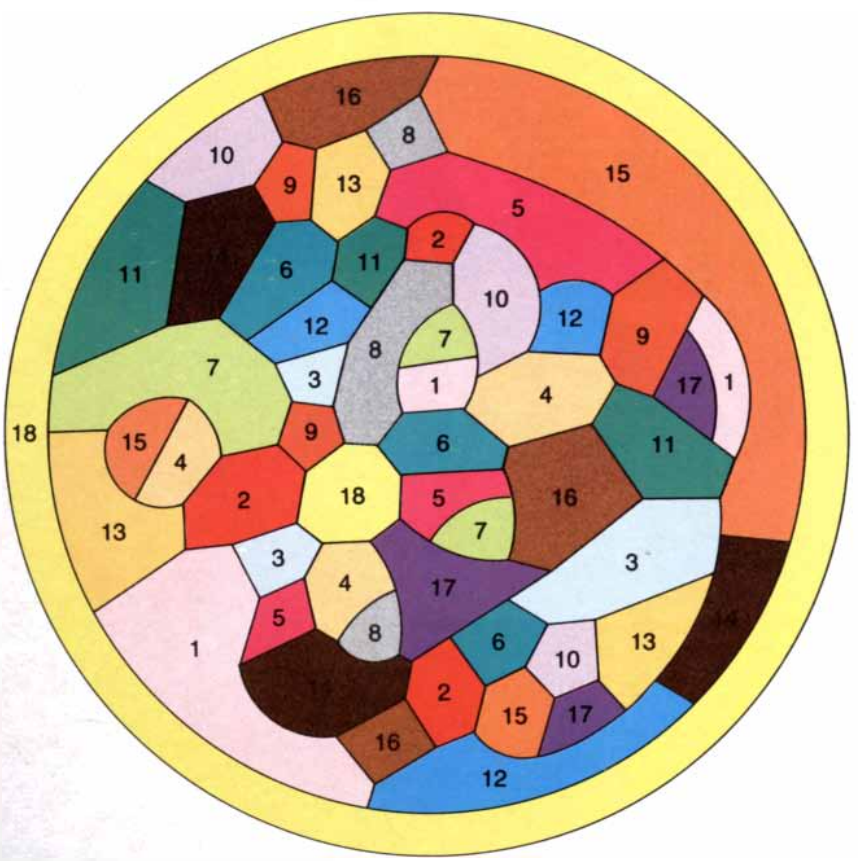
In December of 1976 G. Spencer-Brown, the maverick British mathematician, startled his colleagues by announcing he had a proof of the four-color theorem that did not require computer checking. Spencer-Brown's supreme confidence and his reputation as a mathematician brought him an invitation to give a seminar on his proof at Stanford University. At the end of three months all the experts who attended the seminar agreed that the proof's logic was laced with holes, but Spencer-Brown returned to England still sure of its validity. The "proof" has not yet been published.

Spencer-Brown is the author of a curious little book called *Laws of Form,* which is essentially a reconstruction of the propositional calculus by means of an eccentric notation. The book, which the British mathematician John Horton Conway once described as beautifully written but "content-free," has a large circle of counterculture devotees. Incidentally, after Brown's announcement that he had proved the four-color theorem was reported in newspapers around the world the *Vancouver Sun* for January 17, 1977, printed a letter from a woman in British Columbia. Brown could not have proved the theorem, she wrote, because in April, 1975, *Scientific American* had printed a map that required five colors. She was referring to a map that appeared in this department as an April Fools' joke!

While topologists go on with their search for a simple proof of the four-color theorem, some are also working on two fascinating but little-known generalizations of the problem that are still unsolved. In what follows I shall draw heavily on a private communication from Herbert Taylor. Formerly a mathematician at California State University at Northridge and at the Jet Propulsion Laboratory of the California Institute of Technology, he is currently studying electrical engineering with Solomon W. Golomb at the University of Southern California. He was also once rated one of the world's top three non-Oriental go players.

As Taylor points out, one way to generalize the four-color problem is to consider a map on which each country, or area to be colored, consists of m disconnected regions. If all regions of a single country must be the same color, what is the smallest number of colors necessary for coloring any such map so that no two regions of like color share a common border? Taylor calls this question the m-pire problem and the number of colors required the m-pire chromatic number.

If m equals 1 (that is, if each country consists of only one region), the problem is equivalent to the four-color problem, and Haken and Appel established that the chromatic number is 4. If m equals 2 (think of each country as having one colony with the same color as



Herbert Taylor's map proving 18 colors are required for the **m***-pire problem when* **m** *equals 3*

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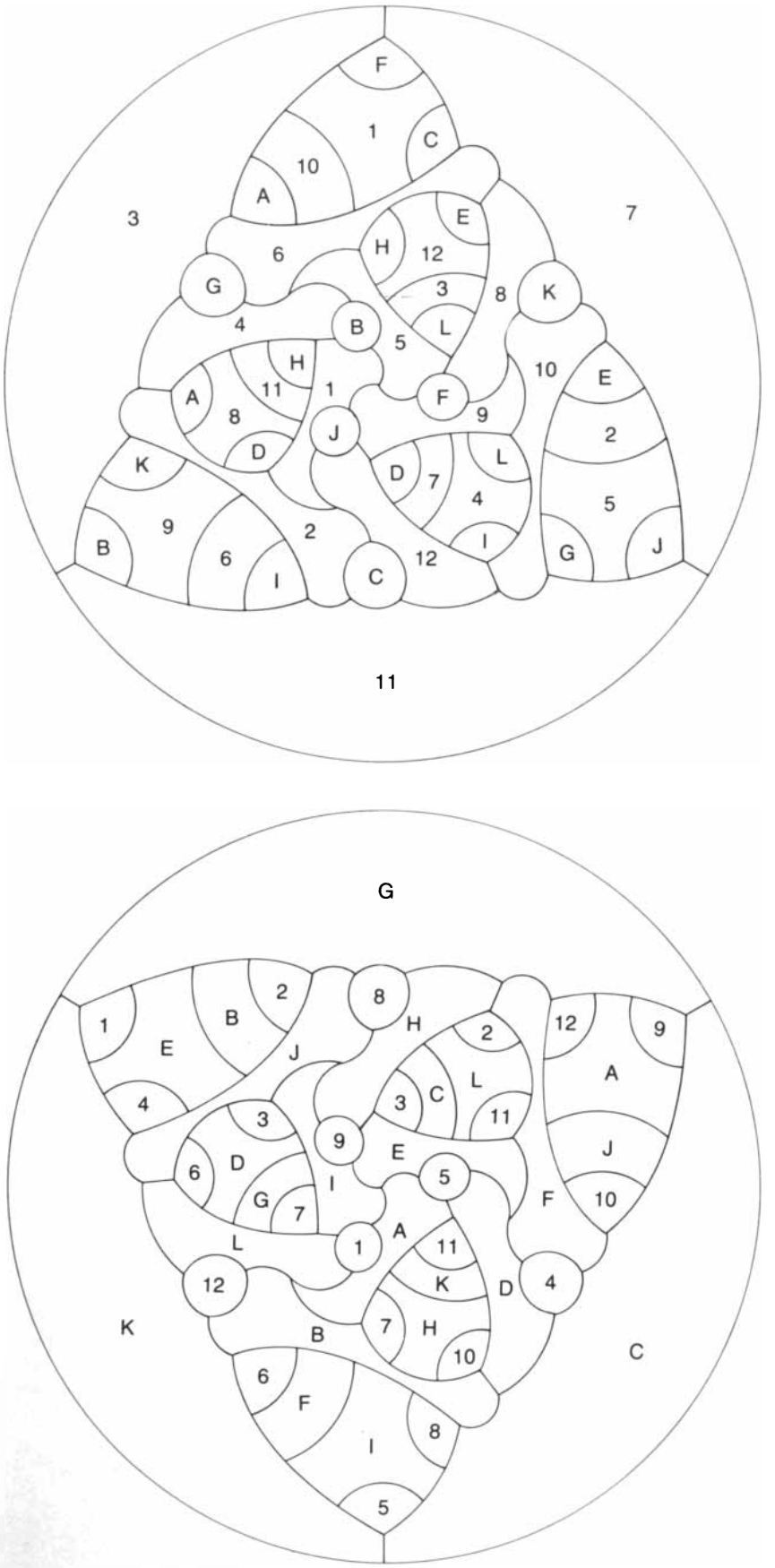

Taylor's two-part map showing that 24 colors are needed when **m** *equals 4*

the country), the chromatic number is 12. Surprisingly, this result was presented by Heawood in 1890 in the same paper in which he demolished Kempe's proof of the four-color theorem. In other words, the solution to the m-pire problem for the case $m = 2$ was obtained long before the solution for the case $m = 1$. In Heawood's proof he first showed that for any positive integer m the required number of colors for an m-pire map is no more than $6m$. Then he exhibited a "2-pire" map that required 6×2, or 12, colors, a map he said he "obtained with much difficulty in a more or less empirical [m-pirical?] manner." That map is shown in the illustration at the left on page 14.

Note that Heawood's map has no symmetry. Taylor found a fairly symmetrical version (which can be obtained from the map shown at the top of the illustration at the left by shrinking the lettered regions to points), but the most symmetrical map was devised recently by Scott Kim, a graduate student at Stanford University. Kim's beautiful map is shown in the illustration at the right on page 14. As Heawood remarked of his own map: "What essential variety there might be in such an arrangement of 12 two-division countries . . . is a curious problem, to which the one figure obtained does not afford much clue."

Heawood was convinced that $6m$ provides the chromatic number for all m-pire maps. Examine Heawood's map or Kim's for the case $m = 2$, and you will see that each 2-pire touches all the others, thereby proving that 12 colors are necessary. Heawood believed that for every m there exists a similar pattern of $6m$ regions, with each m-pire touching all the others. Taylor recently proved that this conjecture is true when m equals 3, using the map requiring 6×3, or 18, colors on page 16. (Note that only two regions on the map are numbered 18 and colored yellow. The third region of this 3-pire is disconnected from the rest of the map and can be anywhere on the plane.)

Taylor later confirmed Heawood's conjecture for the case $m = 4$ by constructing the two-part map requiring 6×4, or 24, colors at the left. Think of the two parts of the map as being two hemispheres of the same sphere. (Any map on a spherical surface can be converted into a topologically equivalent planar map by puncturing the surface inside any region and then stretching the hole until the map can be laid flat.) Note that each 4-pire on the map touches all the others, proving that 24 colors are necessary in the 4-pire problem. Both of these results are published here for the first time. Heawood's conjecture remains unverified for the case $m = 5$ and all higher values of m. For maps drawn on the surface of a torus, however, Tay-

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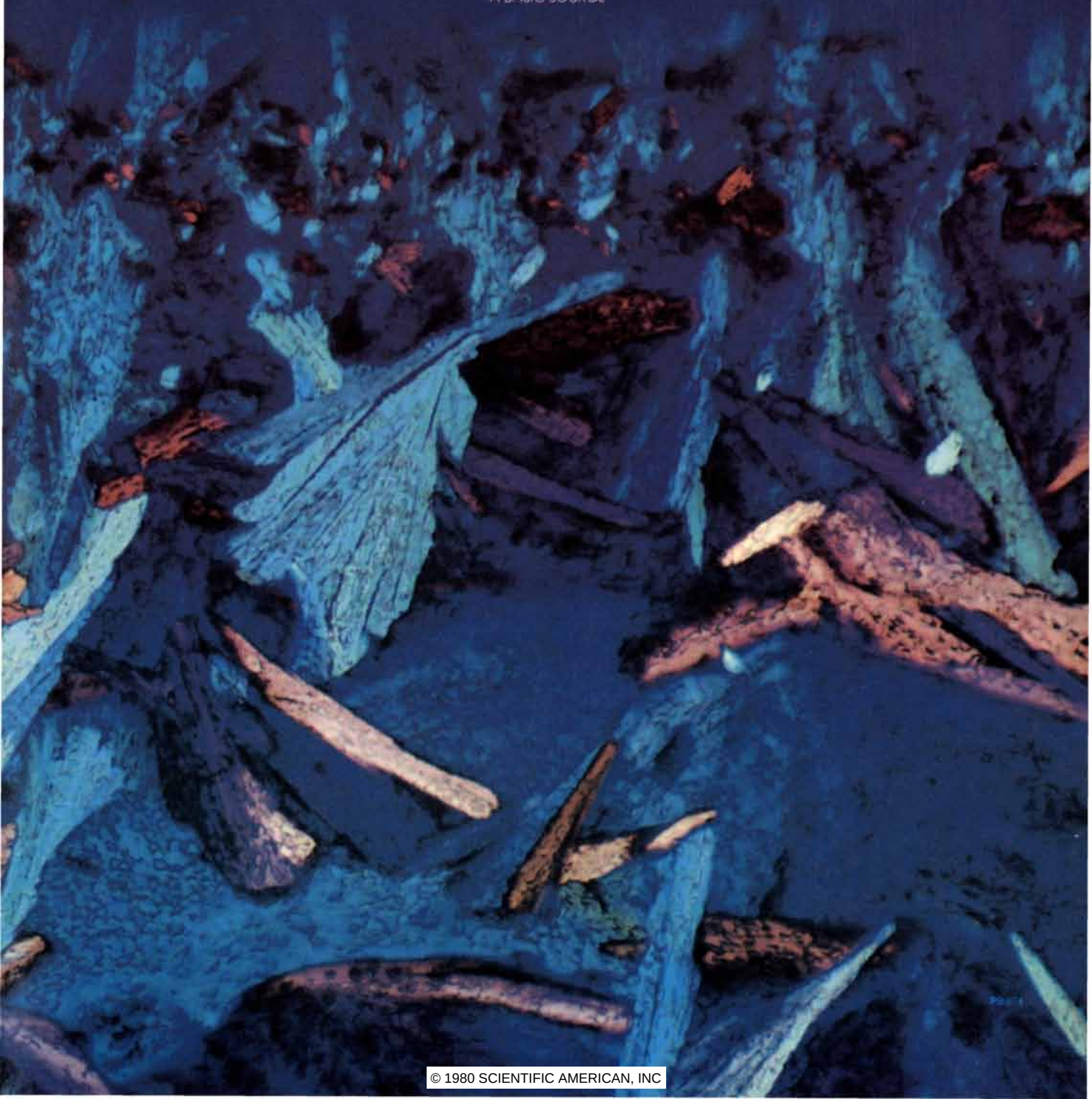

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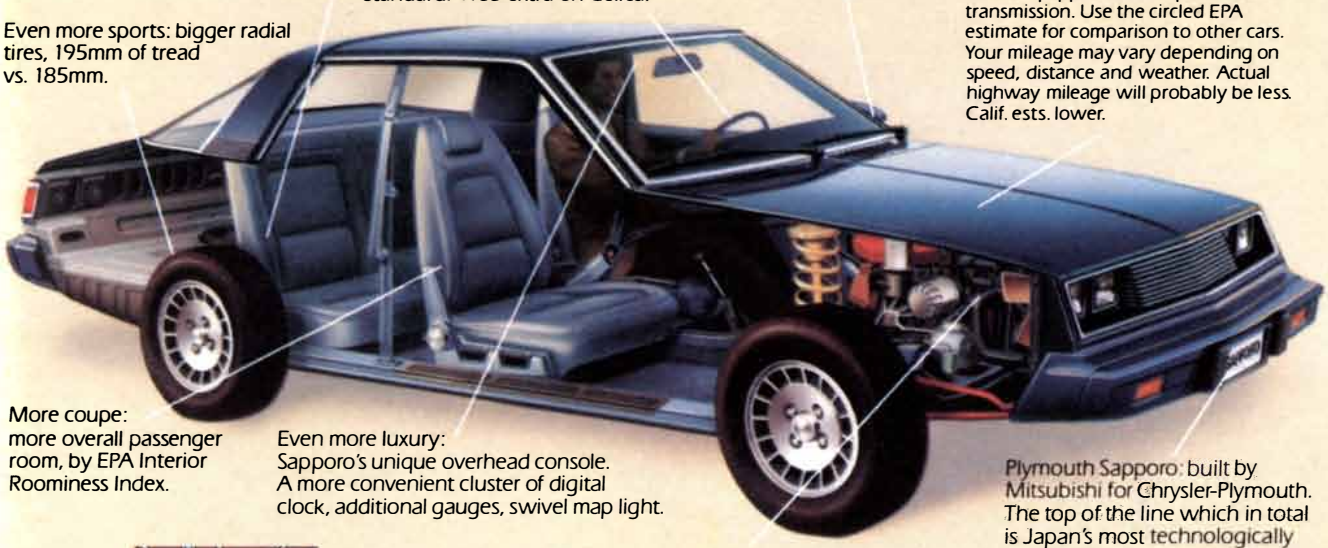

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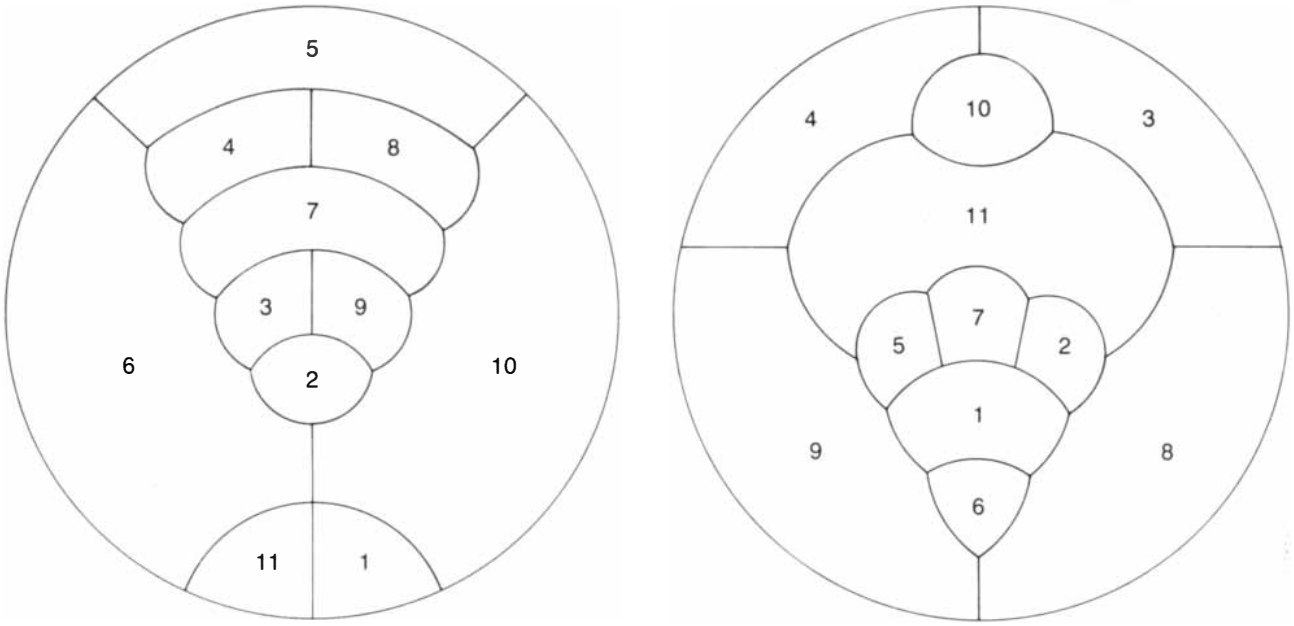


Thom Sulanke's configuration for the earth-Mars map problem

lor recently solved the m-pire problem. He has submitted a note to *Journal of Graph Theory* titled "The m-pire Chromatic Number of the Torus Is $6m + 1$." The problem remains open for all toruses with more than one hole.

In 1959 in a German book dealing with graph-coloring problems Gerhard Ringel posed another problem that is closely related to the m-pire problem. Assume that Mars has been colonized by the nations of the earth and that each nation has one home territory on this planet and one colony on Mars. Each region is simply connected (without holes), and each colony is the same color as its parent nation. Once again the problem is to find the minimum number of colors that will color all possible maps on the two spheres so that no two regions of the same color touch at more than single points. Since maps on spheres are equivalent to planar maps, the same problem can be formulated in terms of two separate maps on the plane.

Ringel showed that the chromatic number for all two-sphere maps is either 8, 9, 10, 11 or 12. The upper bound of 12 is derived from Heawood's upper bound for the m-pire problem of $6m$ as follows. Suppose a pair of maps require more than 12 colors. It would then be possible to convert them into planar maps and join them to create a 2-pire map requiring more than 12 colors, thereby violating the proved upper bound of $6m$.

Ringel guessed the chromatic number for the earth-Mars maps to be 8, a hypothesis that was strengthened in 1962 when Joseph Battle, Frank Harary and Yukihiro Kodama showed that a two-sphere map could not be constructed with nine 2-pires so that each 2-pire touched all the others. In 1974, however, Thom Sulanke, then a student at Indiana University, sent Ringel the pair of maps above. These maps too are published here for the first time. If you try to color the 11 2-pires so that both of the regions having the same number are given the same color, you will find that nine colors are needed! Thus to color the earth-Mars maps nine colors are necessary and 12 are sufficient. No one yet knows if such a pair of maps can be constructed that require 10, 11 or 12 colors.

It is also possible to combine the 2-sphere problem with the m-pire problem. For example, suppose m equals 4 and each sphere is a map on which each country has just two regions. If you think of the figures in the illustration on page 18 as being two separate maps, one on the earth and the other on Mars, they prove that for the case $m = 4$ the number of colors required is 24. We know that 24 are enough as well because Heawood's upper bound of $6m$ also applies here. Hence the problem is solved. Taylor conjectures that for every positive even-integer m there is a map of $6m$ m-pires on a surface consisting of $m/2$ spheres such that each m-pire has two of its m parts on each sphere and each m-pire touches all the others.

I conclude with a delightful coloring puzzle involving the U.S. Ignoring Hawaii and the disconnected parts of states such as the islands that belong to New York and California, note that nowhere on the map of the 49 states of the continental U.S. is there a place where four states all mutually share borders. (The same is not true of other countries. For example, Switzerland has four cantons that are mutual neighbors: Solothurn lies at the center of the configuration, and it is surrounded by Aargau, Basel and Bern.) This situation suggests an intriguing question: Is it possible to color the 49 states with three colors instead of four?

Another way to view this possibility is to consider the Four Color Puzzle Game, marketed last year by Knots, Inc. (2425 Third Street, San Francisco, Calif. 94107). People who buy the game (for $6.95 postpaid) are given two jigsaw-puzzle maps of the continental U.S. In each puzzle each state is represented by a single piece, and the two pieces in the game representing each state are different colors. The task is to choose pieces to make a four-color map of the U.S. in which no neighboring states are the same color. (As in the four-color theorem, states of the same color may touch at a single point.) To restate our question: Is it possible that Knots, Inc., could have used only three colors for their puzzle pieces and asked for a three-color map of the U.S.?

The answer is no, but most people find it annoyingly difficult to prove. Can the reader give a simple proof that the U.S. map requires four colors? Next month I shall supply one.

The first problem given last month was to exchange the positions of the two black and the two white pieces on a 4-by-4 minicheckerboard, making the fewest possible moves. The minimum number of moves needed to solve this minicheckers puzzle is 16. Numbering the black squares of the board 1 through 8, as was shown last month, the first four moves must be 2–4, 8–5, 4–6 and

5–4. The fifth move may be 1–3 or 6–8, with many variations thereafter. A typical sequence of the last 12 moves is 1–3, 4–1, 6–8, 7–5, 8–6, 5–4, 3–5, 4–2, 5–7, 1–3, 6–8 and 3–1.

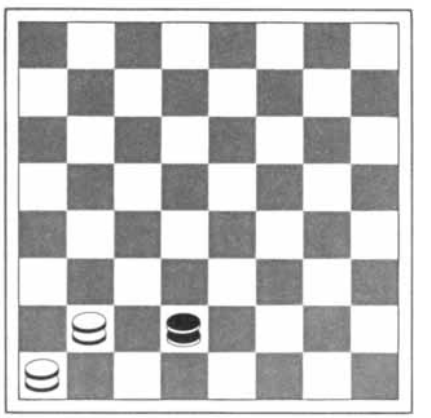
White can win the checkers hustler's wager given last month as follows:

Black	*White*
19–24	29–25
24–28	30–26
21–30	31–27
30–32	

At this point the game is over, and although Black has won the game, he has failed to crown the piece he moved first, thereby losing the wager.

Finally, the illustration below shows a checkers position in which White has two kings against Black's one king and is the next to move. By playing properly Black can force a draw. It is the only position in which one king can draw against two kings.

In this department for November of last year the illustration on page 33 showed the solution to the problem presented in October of finding the largest square inscribable in a regular pentagon, but the explanation of the solution was inadvertently omitted. It is easy to suppose the square shown at the left in the illustration is the largest because the slightest tilting of the square moves one of its corners outside the pentagon. The correct answer, however, is shown at the right. Assuming that the pentagon has a side of 1, the square at the left has a side of 1.0605+, whereas the square at the right has a side of 1.0673+. Note that the bottom corner of the square at the right does not quite touch the base of the pentagon. The illustration is based on a figure that appeared in *Journal of Recreational Mathematics* (Vol. 3, No. 4, pages 232–233; October, 1970), where Fitch Cheney answered the problem he had presented in an earlier issue.



Solution to last month's checkers puzzle

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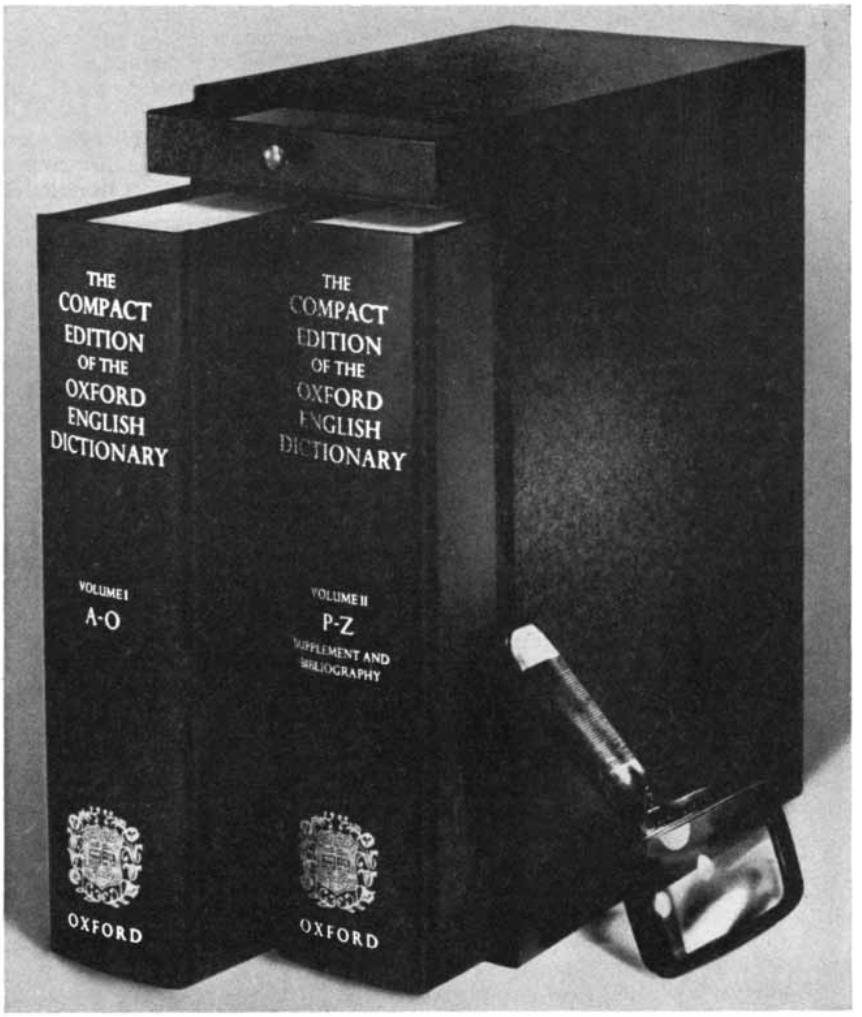

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BOOKS

Cyril Burt's deceptions, the Delphic oracle, big meteor craters, fever and other matters

by Philip Morrison

CYRIL BURT, PSYCHOLOGIST, by L. S. Hearnshaw. Cornell University Press ($19.50). Professor Hearnshaw is a senior historian of British psychology, a writer of talent, serious, precise and open. It was he who gave the memorial address for Sir Cyril Burt in 1971, 11 days after that famous man died at 88, "the first Britisher to devote his life simply and solely to psychology, who was paid for being a psychologist, and who never practised in any other field." At that time, although he had known Burt only slightly, the author held him and his work to be outstanding. A month later Sir Cyril's sister offered Hearnshaw a small grant to prepare a full-length biography of him.

The work began quietly, but within two or three years public attacks on Burt clearly demanded direct attention. Papers at hand, Hearnshaw worked away (now supported by an independent fellowship) and gradually "became convinced that the charges against Burt were, in their essentials, valid.... The problem became, in fact, a medico-psychological one." In a judicious and sympathetic fashion this biography, meant as much for the general reader as for the specialist, gives a "balanced sketch" of Burt's remarkable mind and of his curiously influential research, a corpus that over nearly 30 years came to include a complex fabric of misstatement, falsification and fraud.

The evidence is conclusive. The internal evidence was first called to light publicly a few months after Burt's death by a Princeton psychologist; he observed such internal inconsistencies as three-place agreement between the statistical properties of two very different samples (not merely in one respect but in dozens). The external records are decisive even as to intent. Burt kept a detailed and revealing journal. He wrote important letters palpably in violation of simple facts at hand. It appears that he repeatedly published reviews and papers under false names, organizing entire dialogues in print, with himself playing both parts.

His task was made easy by the fact that he was the editor for almost two decades of a small specialized journal, *British Journal of Statistical Psychology* (its name after 1953), which he ran as a vehicle for himself and his ideas, loading it with long and often irrelevant articles and reviews under his own name. Perhaps half of all the other contributors over the years, apart from the authors of technical papers, are unidentifiable; they seem, judging from the style and content of the notes, letters and reviews, to have been Burt himself. Of course, this kind of elaborate game is not unknown; the mischief was that in this case it led into a morass of claims, public and private, of research never done, data never on hand, checks never performed and manuscripts deceptively modified.

Three topics in Burt's work seem to be vitiated on a substantial scale. He rewrote the history of factor analysis, in a way that belied his own experience of 40 years, to remove credit from his old chief Charles Spearman and to give more credit to two already famous mentors, Karl Pearson and Francis Galton. Then he led a long dance among the numbers to bolster the facts gathered in his early days as psychologist for the schools of the London County Council, adding crucial new pseudodata to his small and poorly reported sample of identical twins reared in contrasting environments (those whose I.Q. scores correlated so wonderfully well). He described continued field activity in his twin studies for a generation past the time when it is at all plausible that he or any co-workers had the time, the access, the funds or the involvement. (Even the existence of his co-workers is under some shadow, although not all of them were fictitious.) Here his game entered into tragedy; in the U.S. the I.Q. controversy is part of the burden of racism our country still shamefully carries. In the end he fabricated in detail data tending to show that scholastic achievement in Britain was declining steadily over the years. Professor Hearnshaw offers detailed evidence for all these statements.

Burt was brilliant, obsessive, tireless. Self-taught in statistics after a largely classical education, he became a leading expert in its applications. He was a polymath, enormously well read, with a penchant for drawing into his discussions the results of genetics, quantum mechanics and even telepathy! His personal life was strained, lonely to a degree, introverted, without sociability. His health was poor. His wartime experiences included a tragic loss of his papers in the bombing of London. He was nonetheless intensely ambitious. What he sought was "neither wealth nor power, but intellectual supremacy." In spite of his energies and talent, that lay beyond him: he was knighted for his public service, but he was never made a Fellow of the Royal Society.

Here Professor Hearnshaw is not as searching as he is in all other facets of Burt's life. It seems probable that this somewhat strange man, with his lifelong emphasis on the heavy analysis of data that cannot be very well defined, had left a trail of tacit distrust within the perceptive community of British science. True, his field was not one much published in the *Proceedings,* but we also learn in one sentence that a very distinguished colleague, himself a Galton Professor with wide interests in both genetics and psychology, had suspected for some time that Burt's "scientific work was unsound." It is made clear that Burt did not hold an animus against this or that group of humanity. Rather he tended to insist that the individual mind, and not any group, was the sovereign psychological variable. His active part in the controversy was a piece of the paranoia of his later years, a determination that his work should be noted, important, seminal. Its false implications nonetheless resonated with the stridencies of oppression. Nothing is more ironic in this sympathetic volume, the story of a remarkably long and active life with its unhappy flaw emerging at the last, than a revealing diary entry young Burt wrote as an Oxford student of 22: "My purpose in life concerns primarily myself. It is to produce one perfect being for the universe."

This book, besides its account of the life and awry mind of the first professional psychologist in Britain, offers clear lessons. Personal brilliance, energy, even the integrity that was finally lost to Burt, are not themselves guarantors of empirical validity. Data cannot remain secluded in a single mind; they must be shared and social. Once by necessity so exposed, they must grow robust enough to withstand the tendentious stresses of social and personal conflict.

THE DELPHIC ORACLE: ITS RESPONSES AND OPERATIONS, WITH A CATALOGUE OF RESPONSES, by Joseph Fontenrose. University of California Press ($22.75). For 1,000 years, first in wood and then in stone, the house of the Oracle at Delphi sheltered one who spoke for the god Apollo in the voice of a

DP Dialogue

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

Unwanted deposits of sediment on the oyster beds in Mobile Bay, on the Alabama coast, can be forecast with the aid of an IBM computer. A mathematical model could be used to describe in detail the "buoyant plume" of river water carrying sediment into the bay.

Probing the Path of Water in Water

Cooling water, returned from a utility plant to the river from which it was drawn, assumes a characteristic shape called a "buoyant plume." So does river water flowing into a bay – or any fresh water from a confined channel entering a larger body that is salty or cooler or both.

Working with Louisiana State University's IBM 3033 Processor, Professor Richard C. Farmer has constructed a mathematical model of the complex patterns of momentum and transfer of both heat and mass of a buoyant plume.

As Dr. Farmer explains, the waters of many rivers carry sediment, some bringing hundreds of millions of tons of it a year to their deltas. "When ship-channel dredging is done, sediment is pulled off the bottom and moved elsewhere, affecting the shape of the plume. Where will newly arriving sediment now begin to settle? If there are oyster beds, how much will be deposited on them?

"It's a difficult phenomenon to model," notes Farmer, a member of LSU's Chemical Engineering department. "For example, if you try to simplify by omitting one dimension, you miss major effects."

Currently, Farmer's model is used almost daily by the Tennessee Valley Authority, which operates a number of thermal power plants that draw river water to carry off waste heat. It is only a degree or two warmer at discharge, but this can be enough to affect the fish and plant life of the river.

"Depending on their goals," Farmer says, "the plant operators may want to minimize the thermal impact by spreading it over a wide area, or confine it to a narrow flow to preserve downstream fishing. In either case, they can control it by manipulating geometry and volume, and by coordinating the discharge with the velocity of water in the river."

APL Keeps Analog Devices "In the Chips"

William Carlson works at a computer terminal to plan production of integrated-circuit chips. A production planning supervisor for Analog Devices, Inc., he uses a program he wrote in APL, a user-oriented IBM programming language.

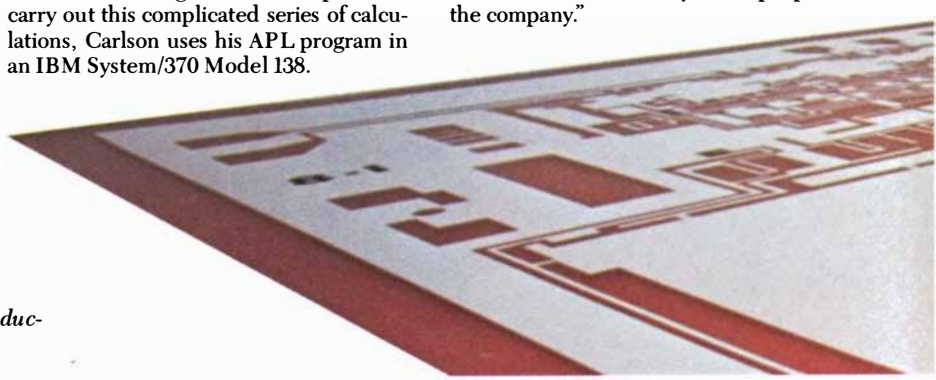
"Because I write and execute my own programs," Carlson says, "I can modify them as my needs change or as I understand them better. Now I do work in a few days that took three months when I turned it over to a programmer-analyst."

Analog Devices is a leading manufacturer of electronic circuits for signal conditioning and data conversion. Its high-precision products are used in scientific research, industrial control, aerospace instrumentation and medical systems. The Norwood, Massachusetts-based company maintains a catalog of about 350 standard products, incorporating about 50 types of integrated-circuit chips.

To plan production, Carlson explains, he must first determine the requirements for finished products made at several manufacturing sites. Then, to arrive at specific assembly schedules for each site, he must take into account the production yield for each type of device, the near-term production schedule, current inventory, work in process, output capacity, and the manufacturing costs at each plant. To carry out this complicated series of calculations, Carlson uses his APL program in an IBM System/370 Model 138.

"The yields, selling prices, inventory cost of goods and labor costs by location are all in a permanent data base under APL," he says. "If I'm not satisfied with the plan the first time around – perhaps I'd prefer a different plant loading – I can change one parameter and regenerate the entire schedule in moments.

"Using APL, I actually design the application and program it in one operation. I think it out and see logical errors as I go. It is easy to maintain, and to build a data base that can be used by other people in the company."



The masking pattern for one layer of an integrated circuit is prepared at 500 times actual size. To minimize inventory and manufacturing costs, Analog Devices plans chip production with the aid of programs written in APL.

This antenna is part of a radar system for a military surface vehicle. To produce such electronic systems, Hughes Aircraft Company uses CADAM and an IBM computer to generate a step-by-step "picturebook" for each manufacturing work station.

From Picturebook to Radar System– In A Thousand Easy Steps

To fabricate and assemble complex electronic systems, production workers must follow a long series of detailed procedures. At the Radar Systems Group of Hughes Aircraft Company, each worker is guided by a set of step-by-step illustrated instructions, called a "picturebook," created with the aid of an IBM computer.

For each blueprint or specification supplied by the designers, the manufacturing engineers must develop over 100 pages of combined pictures and text. Fabricating the fire control system for the F18 supersonic aircraft, for example, requires 500 separate picturebooks, ranging from one to many pages in length.

Pictures and Text

At the Group's headquarters in El Segundo, California, a System/370 Model 138 helps to prepare both the pictures and the text. E.R. Gustason, Jr., head of CAM production engineering, explains that RSG uses the Computer-Graphics Augmented Design and Manufacturing (CADAM®) system to create the illustrations. A companion program, called Computer-Aided Process Planning (CAPP), helps the engineers generate the routing of each workpiece and the text for each picturebook. CAPP was developed with the support of Hughes and 60 other companies.

"For convenient presentation to the production worker." Gustason notes, "we put the pages of some picturebooks on 35mm slides and equip those work stations with slide projectors. This is particularly useful for complex assembly procedures: CADAM drives a four-color plotting machine, and we make color slides that clarify detail.

"We also plot transparent mylar overlays, to check on interference between parts during assembly," says Gustason. "Or, to look for interference among moving parts, we put an animated display on the screen. In addition, the computer stores an index of previously developed components; whenever an existing part – a power supply, say – will serve a purpose, we can retrieve and reuse the engineering and the production planning.

More Cost-Effective

"Soon," he adds, "as the designers adopt CADAM, our input will arrive – machine-readable – in a computer disk-pack with the drawings in the form of mathematically defined shapes. This will eliminate the initial digitizing steps, making computerized planning even more cost-effective than it is today."

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woman. She was legally silenced, along with all other divination, by a Christian emperor's edict in A.D. 391. What was it like to confront that Pythia, whose words conveyed the mind of the god? From Agamemnon to Hadrian and beyond the great consulted the oracle, both in simple fact and in richer poetic fancy. What did they hear, and how?

From the 10,000 to 15,000 books and the inscriptions that are the haphazard legacy from classical antiquity the scholars have sought out whatever authors reported of the responses of the oracle. A volume published by two British classicists in 1956 reported the full corpus. Now a Berkeley scholar presents a summary catalogue of all those 615 preserved responses, "historical, quasi-historical, legendary and fictional." They are given in a single uniform format: consultant, occasion, query, response and source. Riddles and commonplaces, they form a body of evidence so persuasively interpreted, mainly by carefully reasoned counts of types and circumstances—fully statistical results without any formal statistics—that we come to grasp what the oracle really said.

The central argument is as sharp as a razor. Divide all reports of responses into those that record contemporary events ("historical") and those that tell what the oracle said either in legendary times (in the epic days of Greece before 800 B.C.) or at other times before the lifetime of the author of a report. There are more than 70 contemporary reports, spanning 500 years, but there are 170-odd responses called legendary, referring to magical times.

Now examine the nature of each response. Is it a simple command or a warning? Is it clear or ambiguous? Does it concern religious questions or matters of state? What was the occasion of the consultation? Was it an acute problem such as a plague or merely a matter of some uncertainty in forms of religious worship? Finally, how was the question put? Was it an innocent "What shall/should I do?" or a more explicit "Is it better for me to do *X*?" The result of the careful counts is a surprise, less in the conclusion than in its definiteness. The historical oracles are "pretty much confined to sanctions of laws and proposals, particularly on religious subjects." Eighty percent of the historical oracles are clear commands or sanctions: instructions to give this or that to the gods or simple approval of such intentions.

About half of the legendary reports are also such commands. Of the historical responses, however, three-fourths are on matters of cult, law, custom and sacrifice; in legendary times only about a fourth are on such topics. More than half of the legendary responses relate to personal affairs, pointing to fulfillment in nonreligious and nonpolitical terms. Fewer than a tenth of the historical responses follow that path; a personal question in historical times was likely to receive a religious answer. Of the legendary responses, 26 (15 percent) offer indications of a place ("Where white ravens appear"). Not one historical answer fits this bill of particulars.

So the careful construction progresses. It is important to note that almost 300 more responses are historical if they are taken at face value, that is, they refer to historical dates but come to us only from writers who lived much later than the stated time of the response. This large sample is divided according to the same rules. It turns out that in both modes and topics these responses lie much closer to the legendary than to the historical. In the end they are broadly rejected as not being genuine, a "wholesale dismissal." That seems just: if over five centuries contemporaries find their Pythia speaks mainly simple commands on religious matters, why should we believe in her remarkable responses only during periods that are less well documented?

It was Plutarch who first recognized this difference between oracle past and oracle present; he believed all the Greek reports were genuine and was forced to conclude that the Delphic Oracle, like all the other oracles, had entered an age of decline. The counts, however, speak eloquently. "The Delphic Oracle not only wasn't what it used to be: what was more, it never was. The Pythia had never spoken any other kind of response than what she was speaking in Plutarch's time." The famous enigmas and double meanings, like the tale of great Birnam Wood that came to Macbeth's high Dunsinane, were either the work of a gifted poet or the poetic lore of the folk. "Should I make war on the Persians?" asked Croesus, king of Lydia. At Delphi, they say, he was told quite truly: "If you make war on the Persians, you will destroy a great realm." It is the wit and the form, not the fact, that endure through centuries.

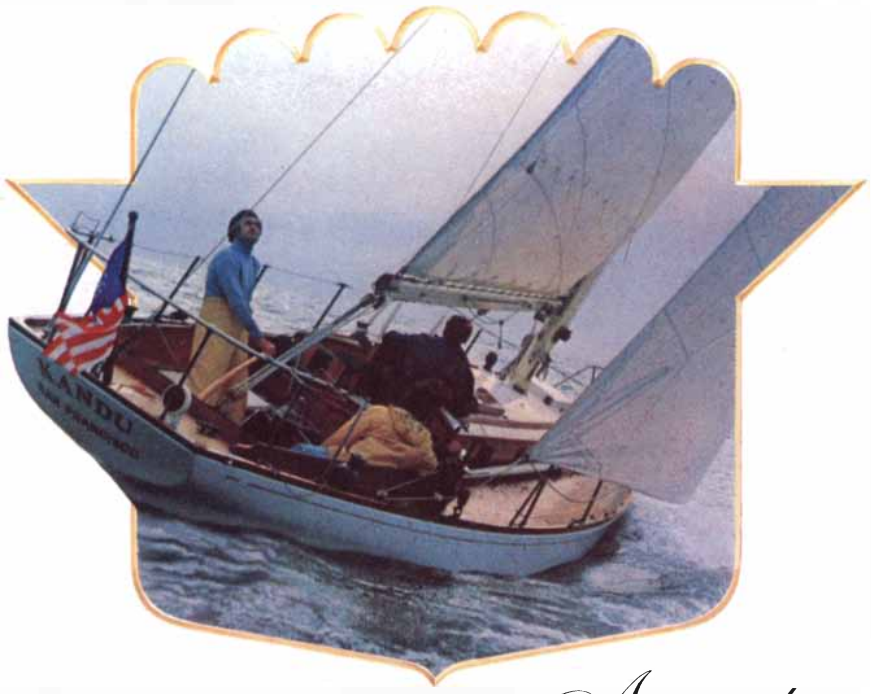
Professor Fontenrose has pursued these mysteries for more than 40 years. He has himself gone to Delphi a dozen times. There in the limestone country he has come to doubt as well the views of modern rationalist scholars who have long set aside the hypothesis that the great prophetic feats were divine. But they have instead sought to invoke the fury of the possessed, whose strange sounds were given the form of wise speech on the spot by clever and prescient attendant priests. Were there perhaps exhalations from the earth, volatile hallucinogens that induced wild speech and remembered belief? Here too the evidence falls away. Delphi has no volcanism or hot springs.

The vase paintings show us a quite formal person seated on the tripod, far from any shaman's trance. The offered scheme is implausible and unnecessary; the wonders of the oracle and its mysterious prevision are part not of history but of literature. It was never Delphi that sent Sparta to war against Athens; Sparta only sought sacred confirmation of her grave decision. The Greeks valued Delphic sanction above all for their laws of cults and religious institutions; their polity was not guided by the voice of Apollo except in those shadowy times of Cadmus and Orestes, times important enough to Greek life and thought but far below the surface of actual history.

ASTROBLEMES—CRYPTOEXPLOSION STRUCTURES, edited by G. J. H. McCall. Benchmark Papers in Geology, Volume 50. Dowden, Hutchinson & Ross, Inc. ($39.50). The airless, cratered moon, where the scars of giant impacts endure over all geologic time, is the familiar victim of astroblemes ("star wounds"). A dozen smaller terrestrial features, from the Canyon Diablo crater in Arizona to the Tunguska forest blowdown in Siberia, have been established beyond a doubt as impact consequences. Most of them are modest enough, sites measured in tens or hundreds of meters. They were well described in an earlier anthology of the literature collected by the same editor (a well-known expert now at the University of Liverpool), another volume of the same series of collections of original papers (Volume 36, which appeared in 1977). Here Dr. McCall has put together, along with his helpful and judicious comments (showing a few typographic blemishes in units and exponents), three dozen additional papers (a few abridged) published in the past 20 years.

Most of these seek grandly to extend the class of known meteor craters. In addition to the proved dozen another 15 sites are known where recognizable craters are present without associated meteoritic material. The largest of these likely sites is a few miles in diameter. But those more debatable features that are the topic of the present volume reach diameters of 160 kilometers. The energy expended in the vaporization and excavation of the rock that once filled Meteor Crater is estimated, in the grim unit of our times, at some 10 megatons of TNT equivalent. In contrast, the great explosion that produced the Vredefort ring in the Rand of South Africa had a yield a million times greater!

The scars studied here are those so old, so deeply buried or so complex that they do not display a manifest crater form. Sometimes there is no raised lip, only a circular cavity that is often filled; sometimes there is a central rise. Half a dozen local signs of impact are proposed by various authors, based both on field work and on close examination of minerals exposed to man-made explo-



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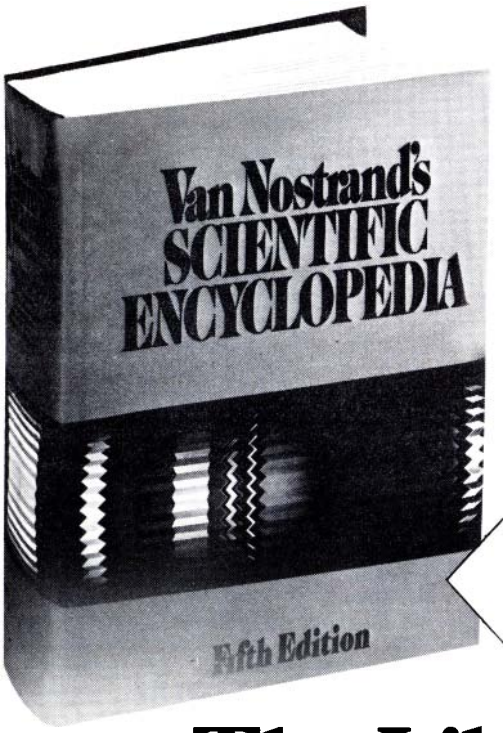

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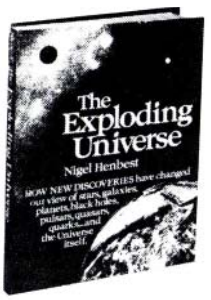

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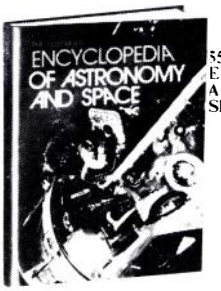

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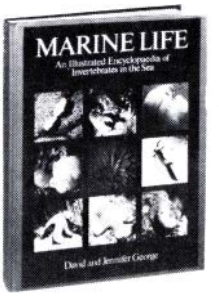

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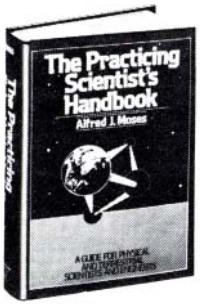

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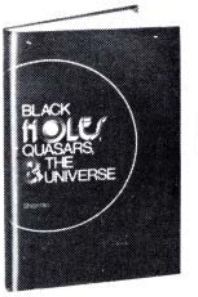

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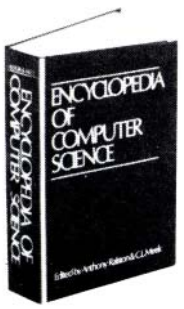

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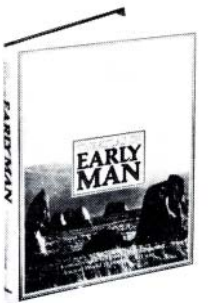

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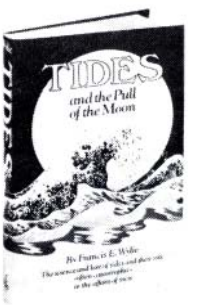

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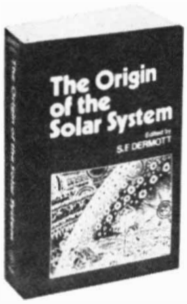

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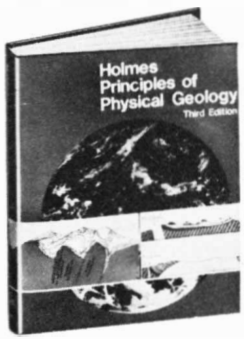

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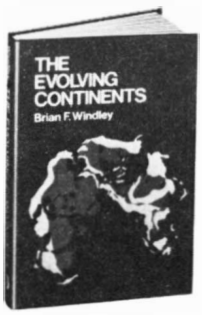

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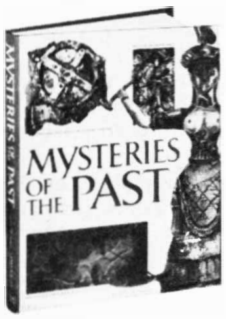

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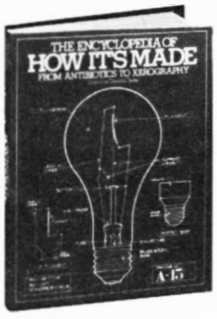

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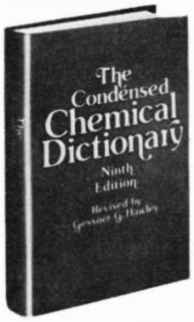

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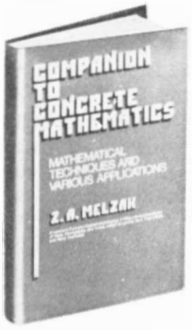

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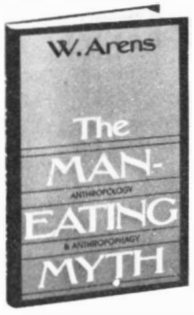

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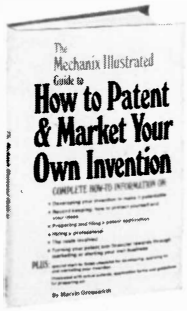

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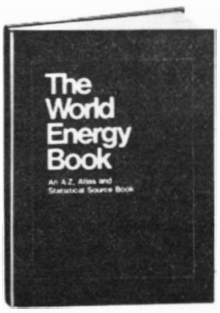

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sions. These are summarized neatly by McCall. They include conical fracture surfaces, which develop in dense rock when a shock encounters a small inhomogeneity. When an entire series of these "shatter cones" found in distant sedimentary layers can be "unrolled," or restored to the original horizontal, to disclose a fossil spherical shock wave around a focus many miles away, an intense and explosive event in one small volume is pretty much proved.

That has been done at Vredefort. Of course, one explosion is like another, given the energy, and the alternative notion of some internal "cryptovolcanic" event powerful enough and concentrated enough to generate highly supersonic shocks cannot be excluded. Our times on the earth know no such volcanic phenomena. We do not know either, however, what formed the diamond pipes, and yet those explosions were real enough. And so "the file on cryptoexplosion remains open."

No fewer than 10 probable impact craters are known in Europe. Their properties are here neatly tabulated: shatter cones; a detritus of expelled, weakly shocked material, some of which fell back and some of which was thrown out; glassy ejecta; melt rocks; solid-state glasses of the same kind produced by experimental shocks; a few high-pressure polymorphs of silica and even feldspar. Shock was certainly a factor in the production of these mineral phases, but what made the shock? Out on the plains between the Lena and the Yenisei rivers in Siberia is Popigay, a 100-kilometer ring recently recognized. The Canadians have plenty of startling candidates too, including the rich Sudbury nickel-copper district, a complex structure over which debate rages. That Sudbury and Vredefort are so different (the Canadian site flooded by igneous ore-bearing rocks and the South African one lacking such rocks almost completely) must mean the two meteorites caused quite different reactions in the wounded crust. Or was it all from within? Some structures seem to be double; some show alignments. Was there a common internal root, or was there a cluster of simultaneous impacts?

In the central Australian desert stands Gosses Bluff. To the nongeological eye it looks like a lunar crater five kilometers across, but that form is mainly an accident: both the crater-floor material and the postimpact sediment that lay outside have eroded away. Yet a plausible scenario, in five geological acts, is consistent with meteorite impact, viewed after a delay of 100 million years.

Dr. McCall offers a terse list of 45 structures "erroneously attributed to extraterrestrial agencies." These are mainly very large circular landforms, such as the arc of Hudson Bay, which is about 500 kilometers across. One wonders if all those attributions will turn out in the long run to be truly erroneous. Some truths are buried deep.

FEVER: ITS BIOLOGY, EVOLUTION, AND FUNCTION, by Matthew J. Kluger. Princeton University Press ($15). If even the skunk cabbage acts to determine its own temperature, sending its fast-growing flowering spadix at blood heat up through the snow, one ought not to be surprised that human beings share this adaptive feature with the desert iguana, the tuna and the bumblebee. The warm-blooded mammals have no exclusive patent on thermoregulation; rather, what they boast is an advanced internal means of thermal control.

The desert iguana prefers to keep its core temperature at about 39 degrees Celsius, plus or minus a degree, but it can do so only by basking in the sun or taking prudent shade. Night brings enforced torpidity to the iguana. The mammals have instead invested so heavily in fancy electronics and in a variety of biochemical specialties that they have to regulate their temperature, and with it their biochemical reaction rates, all the time (except during hibernation). The bill for keeping steadily warm is high; only 3 percent of the normal diet would be needed to support a resting man if, like an alligator of about the same size, he had no need to keep warm day and night. The choice of temperature maintained by thermoregulating animals makes engineering sense. Nearly all of them try to keep their body's core between about 35 and 42 degrees C. Above 45 degrees the weakened bonds of protein tertiary structure tend to melt; below 30 or 35 degrees the organisms would be forced, on an earth whose mean temperature is about 16 degrees, to undertake costly active cooling as a regular task.

No physiological abnormality is more commonly shared by human beings than an abnormally high temperature (above about 38 degrees). In fever the thermostat goes awry. Every familiar laboratory animal (all of them mammals, from the everyday rabbit and guinea pig to the unusual echidna) can develop fever. The laboratory stimulus is similar in each species: the injection of certain smallish proteins, called endogenous pyrogens, or of cells that release such proteins or of substances that can induce the formation of the proteins within the host's own cells.

Such artificial fevers are much studied; they clearly show some upset of the thermostat, a complex body-wide servo system with its seat somewhere in the brain stem. One most interesting experiment by the author himself is reported. Provide the desert iguana, a sun-basking "heliothermic" reptile, with a simulated desert: a few square meters of sandbox in a room kept warm and bright by day, cool and dark at night. Above the sand surface hang a set of heat lamps, some of them turned on during most of the 24 hours. Each iguana could find by day a spot at any temperature between 30 and 55 degrees, and then spend a cooler night. Control lizards arranged themselves with respect to the lamps so that their bodies remained near 38 degrees until the sleepy evening. Lizards rendered febrile by the injection of dead bacteria known to be reptilian pathogens developed a high fever, up to 42 degrees.

They could do so, of course, only by seeking the heat lamps; the iguana has no adequate internal heat source. The lizards behave as though the induction of fever is the result not of an out-of-order thermostat but rather of response to a regulator still in control but whose desired set point has been increased some four degrees by the infection. All vertebrate classes tested (no sharks or lampreys as yet) behave the same way. Bluegills and tree frogs, pigeons and rabbits, all show a febrile response. It is no recently evolved ability of our kind; even crayfish develop fever! The act of infection, probably associated with the telltale proteins, seems to set every animal thermostat up a few degrees.

Why? This comparative study suggests strongly that fever is in fact adaptive, a regulatory response to infection widely acquired over 400 million years of animal evolution. A direct test can be made with the iguana. The lizards can be injected and placed in a constant-temperature chamber so that their core temperature cannot change. The brainstem center calls for higher temperature, but there is no way to attain it; there are no sun's rays for the needed extra therapeutic basking. Most infected lizards died within three days unless they were kept at a temperature above 40 degrees. Even at the high-fever temperature of 42 degrees they survived well for the three days, although with some mortality after a week at such a temperature. A fever-reducing drug (among the most familiar for human beings too) prevented recovery; all the injected but afebrile lizards died. (Control animals served to exclude the effects of the drug alone and other alternatives.)

The case is made: fever seems to be adaptive in cases of infection, an old defense. Obviously very high and prolonged fever brings dangers of its own, so that clinical measures to cut off such peaks are warranted and even necessary. Moderate fevers, however, seem to inhibit infection, perhaps both by their effect on the microorganisms and by modifying the responses of the host. The ancient wisdom of the phylum is not to be gainsaid. Even the noble aspirin ought to be used with discretion, under the dictate of the wise Thomas Sydenham, phy-

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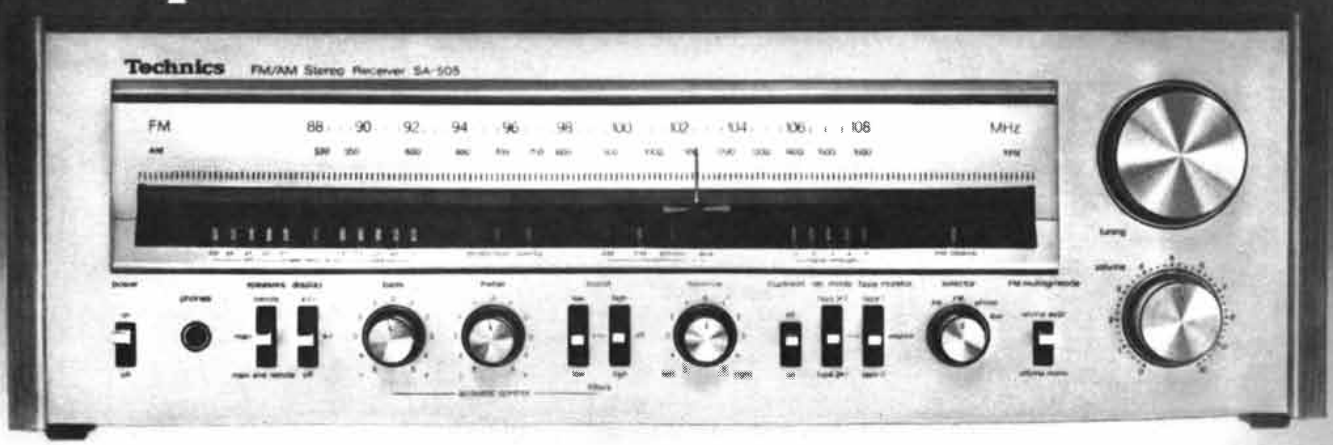

sician and friend to Robert Boyle, who wrote, "Fever is Nature's engine which she brings into the field to remove her enemy."

This is a brief, meaty book appropriate for the general reader in its breadth, its clear argument and its novel data, although in style it has not fully escaped the sway of medical jargon. Particularly on the biochemical side, much more is reported, both as concept and experiment, than can be summarized here.

THE ILLUSTRATED ORIGIN OF SPECIES, by Charles Darwin, abridged and introduced by Richard E. Leakey. Hill and Wang ($25). It is a precarious business to abridge and transform a work of genius, but *The Origin of Species,* "without doubt the most important biological work ever written," is prolix, in our eyes overrich in example, rather too tentative in tone; it has never been easy reading. Here we have a well-thought-out but severe cutting of the text, which has been reduced to about a third of Darwin's last edition and then enriched by a sensible brief introduction and appraisal by Leakey; his updating editorial asides and captions follow passim. The text is made much more readable thereby, not least by mere brevity. For our pleasure the London designers and editors and the Tokyo color printers have studded the book with excellent graphs, maps and biological drawings, as well as a bonus of beautiful and apt color reproductions. Among them are a delightful page of thumbnail sketches of bats and a lovely tawny painting of the *Beagle,* lying under snowy peaks in Tierra del Fuego among a few canoes of the Fuegians, that was done during the voyage by Conrad Martens. Darwin's problems and errors, and also some paths for Darwinian studies in the future, come clear in a second voice below that slow, strong Victorian melody.

ANATOMY ILLUSTRATED, by Emily Blair Chewning. Simon and Schuster ($6.95). Gross anatomy is perhaps the crudest essay toward the philosopher's goal of self-knowledge. A sense of portent thus surrounds all representations of the body viewed as an anatomical preparation. This striking and inexpensive paperbound book offers some 75 such images, most of them reproduced in color on an entire large page, along with an explanatory text (which is a little hazy when it comes to precise sources). The images, whether from old Persian or Japanese artists, from Thomas Eakins or Pavel Tchelitchew, whether the delicate engravings of the Enlightenment anatomists or the false-color-coded output of modern radiography, are a stunning set. A fascinating subtheme is that of humanity in utero, from a drawing by Leonardo to a dreamlike color study by Gautier d'Agoty.

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The Mura weighs only 12 ounces and measures 1½"x 2¾"x 6½". The system includes a base unit that plugs into your telephone jack. You carry your cordless telephone with you and when your phone rings, you press a button and answer. And you can talk to anyone as long as you remain within 400 feet of the base unit.

But wait. We mentioned that the phone had major disadvantages. And it does. But first, let's outline some of its major advantages.

Convenience You don't need an extension telephone. With the Pocket Phone you have an extension phone that you can take with you—in the bath, in the den, in the garden, or to your neighbors.

Intercom You can use the base unit to page the person holding the cordless telephone. For example, if you're in your office and someone outside has the unit, you can press a button on the base unit and buzz the portable phone—just like on an intercom. Simply by talking on the phone plugged into your base unit, you can talk with someone on the remote phone. It's ideal for home or factory use.

Price The cost of the Mura remote telephone is only $89.95. Compare this price not only with the cost of other $300 remote telephones but with conventional phones as well, and you can appreciate what a major breakthrough the Mura system represents. But there's more.

You can plug any conventional phone into the base unit and carry on a three-way conversation. You can answer a call at the base unit and signal the remote unit to pick up the line. You can cut out the remote phone from the base unit if you want to keep a conversation private.

TALK OF VALUE

You can carry the cordless telephone with you with its antenna collapsed and the battery on standby. When a call beeps your unit, you simply extend the antenna, turn the power on, and start to talk.

The unit is FCC approved for connection directly into your telephone line. If you don't have a four-pronged jack or a modular connector, simply call your telephone company. They'll promptly install a jack for you and the cost will be around $15 or less depending on your location.

NOW THE CATCH

We mentioned that there was a catch—a few major disadvantages that you, as the consumer, should know about before you consider purchasing this product. Here they are:

Forget About Dialing The new Mura Pocket Phone can't dial out. It only receives calls. To many people, this doesn't matter because 90% of remote phones are used to receive calls and not to place them. By eliminating the dial, Mura has cleverly saved consumers hundreds of dollars.

Forget About Steel Walls The Mura unit won't penetrate them. This means that if you want to use your phone in a factory with metal walls, your unit won't work. But for most factories and practically all homes, the unit is ideal.

Forget About Snooping The unit has only a 400 foot range. At first this might seem awfully short, but nobody can snoop in on your conversations if that person is beyond this range, and 400 feet is more than enough for most applications. Most cordless telephones operate in the 27 megahertz range—the same frequency area used for citizen band radios.

The base unit for the Mura can also be used as a personal paging system or intercom.

The Mura uses the 49 megahertz range. This frequency has clearer reception with practically no interference.

The above are the disadvantages. For 90% of you, they don't mean a thing. For those 10% of you who need a dial, we would recommend the more expensive cordless telephones.

But for those of you who will accept its disadvantages, you'll be in store for the greatest idea in telephone convenience since the cordless telephone was first introduced. In fact, rather than install an extension phone, why not consider the Mura instead?

TRY IT FIRST

We suggest you try the Mura Cordless telephone system in your own home, office or factory. Use it for 30 days. Take the phone to your next door neighbor's house or with you to the bathroom while you take a shower or bath. Take it with you on your patio or balcony, or bring it in your garden as you work. Use it in your factory as an intercom or in your office as a remote telephone.

After you've given it a thorough test, then decide if you want to keep it. If not, no problem. Simply return your system for a prompt and courteous refund including your $3.50 postage and handling. You can't lose.

HERE'S THE WAY

To order your unit for a 30-day test, simply send your check for **$89.95** plus $3.50 postage and handling to JS&A Group, Inc., One JS&A Plaza, Northbrook, Illinois 60062. (Illinois residents please add 5% sales tax.) Credit card buyers, call our toll-free number below. We'll send your base unit, cordless telephone, rechargeable batteries, recharger, complete instructions, our 90-day limited warranty, and the address of the closest Mura Service Center or service-by-mail station.

Your unit is backed by Mura Corporation, a 17-year old company famous for their microphones, headsets, and other audio products. JS&A is America's largest single source of space-age products—further assurance that your modest investment is well-protected.

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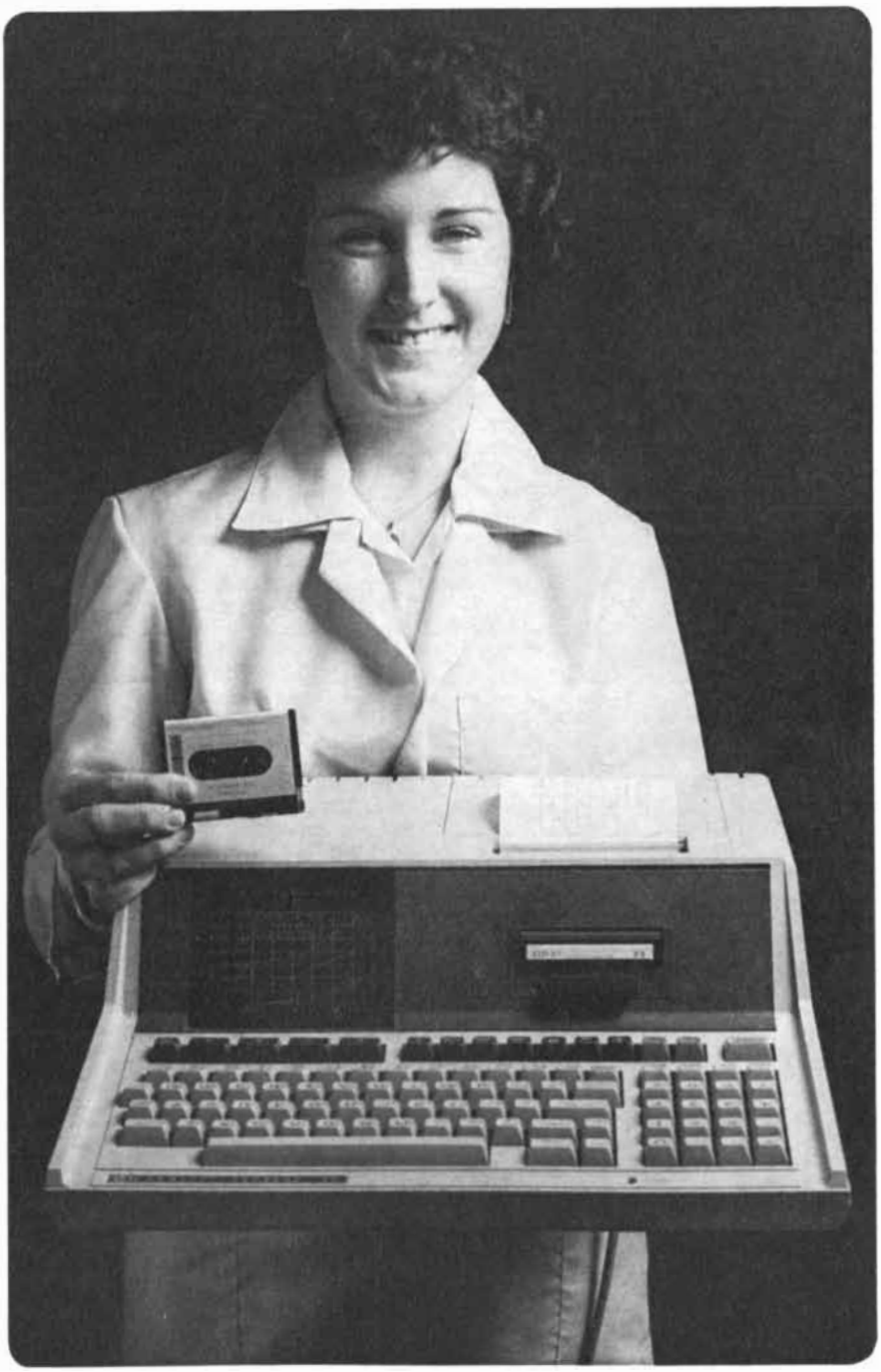

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The Allocation of the Radio Spectrum

The electromagnetic spectrum from 10 kilohertz to 300 gigahertz is a natural resource of communication that must be fairly allocated. Reforms in the system of allocation are currently being considered

by Charles Lee Jackson

It is clear that both national and international wireless communication would dissolve in chaos without some system for allocating the finite number of places on the radio spectrum among the many claimants. It is not so clear that the systems now in force are the best ones possible or that they work as efficiently as they could. My purpose in this article is to describe how the spectrum is currently managed (with the system in the U.S. serving as the principal example) and to outline the major reforms that are under consideration.

The part of the electromagnetic spectrum that is regarded as the radio spectrum (the term radio encompassing all forms of wireless communication, including television, all radio broadcasting, telephone calls sent by microwave radio and so on) can be described in terms of both frequency and wavelength. It ranges from very low frequencies of a few kilohertz (thousands of cycles per second) and wavelengths of several kilometers up to 300 gigahertz (billions of cycles per second), where radio microwaves shade into the far infrared. The officially allocated part of the spectrum extends from 10 kilohertz (wavelength 30 kilometers) to 300 gigahertz (wavelength one millimeter) and is densely populated by communication services of all kinds.

Frequency is not the only component of the spectrum resource. Geographical location also makes a difference. A given frequency can be assigned to several locations if they are far enough apart. For example, in the U.S. Channel 4 serves television stations in Boston, New York, Washington and about 50 other communities. The necessary separation is determined by the propagation characteristics of radio waves at the particular frequency and by the design of the communication system.

The primary international institution established to allocate places on the spectrum and to promulgate technical rules is the International Telecommunications Union, usually referred to as the ITU; it is a specialized agency of the United Nations. In the U.S. the responsibility for managing the spectrum is divided between the President, in whose name the part of the spectrum assigned to agencies of the Federal Government is controlled by the National Telecommunications and Information Agency in the Department of Commerce, and the Federal Communications Commission (FCC), which oversees all other users. The FCC's jurisdiction extends not only to commercial television and radio stations but also to state and municipal mobile-radio activities, the wireless part of the telephone system, citizens-band radio and even the small radio units that open and close garage doors.

Although the focus of this article is on the allocation of the spectrum, the reader should bear in mind that national and international policy on the management of the spectrum deals with other issues. It has a bearing on the structure of a nation's system of mass communications. In many countries it involves the question of how to manage the design of large communication systems with multiple owners. It also addresses the questions of how to distribute the benefits of a public resource and how to compromise such conflicting alternatives as expanded broadcasting service and improved communications for power-company repair crews. I shall treat such issues as special subproblems of allocation, but actually the subject of spectrum policy could be discussed with any of them as the focus.

To understand spectrum-allocation policies one must understand how the spectrum is utilized. Its use is governed by the physics of radio-wave propagation and by the practical limitations of communications engineering. The operation of a typical amplitude-modulation (AM) radio station, WNBC in New York, illustrates a simple radio-communication link.

When an announcer speaks in the studio, the microphone transforms the sounds into electrical signals. They are carried by cable from the studio to the transmitter, which is on High Island, 20 kilometers east of New York. There the signals modulate an electromagnetic wave oscillating at a carrier frequency of 660 kilohertz. The modulated wave is fed to an antenna, from which it spreads out in all directions as electromagnetic radiation.

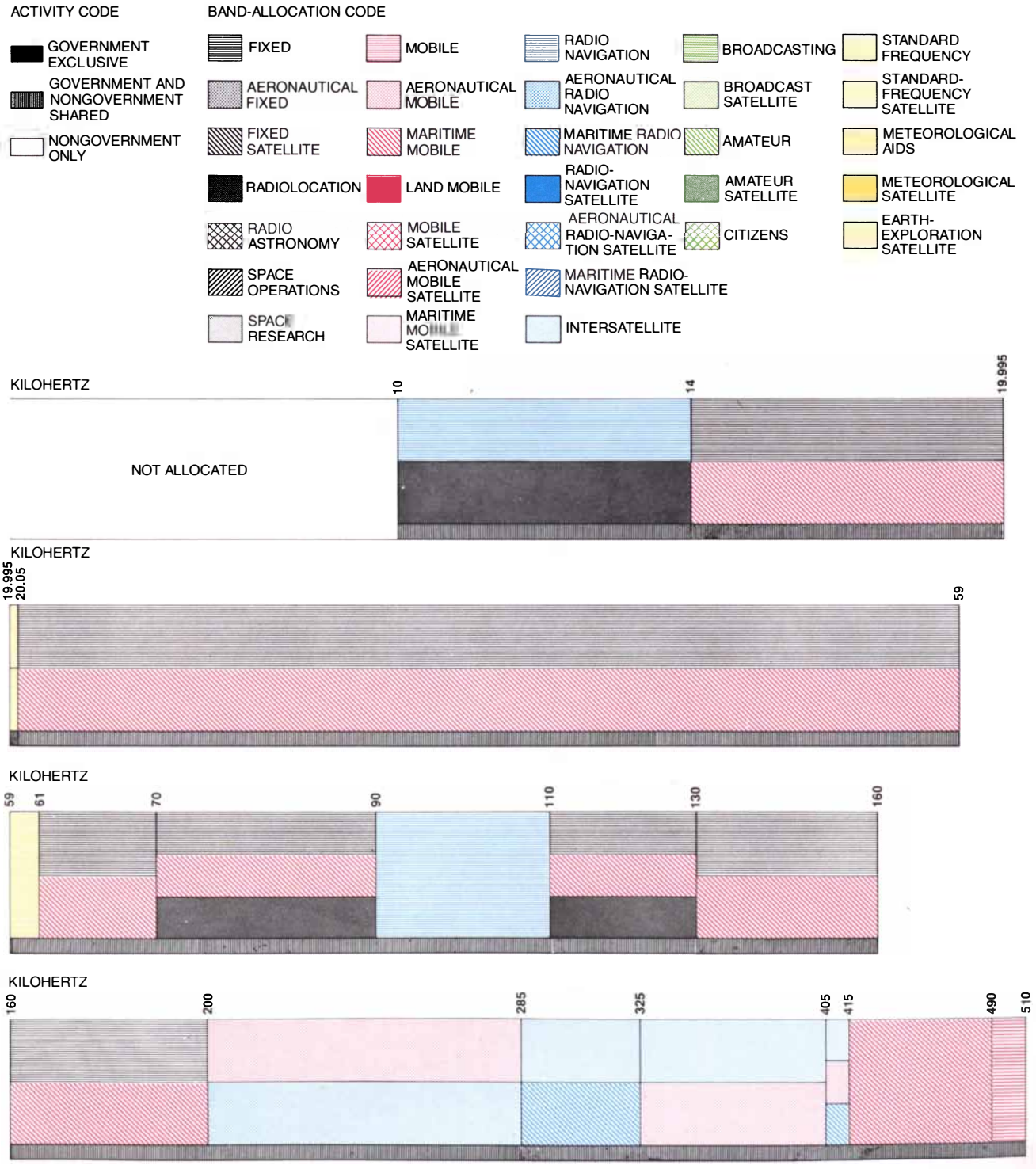
Now picture a listener with a portable transistor radio on Jones Beach, about 30 kilometers from the transmitter. A small fraction of the radiated signal is captured by the antenna of the radio. The radio selects the WNBC signal from among all the radio signals reaching the antenna because the radio is tuned to 660 kilohertz. The radio amplifies the signal and demodulates it, thereby recovering the electrical signal that represents the announcer's voice. The signal then goes to a speaker that transforms it into sound.

The radio captures only a tiny frac-

tion of the 50 kilowatts transmitted by WNBC. If the transmitted power were spread out evenly in all directions from the transmitter, the density of the energy at a distance of 30 kilometers would be down to .000004 watt per square meter. Actually the power does not spread out evenly, since the transmitter directs most of it toward the horizon. Nevertheless, the signal the transistor radio must work with is about a millionth of a watt.

Noise, meaning various kinds of interfering radio waves, ultimately limits a receiver in picking up a signal at a certain level of weakness. Noise can be generated both within a receiver and by external processes. External noise comes from many sources but can be classified in three broad categories: natural radiation, incidental man-made radiation and radiation from other communication systems. Natural phenomena, notably lightning, generate radio signals that can interfere with communication. Elec-

THE ALLOCATED RADIO SPECTRUM in the U.S. is presented on a logarithmic scale starting below and continuing over the next three pages. The color key on this page indicates the kinds of communication services that have been allocated part of the spectrum. The chart is based on the most recent one that has been prepared by the Department of Commerce and the Executive Office of the President.



trical equipment such as sewing machines and power tools can generate radio waves capable of interfering with communication, as when horizontal streaks appear on a television screen during the operation of a power tool nearby. Finally, each radio transmitter generates signals that constitute noise to anyone who is not trying to receive that particular signal. An example is the common experience of not being able to tune in a particular AM radio station at night without picking up another station in the background or hearing an objectionable whistle caused by interference.

The control of interference lies at the heart of spectrum allocation, which entails the development of systematic plans for the use of frequencies in radio communication. The process usually involves three steps: allocation, assignment and licensing. In the allocation step regions of the spectrum are set aside for specific purposes. For example, the band from 535 to 1,605 kilohertz is reserved internationally for AM radio broadcasting.

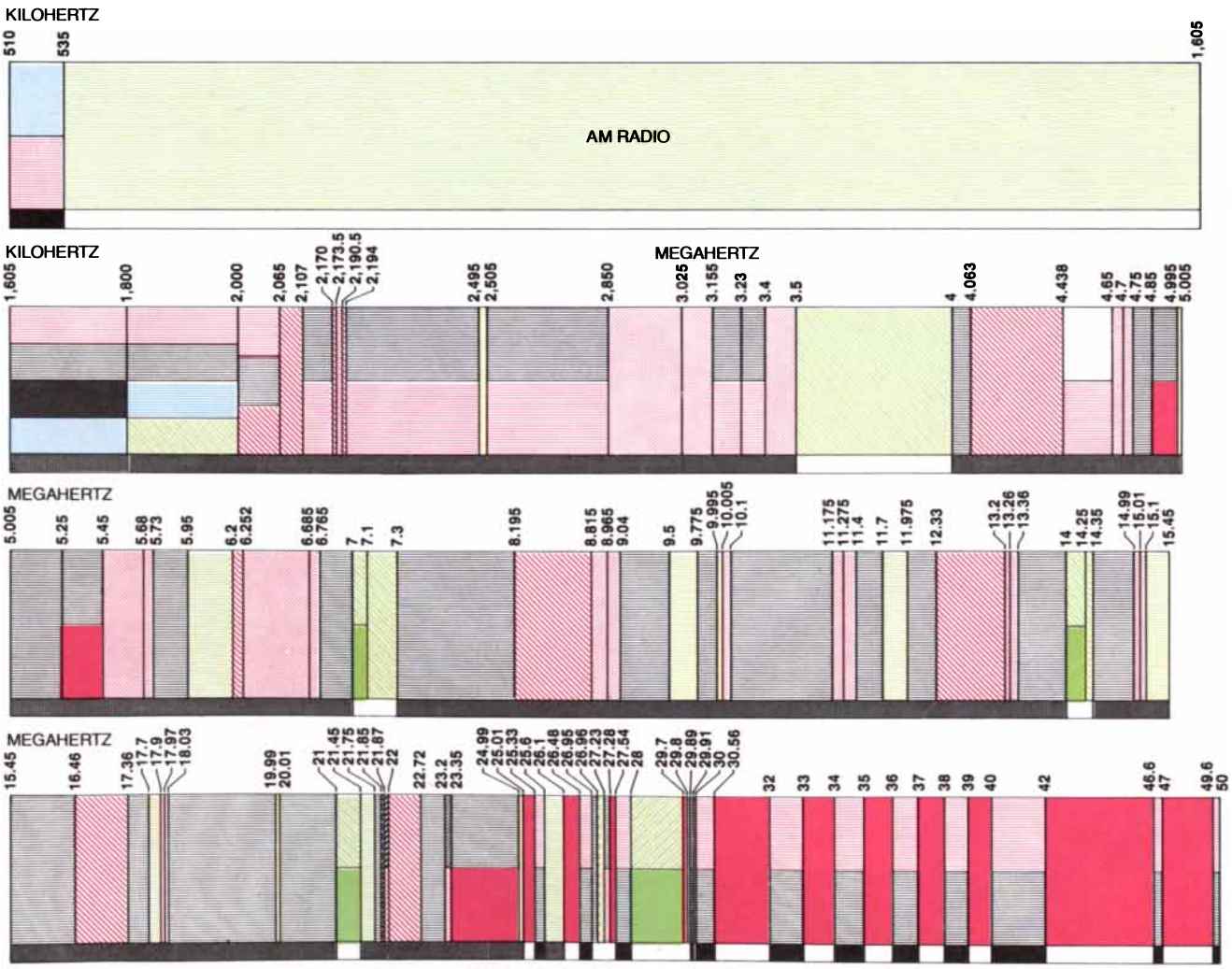
Setting aside regions of the spectrum for clearly defined, compatible uses simplifies the control of interference. Television broadcasting stations interfere with one another symmetrically: if station *A* interferes with station *B*, *B* interferes equally with *A*. A mobile radio and a broadcasting station, however, may interfere quite asymmetrically. For example, a mobile radio may interfere with television reception whereas the signals from the television station do not affect the mobile station. Hence the incentives for cooperation and coordination are much greater if a single class of radio users is assigned to each region of the spectrum.

The methods of assignment vary. For citizens-band radio there is no method; anarchy prevails. For the AM broadcasting band and the land mobile-radio bands the method is first come, first served. A prospective user searches for a place in the band where a new assignment is possible. If he finds one, he registers his intent to use it, and assignments must not conflict with his choice.

Sometimes the regulators put more structure into the assignment process. The FCC worked out a table of assignments for television broadcasting before it opened the band for licensing. The commission's objectives were to simplify the process of licensing and to ensure balance in assigning frequencies to communities. Licensing is a specific authorization to a broadcaster to use a frequency. The steps of assignment and licensing are often combined.

The allocation of the spectrum can be viewed as the allocation of a resource. The problems of spectrum allocation and management can also be viewed in other ways. In the most fundamental one the spectrum-management process is seen as providing the crucial coordination needed to avoid interference. Even if twice as many channels were available as could ever be used, it would still be necessary to register and coordinate the uses in order to avoid interference.

Another view sees spectrum management primarily as the structuring of communications, in particular mass communications. Broadcasting policy



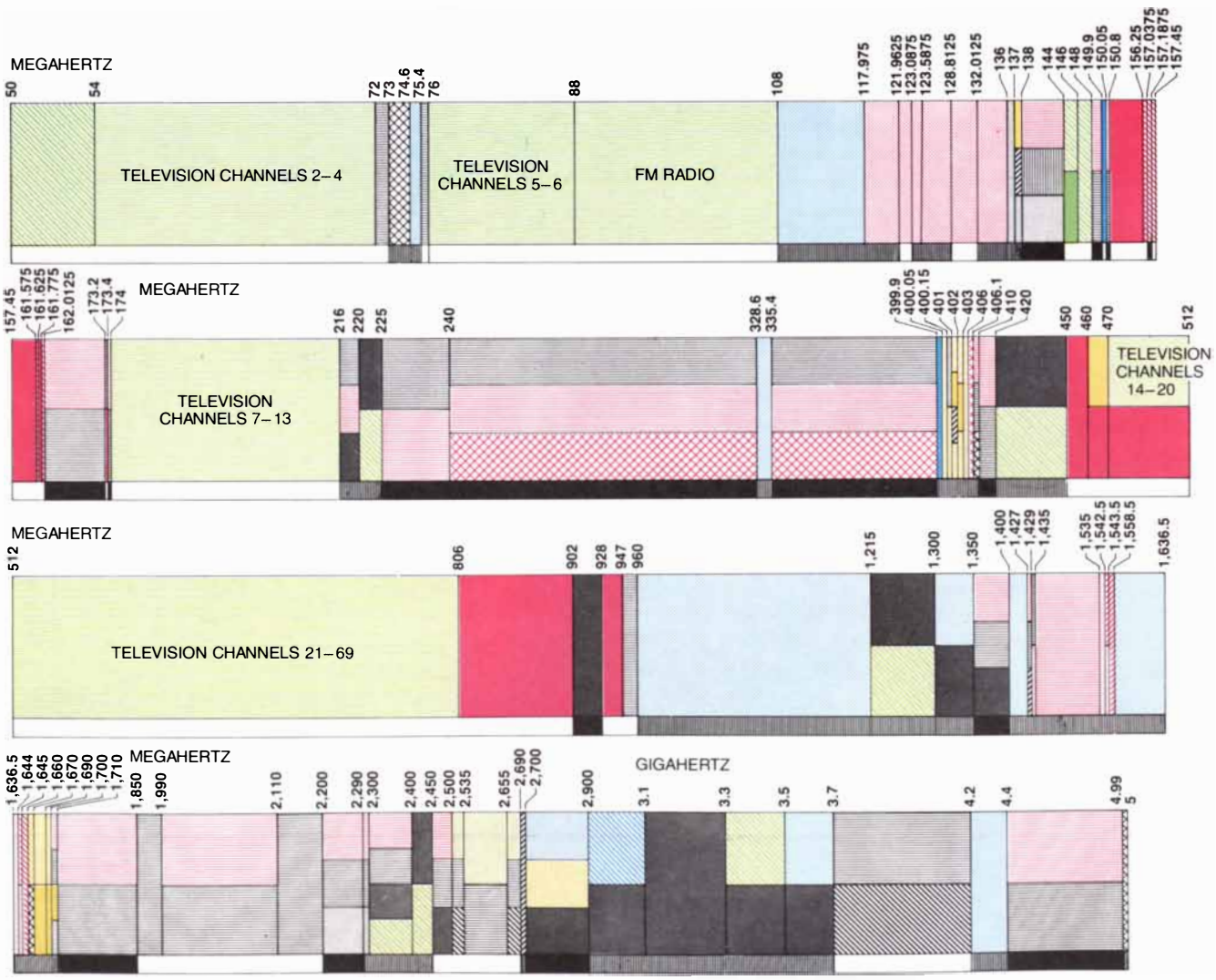
consists of many elements: technical standards, the choice of the number of outlets in each community, rules on ownership and the definition of the kinds of service to be provided by broadcasters. In many countries only the government owns broadcasting stations. In the U.S. the FCC puts on broadcasters certain requirements that are not applied to the owners of other media. For example, broadcasting stations are required to cover controversial issues of public importance "fairly." No such rule applies to newspapers, magazines or book publishers. The Supreme Court has upheld the policy, stating: "In view of the scarcity of broadcast frequencies, the Government's role in allocating those frequencies, and the legitimate claims of those unable without governmental assistance to gain access to those frequencies for expression of their views, we hold the regulations and ruling at issue here are both authorized by statute and constitutional."

The point to be emphasized is that (at least in the U.S.) broadcasting policy flows from spectrum-management policy. The practical result is that since the Government allows some people to broadcast and excludes others, it must have a mechanism for choosing among applicants. Nothing in the laws of physics or politics requires this mechanism of choice to focus exclusively on technical standards. Indeed, social and political forces push toward the consideration of nontechnical criteria in deciding who should operate broadcasting stations. Spectrum-allocation policy becomes linked with fundamental social and political activities.

The allocation of the spectrum can also be viewed in terms of economics. Economists writing about spectrum-allocation policy usually treat the spectrum as an example of a resource (like land and water) that requires economic management. It is an unusual kind of resource, however, in that the people who are authorized to use it do not pay for their part of it and cannot sell or share the allocation without the approval of the granting agency. Moreover, large bands of the spectrum are allocated to various users—commercial television and radio, mobile radio, local governments and so on—that may underuse their part of it, but it cannot be transferred from one type of user to another.

Another aspect of spectrum allocation is the creation and distribution of wealth. The close link between the two is illustrated by an idealized television market based on three assumptions: (1) total advertising revenue is fixed at $20 million per year regardless of the number of stations in the market; (2) the operating cost for each station is $3 million per year, and (3) the revenue is shared equally by all the stations. If the regulating agency assigned three stations to the market, each station would make $3.6 million in profit per year. The assignment of a fourth station would lower the profit of each station to $2 million; with a fifth station the profit would be $1 million. One can see how sensitive the economics of broadcasting is to slight changes of policy on allocating television stations and what incentives broadcasters have to oppose the addition of new stations to a market.

Historically the allocation of the spec-



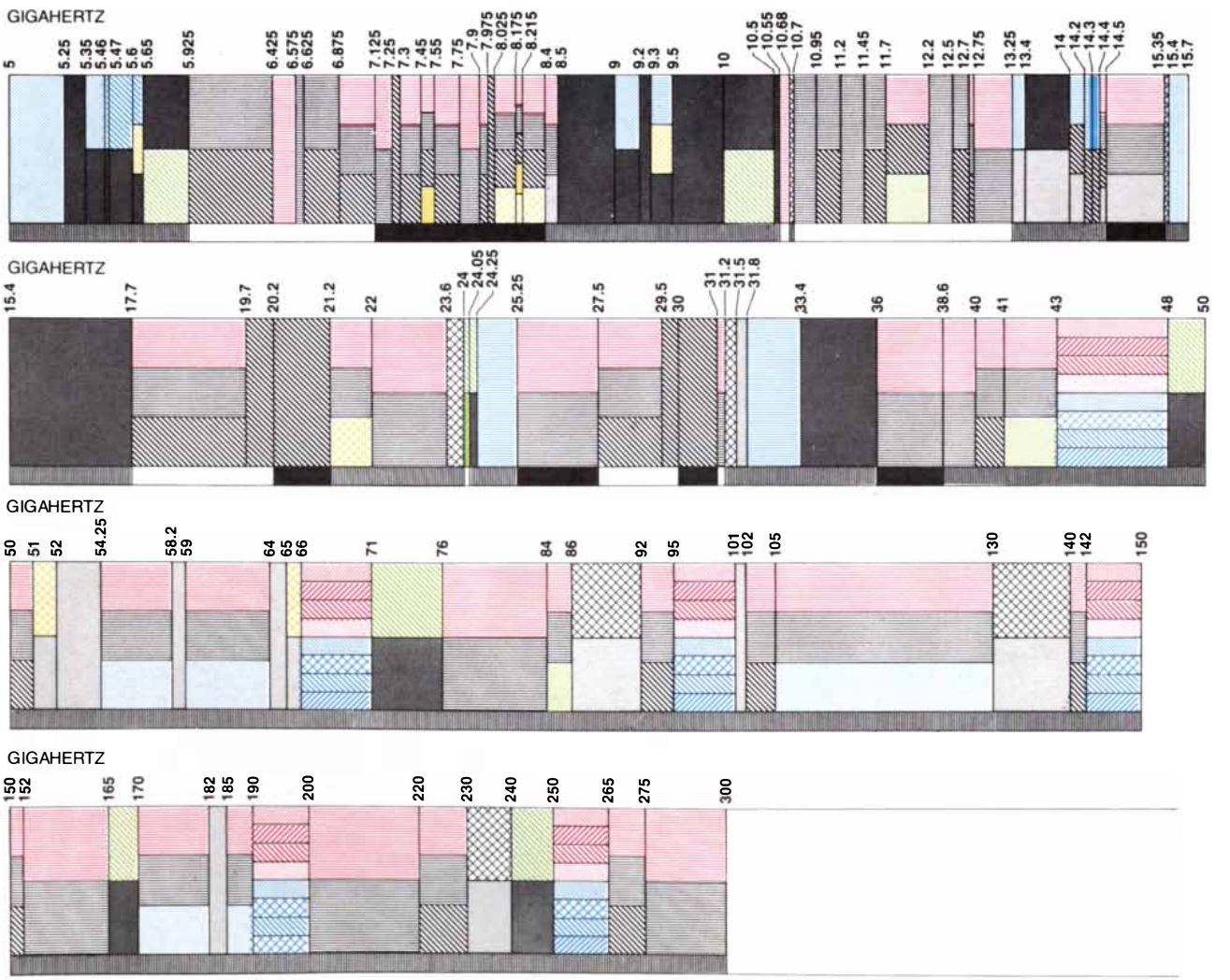
trum has followed a simple pattern. The regulatory authority would set aside a region of the spectrum for a service and would establish technical rules. Prospective users would then apply for licenses on a first-come, first-served basis. Latecomers had to engineer their systems around the earlier ones. This pattern has been followed consistently both internationally and within nations, with few exceptions. The system had (and to a large degree still has) several major advantages, among them its simplicity, low cost and the fact that only a minimal transfer of information is needed to make it work.

The system has been able to meet the expanding demand for space on the radio spectrum by the fortunate circumstance that as demand grew, technology advanced, so that more of the spectrum could be exploited and all of it could be utilized more efficiently. The system does give rise to certain problems, however, a major one of which can be illustrated with a comparison of the broadcasting and telephone systems in the U.S. In 1960 the U.S. had 474 television stations on the very-high-frequency (VHF) band, encompassing channels 2 through 13. Today there are 617. In 1945 the country had 900 full-time AM radio stations; now the band set aside for them supports 2,000 full-time stations. As for telephones, in the early 1950's the Bell System began sending some of its telephone calls by microwave radio. At that time the common-carrier equipment could fit only 2,100 telephone circuits into the microwave band. Today's equipment can fit 36,000 telephone circuits into the same band.

To put it another way, the technical efficiency of the broadcasting system has not really improved at all during a time when the efficiency of the common-carrier microwave system improved by 2,000 percent. This disparity grows out of the incentives offered by the system of spectrum management. The telephone industry and its customers share in the benefits of improved efficiency, so that a telephone company has an incentive to develop and install equipment that makes more efficient use of the spectrum. A broadcasting station cannot share in such benefits, all of which flow to others (such as the buyers of radios and television sets). Indeed, more efficient technology would make it possible for more stations to operate in each market. The advertising revenues and profits of the existing stations would go down.

It should also be recognized that the adoption of new technology is harder in broadcasting than in the telephone system. The ownership of a broadcasting system is divided between the broadcaster, who owns the transmitter, and the listeners, who own the receivers. The larger part of the investment is in the receivers. Most technical changes require changes in both the transmitter and the receiver, and coordinating any change in the millions of receivers would be difficult.

Another kind of difficulty with the present system appeared at the general meeting of the World Administrative Radio Conference in Geneva last fall. (The general meetings, which are held about every 20 years, provide the means whereby the member nations of the International Telecommunications Union allocate regions of the spectrum. The



group also holds more frequent meetings on specific subjects, such as satellite communications. All the meetings entail complicated multilateral negotiations, whose substantive results are embodied in treaties.) Many of the newer nations, which were colonies at the time of the last general conference, are now moving to establish their own satellite-communications and short-wave radio systems. They are therefore competing fiercely to obtain places on the spectrum, many of which are already occupied or assigned to developed nations. The issues were largely unresolved by the conference and therefore remain pending.

Many people have put forward detailed suggestions for making the process of spectrum allocation work better. The suggestions fall into three groups: (1) Improve the current system. (2) Find ways to design radio systems that require less human management. (3) Change the economic incentives so that all users are encouraged to adopt the most appropriate technology.

The current system can be improved in at least two ways. One is to apply more resources (people, money and computers) to the problem. Another is to computerize the traditional process to a greater degree. Both approaches are being taken to some extent already. Data on the uses of the spectrum were once kept in manual files; now they are increasingly being put into a form that can be read out by machine. Searches of the files are being done by computer rather than by hand. Expenditures on the management of the spectrum are increasing.

Another possible improvement in the U.S. is to do away with the present two-headed system of managing the spectrum. Although the division of authority between the FCC and the President has worked reasonably well in the past, a single authority for the allocation of the spectrum would probably do better at shifting allocations between Federal and civil users when such shifts are possible and appropriate.

Improvements that come under the heading of designing radio systems that require less human management introduce a concept that could be called the "anarchy band." (Other names that have been suggested are freedom band, bedlam band and frontier band. They all reflect the relative lack of formal management embodied in the concept.) To make an anarchy band work the regulators would have to arrive at two initial decisions. The subsequent tasks of enforcement and collecting data would then be minimal.

First the regulators must designate a band where anarchy would be the operating principle. Then they must define the technical standards for the equipment that would serve the band. The standards must be chosen to make the overall system work well. The remaining task for the regulators is to ascertain that only the proper equipment is put in service. They can accomplish the task by controlling the sale of equipment.

A good example of an ideal anarchy-band technology would be a radio with a range limited to 10 meters. Such a radio would be particularly suitable for communications within a household or between adjacent households for such purposes as burglar alarms, garage-door openers and the remote control of appliances. The limited range of the transmitters would preclude interference.

To some extent the anarchy-band concept has already been adopted. The Advanced Research Projects Agency (ARPA) of the Department of Defense has developed a system called packet radio that provides voice and data communication over ranges of up to several kilometers. The essence of the system is that each packet, or short sequence, of data is sent over whichever one of a designated group of channels is available. A receiving radio can detect an error in the transmission of a packet due to interference or noise; when such an error is detected, the packet is automatically retransmitted. In terms of the utilization of the spectrum the system can be described as dynamic allocation; it contrasts with the preallocation that characterizes commercial television and radio.

Citizens-band radio is another example of a working anarchy band, although it is far from the ideal because the technical rules applying to the band are so loose. As a result a user of the band often encounters excessive interference. Nevertheless, the band provides a communication service with a minimum of regulatory activity.

The application of economic techniques to the management of the radio spectrum is both promising and possible. The techniques include charging users a fee, auctioning places on the spectrum and even assigning property rights so that a user could buy or trade an allocation. The methods would give the user an incentive to make the most of an allocation and would help to guide the use of the spectrum into more valuable areas. They would also enable the regulators and the users to treat the spectrum as another economic resource like land or electricity. Legislation authorizing the utilization of economic techniques in the management of the radio spectrum has been introduced in each house of Congress by the chairman of the respective subcommittees on communications. Moreover, last September, President Carter sent Congress a message supporting the use of economic techniques in managing the nonbroadcasting portion of the spectrum. Even with such high-level support, however, the concept will be difficult to enact because it is opposed by many of the spectrum's present users.

Both the anarchy-band concept and the application of economic techniques can be characterized as moves away from the present system of centralized regulation toward a decentralized system dominated by the users. Actually all three systems can coexist. They are complementary. Different uses of the spectrum require different techniques of management. No single approach is ideal in all cases.

Looking to the future, one can predict that the already valuable radio spectrum will become more valuable as the cost of complementary resources, particularly electronic equipment, goes down. Hence one can foresee increasing demands for access to the spectrum and an increasing need for its better management. The most easily adopted of the new management techniques, and therefore the most promising one, is the anarchy-band concept. It can be applied within the constraints of the current regulatory framework. The essence of it is the replacement of high-cost human administrators with low-cost electronic equipment.

Controversy over the allocation of the spectrum is likely to be focused on two areas: the ultrahigh-frequency (UHF) television band and the satellite bands. UHF will draw attention because of its convenience and availability. Designers of communications systems find the UHF region of the spectrum well suited to their purposes. The equipment is inexpensive and the propagation of the signal is good. Moreover, much of the UHF spectrum is unused even though it has been nominally allocated to broadcasting.

That situation arises from decisions made by the FCC when it originally assigned UHF channels. The commission carefully assigned the channels to cities by taking into account technical constraints that would minimize the cost of UHF sets to the public. Because of improvements in electronics the constraints no longer need to be applied. All existing UHF stations could be accommodated in less than half of the present UHF band, thereby freeing a significant portion of the spectrum for expanded broadcasting or for other services.

The problem with communication satellites arises chiefly from the fact that they must be "stationary," that is, the period of their orbit must coincide with the period of rotation of the earth. They are positioned above the Equator at an altitude of about 22,300 miles. As one might expect, satellite systems at that altitude become an international concern. The U.S. must coordinate its use of the orbital arc with the other nations in the Americas. If markets for satellite communication develop rapidly but the technology advances slowly, contention over the utilization of the satellite portion of the spectrum is certain to arise.

Transposable Genetic Elements

They bypass the rules of ordinary genetic recombination and join together segments of DNA that are unrelated, transferring groups of genes among plasmids, viruses and chromosomes in living cells

by Stanley N. Cohen and James A. Shapiro

Natural selection, as Darwin recognized more than a century ago, favors individuals and populations that acquire traits conducive to survival and reproduction. The generation of biological variation, which gives rise to new and potentially advantageous combinations of genetic traits, is therefore a central requirement for the successful evolution of species in diverse and changing environments.

Hereditary information is encoded in the sequence of the building blocks, called nucleotides, that constitute a molecule of DNA, the genetic material. The basic step in the creation of genetic variation is the mutation, or alteration, of the DNA within a gene of a single individual. Mutations involve changes in nucleotide sequence, usually the replacement of one nucleotide by another. This can lead to a change in the chain of amino acids constituting the protein encoded by the gene, and the resulting change in the properties of the protein can influence the organism's biological characteristics. Spontaneous mutations are too rare, however, for genetic variation to depend on new mutations that arise in each generation. Instead variation is generated primarily by the reshuffling of large pools of mutations that have been accumulated within a population in the course of many generations.

In higher organisms this reshuffling is done in the process of sexual reproduction. The genes are arrayed on two sets of chromosomes, one set inherited from the female parent and the other set from the male parent, so that there are two copies of each gene. Sometimes the nucleotides of a genetic sequence differ slightly as a result of earlier mutation, producing alleles, or variant forms of a gene. In the formation of gametes (egg or sperm cells) the breakage of structurally similar pairs of chromosomes can result in the reciprocal exchange of alleles between the two members of a pair of chromosomes. Such genetic recombination requires that the segments of DNA undergoing exchange be homologous, that is, the sequence of nucleotides on one segment of DNA must be very similar to the sequence on the other segment, differing only at the sites where mutations have occurred.

The ability of segments of DNA on different chromosomes to recombine makes it likely that in complex plants or animals the particular collection of genes contained in each egg or sperm cell is different. An individual produces many eggs or sperms, which can potentially interact with sperms or eggs from many other individuals, so that there is a vast opportunity for the generation of genetic diversity within the population. In the absence of intentional and extended inbreeding the possibility that any two plants or animals will have an identical genetic composition is vanishingly small.

Genetic variation is also important in the evolution of lower organisms such as bacteria, and here too it arises from mutations. Bacteria have only one chromosome, however, so that different alleles of a gene are not normally present within a single cell. The reshuffling of bacterial genes therefore ordinarily requires the introduction into a bacterium of DNA carrying an allele that originated in a different cell. One mechanism accomplishing this interbacterial transfer of genes in nature is transduction: certain viruses that can infect bacterial cells pick up fragments of the bacterial DNA and carry the DNA to other cells in the course of a later infection. In another process, known as transformation, DNA released by cell death or other natural processes simply enters a new cell from the environment by penetrating the cell wall and membrane. A third mechanism, conjugation, involves certain of the self-replicating circular segments of DNA called plasmids, which can be transferred between bacterial cells that are in direct physical contact with each other.

Whether the genetic information is introduced into a bacterial cell by transduction, transformation or conjugation, it must be incorporated into the new host's hereditary apparatus if it is to be propagated as part of that apparatus when the cell divides. As in the case of higher organisms, this incorporation is ordinarily accomplished by the exchange of homologous DNA; the entering gene must have an allelic counterpart in the recipient DNA. Because homologous recombination requires overall similarity of the two DNA segments being exchanged, it can take place only between structurally and ancestrally related segments. And so, in bacteria as well as in higher organisms, the generation of genetic variability by this mechanism is limited to what can be attained by exchanges between different alleles of the same genes or between different genes that have stretches of similar nucleotide sequences. This requirement imposes severe constraints on the rate of evolution that can be attained through homologous recombination.

Until recently mutation and homologous recombination nevertheless appeared to be the only important mechanisms for generating biological diversity. They seemed to be able to account for the degree of diversity observed in most species, and the implicit constraints of homologous recombination—which prevent the exchange of genetic information between unrelated organisms lacking extensive DNA-sequence similarity—appeared to be consistent with both a modest rate of biological evolution and the persistence of distinct species that retain their basic identity generation after generation.

Within the past decade or so, however, it has become increasingly apparent that there are various "illegitimate" recombinational processes, which can join together DNA segments having little or no nucleotide-sequence homology, and that such processes play a significant role in the organization of genetic information and the regulation of its expression. Such recombination is often effected by transposable genetic elements: structurally and genetically discrete segments of DNA that have the

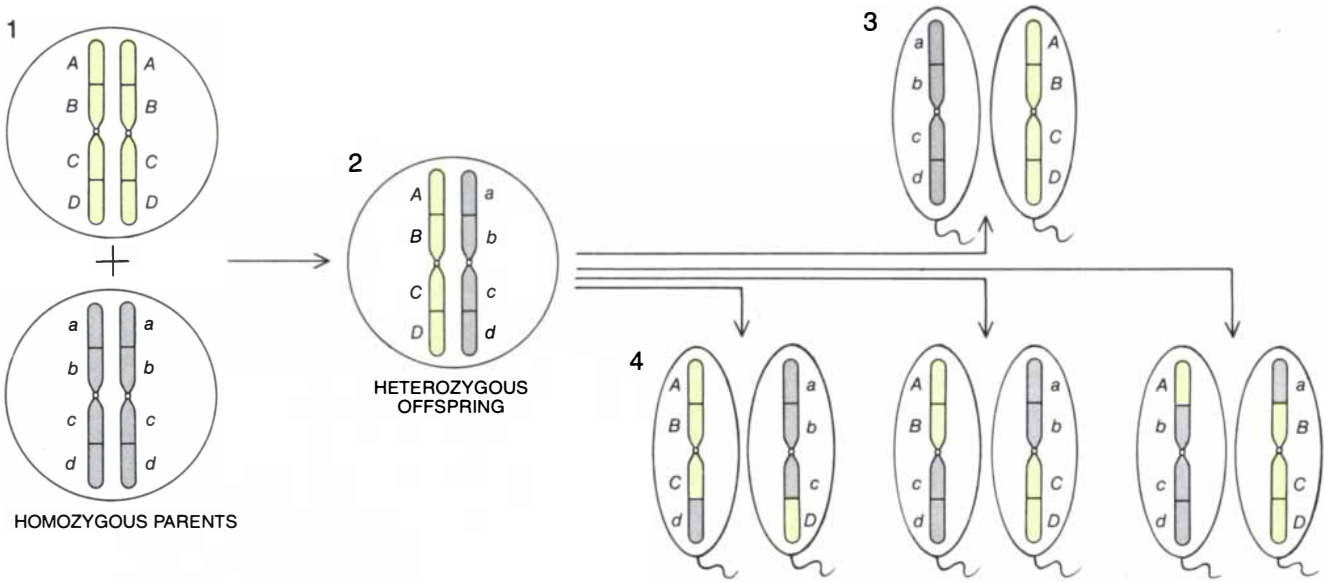
ability to move around among the chromosomes and the extrachromosomal DNA molecules of bacteria and higher organisms. Although transposable elements have been studied largely in bacterial cells, they were originally discovered in plants and are now known to exist in animals as well. Because illegitimate recombination can join together DNA segments that have little, if any, ancestral relationship, it can affect evolution in quantum jumps as well as in small steps.

In the late 1940's Barbara McClintock of the Carnegie Institution of Washington's Department of Genetics at Cold Spring Harbor, N.Y., first reported a genetic phenomenon in the common corn plant, *Zea mays,* that would later be found to have parallels in other biological systems. While studying the inheritance of color and the distribution of pigmentation in plants that had undergone repeated cycles of chromosome breakage she found that the activity of particular genes was being turned on or off at abnormal times. Because some of these genes were associated with the development of pigments in kernels as well as in the plant itself, certain kernels were mottled, showing patches of pigmentation against an otherwise colorless background. The patterns of this variegation were reproduced in successive generations and could be analyzed like other heritable traits. After painstaking study of many generations of corn plants McClintock concluded that the variegation she observed was the result of the action of distinct genetic units, which she called controlling elements, that could apparently move from site to site on different maize chromosomes; as they did so they sometimes served as novel biological switches, turning the expression of genes on or off.

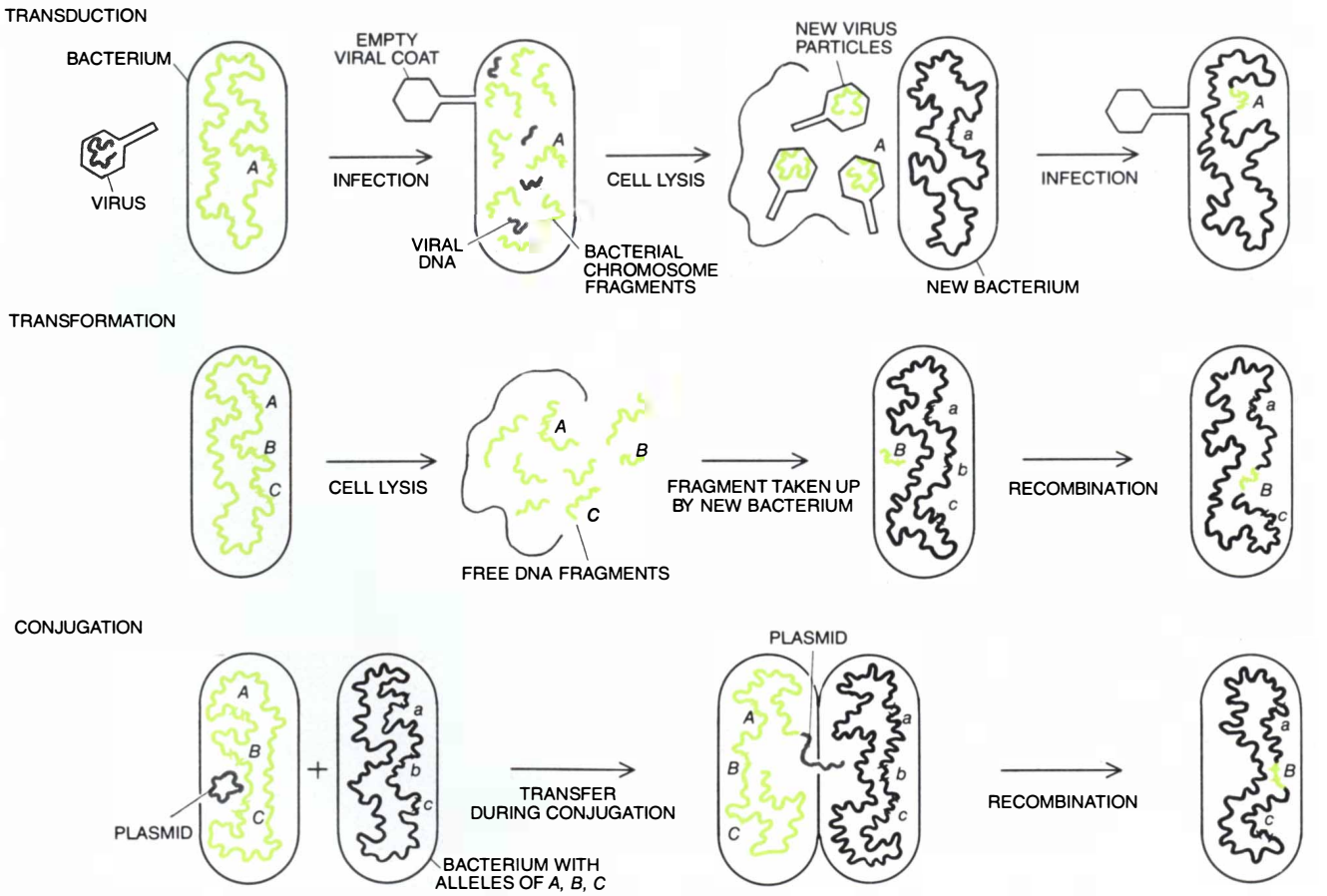
McClintock's genetic analysis showed that some patterns of variegation affected three or more genes simultaneously, suggesting that the structure of one of the plant's chromosomes had been rearranged at the site of a controlling element. Direct microscopic examination of maize chromosomes containing controlling elements confirmed that these genetic elements did in fact serve as specific sites for the breakage and resealing of DNA, thereby giving rise to either minute or gross changes in chromosome structure.

Almost 20 years after McClintock reported her earliest studies on controlling elements in the corn plant Michael Malamy, who is now at the Tufts University School of Medicine, Elke Jordan, Heinz Saedler and Peter Starlinger of the University of Cologne and one of us (Shapiro), who was then at the University of Cambridge, found a new class of mutations in genes of a laboratory strain of the common intestinal bacterium *Escherichia coli.* They were unusual in that their effects were detectable beyond the borders of the mutated genes them-

DNA OF TRANSPOSABLE GENETIC ELEMENT (a transposon) forms a characteristic stem-and-loop structure, which is seen here in an electron micrograph made by one of the authors (Cohen). The structure results from the "inverted repeat" nature of the nucleotide sequences at the two ends of the transposon DNA (*see upper illustration on page 44*). The double-strand DNA of the plasmid *pSC*105, into which the transposon had been inserted, was denatured and complementary nucleotide sequences on each strand were allowed to "reanneal." The joining of the complementary nucleotides constituting the transposon's inverted-repeat termini formed the double-strand stem. The smaller loop was formed by the segment of single-strand transposon DNA between the inverted repeats, a segment that includes a gene conferring resistance to the antibiotic kanamycin. The larger loop represents the single-strand DNA of a miniplasmid derivative of the host plasmid. DNA was spread with formamide and shadowed with platinum-palladium. Enlargement is 230,000 diameters.



HOMOLOGOUS RECOMBINATION is accomplished in higher organisms by the "crossing over" of structurally similar chromosome segments during sexual reproduction. Here the process is shown for a hypothetical animal each of whose somatic (body) cells has a single chromosome pair carrying four genes, each of which may be present in either of two variant forms (alleles). Homozygous parents having the same set of alleles on both paired chromosomes (*1*) give rise to heterozygous offspring (*2*), which in turn can produce gametes (sperms or eggs) containing copies of the original chromosomes (*3*). As a result of crossing over and reciprocal homologous recombination, alleles can be reshuffled in various ways (*4*), producing gametes containing chromosomes that are different from either of original chromosomes.



RECOMBINATION IN BACTERIA requires the introduction into a bacterial cell of an allele obtained from another cell. In transduction an infecting phage, or bacterial virus, picks up a bacterial-DNA segment carrying allele *A* and incorporates it instead of viral DNA into the virus particle. When such a particle infects another cell, the bacterial-DNA segment recombines with a homologous segment, thereby exchanging allele *A* for allele *a*. In transformation a DNA segment bearing allele *B* is taken up from the environment by a cell whose chromosome carries allele *b;* the alleles are exchanged by homologous recombination. In conjugation a plasmid inhabiting one bacterial cell can transfer the bacterium's chromosome, during cell-to-cell contact, to another cell whose chromosome carries alleles of genes on the transferred chromosome; again allele *B* is exchanged for allele *b* by recombination between homologous DNA segments.

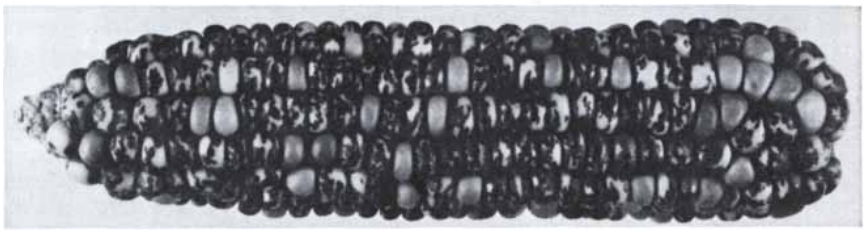
selves; this property could not be explained by any known mutational mechanism.

When the DNA segments carrying these mutations were inserted into particles of a bacterial virus and the density of the virus was compared with that of viruses carrying normal genes, it became clear that the mutated DNA was longer than the normal DNA: the mutations had been caused by the insertion of sizable DNA fragments into the mutated gene. It further developed that a limited number of other kinds of distinguishable DNA segments, which were up to 2,000 nucleotides in length, could also insert themselves within many different genes, interrupting the continuity of the gene and turning off its activity. These elements were named insertion sequences, or IS elements. The observation that a small number of specific DNA segments could be inserted at a large number of different sites in the bacterial chromosome suggested that some type of nonhomologous recombination was taking place; it seemed to be unlikely that an IS element could be homologous with the nucleotide sequences at so many different insertion sites.

At about the same time that IS elements were discovered other microbiologists and geneticists made observations hinting that certain genes known to be responsible for resistance to antibiotics by bacteria were capable of transfer from one molecule of DNA to another. Results obtained by Susumu Mitsuhashi and his colleagues at the University of Tokyo in the mid-1960's suggested that a gene encoding a protein that inactivates the antibiotic chloramphenicol could move from its normal site on a plasmid-DNA molecule to the chromosome of a bacterium or to the DNA of a virus.

Similar instances of the apparent transfer of antibiotic-resistance genes between different DNA molecules in the same cell were reported from the U.S. and Britain. The first direct evidence that such transfer is by a process analogous to the insertion of IS elements was published in 1974. R. W. Hedges and A. E. Jacob of the Hammersmith Hospital in London found that the transfer from one plasmid to another of a gene conferring resistance to antibiotics such as penicillin and ampicillin was always accompanied by an increase in the size of the recipient plasmid; the recipient could donate the resistance trait to still other plasmids, which thereupon showed a similar increase in size.

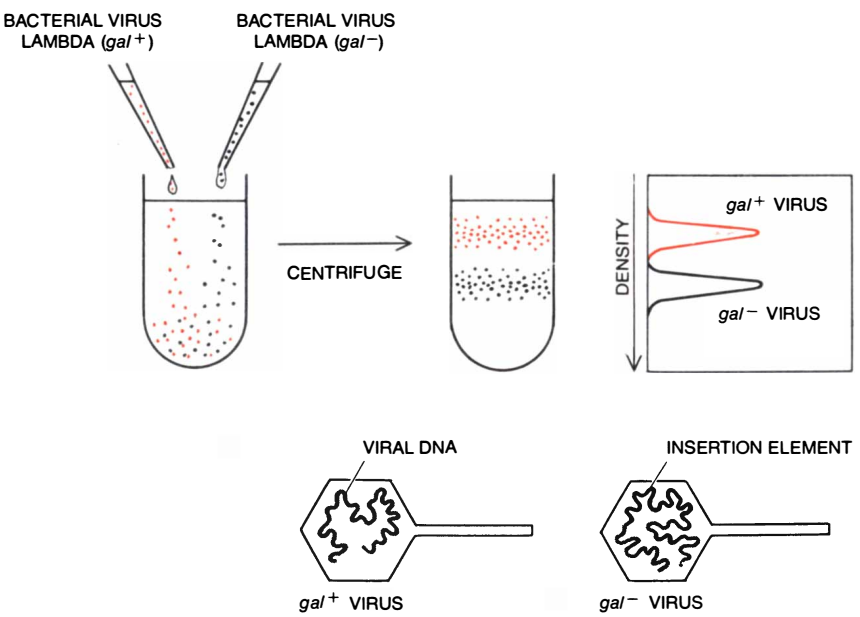
Hedges and Jacob postulated that the gene for ampicillin resistance was carried by a DNA element that could be "transposed," or could move from one molecule to another, and they called such an element a transposon. Their discovery of a transposable element that carries an antibiotic-resistance gene was an important advance. In earlier studies the movement of IS elements had been tracked only indirectly by genetic techniques: by observing the effects of insertions on various genetic properties of the host organism. It now became possible to track a transposable element's intermolecular travels directly by observing the inheritance of the antibiotic-resistance trait.



DIFFERENCES IN PIGMENTATION in kernels of the corn plant *Zea mays* reflect the action of a two-element control system discovered by Barbara McClintock of the Cold Spring Harbor Laboratory. Both elements are transposable. One element is at the locus of a gene whose action it modulates to yield the faintly and homogeneously pigmented kernels. The other element acts on the first one to produce the variegated pattern that is seen in many of the kernels.

While the Hedges and Jacob experiments were being carried out Dennis J. Kopecko and one of us (Cohen), at the Stanford University School of Medicine, were studying the acquisition of a gene for resistance to ampicillin by still other plasmids. It emerged, as Hedges and Jacob had found, that the ampicillin-resistance trait present on one plasmid could be acquired by another plasmid. Surprisingly, however, it also developed that such transfer could take place in mutated bacteria lacking a particular protein, the product of a gene designated *rec*A, known to be necessary for homologous recombination. Examination of the plasmid DNA with the electron microscope revealed that a 4,800-nucleotide segment carrying the ampicillin-resistance trait was being transferred as a characteristic and discrete structural unit. Moreover, the segment could become inserted at many different sites on the recipient plasmid DNA.

Electron microscopy also showed that the two ends of the transposable DNA segment had a unique feature: they consisted of nucleotide sequences that were complementary to each other but in the reverse order. This finding calls for some explanation. The four nitrogenous bases that characterize DNA nucleotides are linked in complementary pairs by hydrogen bonds to form the double helix of DNA: adenine (*A*) is linked to thymine (*T*) and guanine (*G*) to cytosine (*C*). The nucleotide sequence *AGCTT*, for example, is complementary

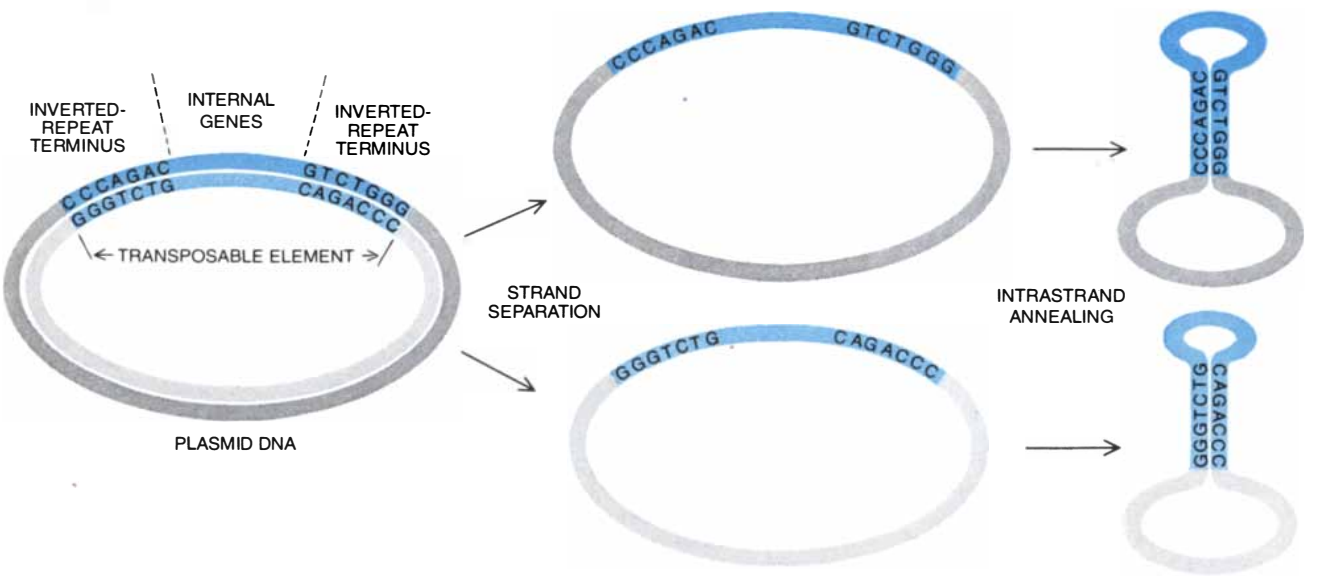


MUTATION BY INSERTION was demonstrated by one of the authors (Shapiro) with phage-lambda particles carrying the bacterial gene for galactose utilization (*gal*$^+$) and particles carrying the mutant gene *gal*$^-$. The viruses were centrifuged in a cesium chloride solution. The *gal*$^-$ particles were found to be the denser. Because the virus particles all have the same volume and their outer shells all have the same mass, increased density of *gal*$^-$ particles showed they must contain a larger DNA molecule: *gal*$^-$ mutation was caused by insertion of DNA.

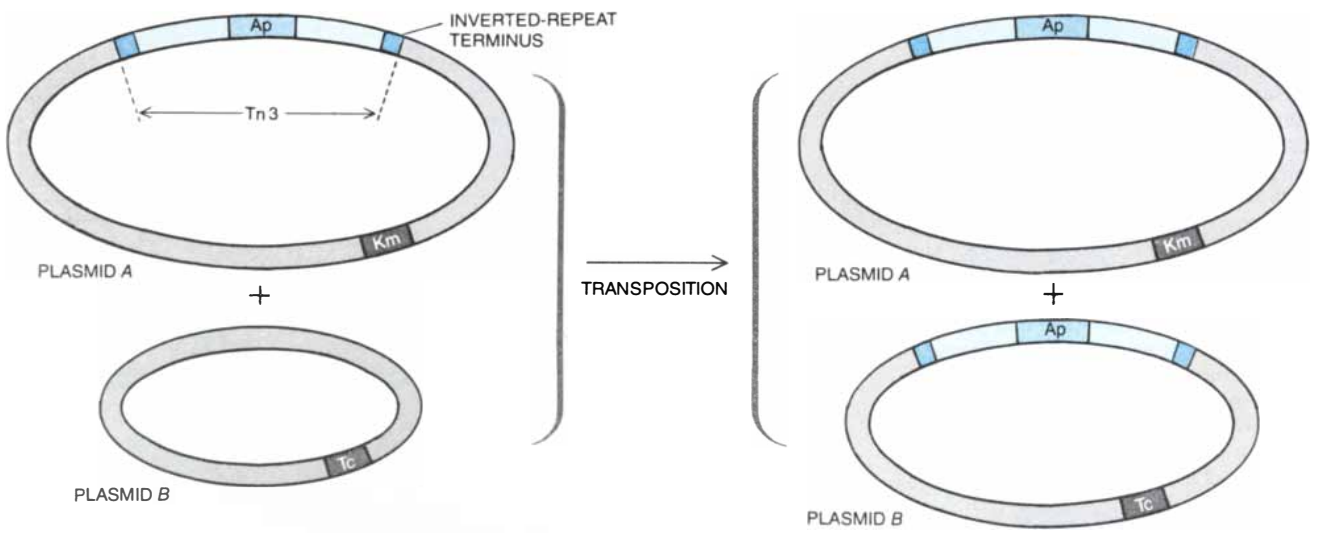
to the sequence *TCGAA*. The nucleotide sequence at one end of the transposable DNA segment was complementary in reverse order to a sequence on the same strand at the other end of the element [*see upper illustration on this page*]. These "inverted repeats" were revealed when the two strands of the double-strand plasmid DNA carrying the transposon were separated in the laboratory and each of the strands was allowed to "reanneal" with itself: a characteristic stem-and-loop structure was formed by the complementary inverted repeats.

The result of the transposition process is that a segment of DNA originally present on one molecule is transferred to a different molecule that has no genetic homology with the transposable element or with the donor DNA. The fact that the process does not require a bacterial gene product known to be necessary for homologous recombination indicates that transposition is accomplished by a mechanism different from the usual recombinational processes.

Subsequent experiments done in numerous laboratories have shown that DNA segments carrying genes encoding a wide variety of antibiotic-resistance traits can be transferred between DNA molecules as discrete units. Moreover, genes encoding other traits, such as resistance to toxic mercury compounds, synthesis of bacterial toxins and the capacity to ferment sugars or metabolize hydrocarbons, have been shown to be capable of transposition. All the transposons studied so far have ends consisting of inverted-repeat sequences, which range in length from only a few nucleotides to as many as 1,400. The ends of at least two transposons actually consist of two copies of the insertion sequence IS1 (which itself has been found to have terminal inverted-repeat sequences). Recent evidence has suggested that the insertion of any gene between two trans-



STEM-AND-LOOP STRUCTURES demonstrate the inverted-repeat nucleotide sequences of the ends of transposable elements. The four bases adenine (*A*), guanine (*G*), thymine (*T*) and cytosine (*C*) of DNA's four nucleotide building blocks are linked to form a helix (shown here schematically as a double strand); *A* always pairs with *T* and *G* pairs with *C*. The termini of a transposable element have sequences (seven nucleotides long here) that are bidirectionally and rotationally symmetrical. When the two strands of a plasmid containing an element are separated and each strand is allowed to self-anneal, the complementary nucleotides at the termini pair with each other, forming a double-strand stem (*right and in electron micrograph on page 41*). The remainder of the DNA is seen as single-strand loops.



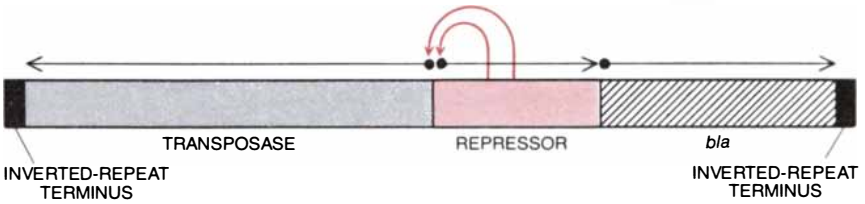
TRANSPOSITION of the transposon Tn3, which carries a gene conferring resistance to the antibiotic ampicillin (*Ap*), is diagrammed. It is shown as originally being part of plasmid *A*, which also includes a gene for resistance to kanamycin (*Km*). A plasmid *B*, which confers resistance to tetracycline (*Tc*), acquires a copy of the transposon. The new plasmid *B* confers resistance to ampicillin and tetracycline.

posable elements makes possible the transfer of the gene to a structurally unrelated DNA molecule by nonhomologous recombination.

Since transposable elements are transferred as discrete and characteristic genetic units, there must be some highly specific enzymatic mechanism capable of recognizing their inverted-repeat ends and cleaving DNA precisely at these locations. The first evidence that genes carried by the transposable elements themselves can encode such enzymes came from a series of experiments carried out by Frederick L. Heffron, Craig Rubens and Stanley Falkow at the University of Washington and continued by Heffron and his colleagues at the University of California at San Francisco. When these investigators introduced mutations that interrupted the continuity of genes at various locations within the ampicillin-resistance transposon designated Tn3, they found alterations in the ability of the element to function as a transposon. Mutation in the inverted-repeat ends or in a particular region of the DNA segment between the ends prevented transposition. On the other hand, mutations within another region of Tn3 actually increased the frequency of movement of Tn3 between the different plasmids, suggesting that this region might contain a gene modulating the ability of Tn3 to undergo transposition.

Recently published work by Joany Chou, Peggy G. Lemaux and Malcolm J. Casadaban in the laboratory of one of us (Cohen) and by Ronald Gill in Falkow's laboratory has shown that the Tn3 transposon does in fact encode both a "transposase"—an enzyme required for transposition—and a repressor substance that regulates both the transcription into RNA of the transposase gene and the repressor's own synthesis. Analogous experiments at the University of Chicago, the University of Wisconsin and Harvard University have shown that other transposable elements also encode proteins needed for their own transposition.

Even though transposons can insert themselves at multiple sites within a recipient DNA molecule, their insertion is not random. It has been recognized for several years that certain regions of DNA are "hot spots" prone to multiple insertions of transposons. Experiments recently reported by David Tu and one of us (Cohen) have shown that Tn3 is inserted preferentially in the vicinity of nucleotide sequences similar to sequences within its inverted-repeat ends, even in a bacterial cell that does not make the *rec*A protein required for ordinary homologous recombination. It therefore appears that recognition of homologous DNA sequences may play some role in determining the frequency and site-specificity of transposon-associated recombination, even though the actual recombinational mechanism differs from the one commonly associated with the exchange of homologous segments of DNA.

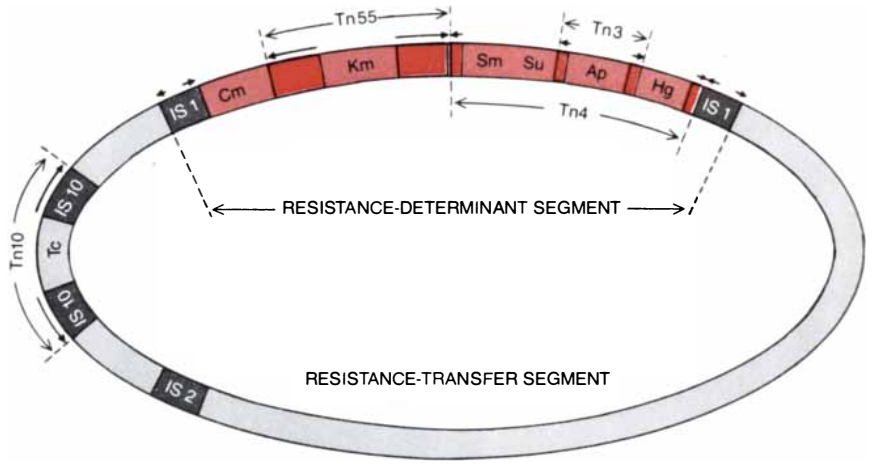


FUNCTIONAL COMPONENTS of the transposon Tn3 are diagrammed (not to scale). Genetic analysis shows there are at least four kinds of regions: the inverted-repeat termini; a gene for the enzyme beta-lactamase (*bla*), which confers resistance to ampicillin and related antibiotics; a gene encoding an enzyme required for transposition (a transposase), and a gene for a repressor protein that controls the transcription of the genes for transposase and for the repressor itself. The arrows indicate the direction in which DNA of various regions is transcribed.

The discovery of the process of transposition explains a puzzling phenomenon in bacterial evolution that has serious implications for public health: the rapid spread of antibiotic resistance among bacteria. Under the selective pressure of extensive administration of antibiotics in human and veterinary medicine and their use as a supplement in animal feeds, bacteria carrying resistance genes have a great natural advantage. For some time it has been known that resistance to several different antibiotics can be transmitted simultaneously to a new bacterial cell by a plasmid, but until transposition was discovered it was not known how a number of genes conferring resistance to different antibiotics were accumulated on a single plasmid-DNA molecule. The explanation seems to be that the resistance-determinant segments of drug-resistance plasmids have evolved as collections of transposons, each carrying a gene that confers resistance to one antibiotic or to several of them.

Work carried out at Stanford and by Phillip A. Sharp and others in the laboratory of Norman R. Davidson at the California Institute of Technology has made it clear that certain bacterial plasmids are constructed in a modular fashion. Plasmids isolated in different parts of the world show extensive sequence homology in certain of their DNA segments, whereas in other segments there is no structural similarity at all. In some instances plasmids can dissociate reversibly at specific sites. Transposable IS elements are found both at these sites and at sites where the plasmid interacts with chromosomal DNA to promote the transfer of chromosomes between different bacterial cells.

Identical transposons are commonly found in bacterial species that exchange genes with one another in nature. In addition antibiotic-resistance transposons



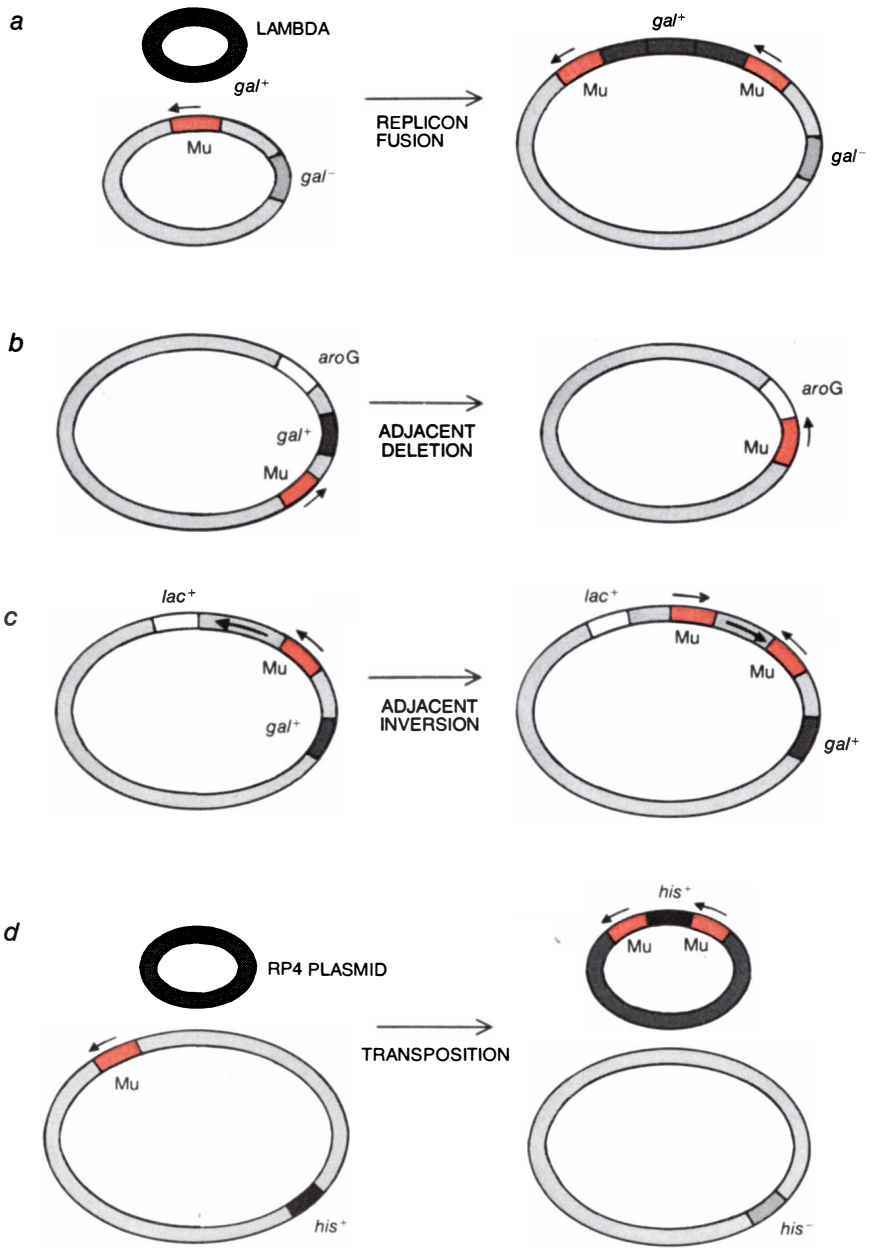
ROLE OF TRANSPOSABLE ELEMENTS in the evolution of antibiotic-resistance plasmids is illustrated by a schematic map of a plasmid carrying many resistance genes. The plasmid appears to have been formed by the joining of a resistance-determinant segment and a resistance-transfer segment; there are insertion elements (*IS1*) at the junctions, where the two segments sometimes dissociate reversibly. Genes encoding resistance to the antibiotics chloramphenicol (*Cm*), kanamycin (*Km*), streptomycin (*Sm*), sulfonamide (*Su*) and ampicillin (*Ap*) and to mercury (*Hg*) are clustered on the resistance-determinant segment, which consists of multiple transposable elements; inverted-repeat termini are designated by arrows pointing outward from the element. A transposon encoding resistance to tetracycline (*Tc*) is on the resistance-transfer segment. Transposon Tn3 is within Tn4. Each transposon can be transferred independently.

appear to be able to move among very different bacterial species that have not previously been known to exchange genes. For example, DNA sequences identical with part of Tn3 have recently been found to be responsible for penicillin resistance in two bacterial species unrelated to those commonly harboring Tn3 and in which such resistance had not previously been observed. Transposable elements seem, in other words, to accomplish in nature gene manipulations akin to the laboratory manipulations that have been called genetic engineering.

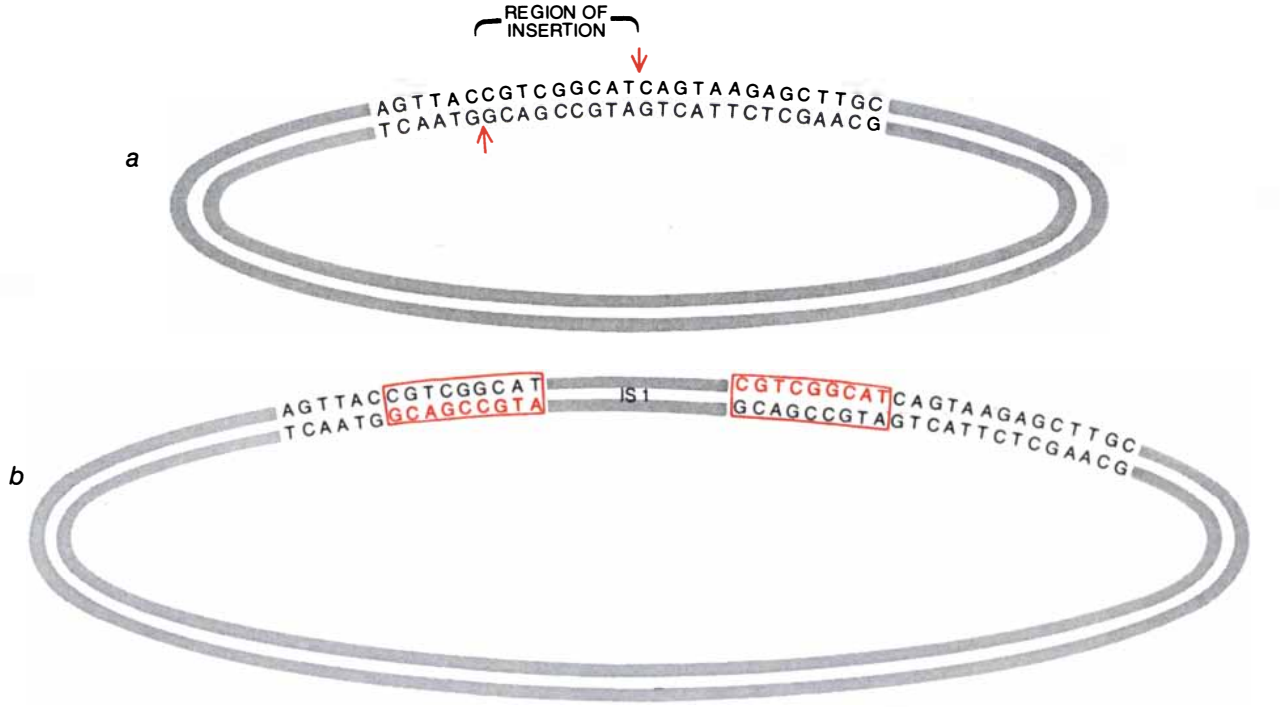
The effects of transposable genetic elements extend beyond their ability to join together unrelated DNA segments and move genes around among such segments. These elements can also promote both the rearrangement of genetic information on chromosomes and the deletion of genetic material. An awareness of these effects has emerged most clearly from studies of a peculiar phage, or bacterial virus, discovered in 1963 by Austin L. Taylor of the University of Colorado. Like other "temperate" bacterial viruses Taylor's phage could insert its DNA into a bacterial chromosome, creating a latent "prophage" that coexists with the bacterial cell and is transmitted to the bacterial progeny when the cell divides. Unlike other temperate phages, however, this one could become inserted at multiple sites within the chromosome, thereby causing many different kinds of mutation in the host bacterium. Because of this property Taylor called his phage Mu, for "mutator."

Further studies have shown that Mu is actually a transposable element that can also exist as an infectious virus. In the virus particle the Mu DNA is sandwiched between two short segments of bacterial DNA it has picked up from a bacterial chromosome. When the Mu virus infects a new cell, it sheds the old bacterial DNA and is transposed to a site in the new host chromosome. Ahmad I. Bukhari and his colleagues at the Cold Spring Harbor Laboratory have shown that Mu's ability to replicate is closely associated with its ability to be transposed; the virus has apparently evolved in such a way that its life span is dependent on transposition events.

While the structure of Mu's DNA and the details of the phage's life cycle were being unraveled Michel Faelen and Arianne Toussaint of the University of Brussels were doing genetic experiments aimed at understanding how the Mu DNA interacts with other DNA in a bacterial cell. The results of experiments carried out over a period of almost 10 years have demonstrated that Mu can catalyze a remarkable series of chromosome rearrangements. These include the fusion of two separate and independently replicating DNA molecules ("replicons"), the transposition of segments of the bacterial chromosome to plasmids, the deletion of DNA and the inversion of segments of the chromosome. Significantly, all these rearrangements seem to involve the nucleotide sequences at the ends of Mu DNA and to require the expression of a Mu gene that had been found earlier to be necessary both for transposition and for virus replication. Experiments done by Hans-Jorg Reif and Saedler at the University of Freiburg and by other groups have shown that many other transposable elements can, like Mu, promote the deletion of DNA; Nancy E. Kleckner and David Botstein and their associates at Harvard and at the Massachusetts Institute of Technology have shown that such elements can also bring about the inversion of DNA sequences. Indeed, there is evidence that some transposable elements may participate in specific re-



CHROMOSOME REARRANGEMENTS mediated by the bacterial virus Mu include replicon fusion, adjacent deletion, adjacent inversion and transposition of chromosome segments to a plasmid. Mu is shown in color; a small arrow gives its orientation. In a cell lysogenic for Mu (having Mu DNA integrated in its chromosome) and containing DNA of a lambda *gal*+ virus (*a*) the viral DNA becomes integrated into the chromosome between two copies of Mu. In a lysogenic cell in which Mu is near integrated *gal*+ genes (*b*) the *gal*+ genes are deleted. In a lysogenic male bacterium (*c*) with Mu near the origin of chromosome transfer (*large arrow*) the origin becomes inverted between two oppositely oriented copies of Mu. In a lysogenic bacterium carrying a plasmid (*d*) a bacterial *his*+ gene is transposed to plasmid between copies of Mu.



DUPLICATION of five, nine or 11 pairs of nucleotides in the recipient DNA is associated with the insertion of a transposable element; the two copies bracket the inserted element. Here the duplication that attends the insertion of IS1 is illustrated in a way that indicates how the duplication may come about. IS1 insertion causes a nine-nucleotide duplication. If the two strands of the recipient DNA are cleaved (*colored arrows*) at staggered sites that are nine nucleotides apart (*a*), then the subsequent filling in of single strands on each side of the newly inserted element (*b*) with the right complementary nucleotides (*color*) could account for the duplicated sequences (*colored boxes*).

arrangements of DNA more frequently than they do in transposition events.

New methods for determining DNA nucleotide sequences rapidly and simply have provided an important tool for elucidating the structure of transposable elements as well as the biochemical mechanisms involved in transposition and in chromosome rearrangements. The sequence of a transposable element (IS1) has been determined in its entirety by Hisako Ohtsubo and Eiichi Ohtsubo of the State University of New York at Stony Brook. An important insight into the mechanism of transposition has resulted from DNA-sequence observations initially made by Nigel Grindley of Yale University and the University of Pittsburgh and by Michele Calos and Lorraine Johnsrud of Harvard, working with Jeffrey Miller of the University of Geneva. Both groups examined the DNA sequences at the sites of several independently occurring insertions of the IS1 element. They found that the insertion of IS1 results in the duplication of a sequence of nine nucleotide pairs in the recipient DNA. The duplicated sequences bracket the insertion element and are immediately adjacent to its inverted-repeat ends. Since the sequence of the recipient DNA was different at each of the various insertion sites studied, different nucleotides were duplicated for each insertion.

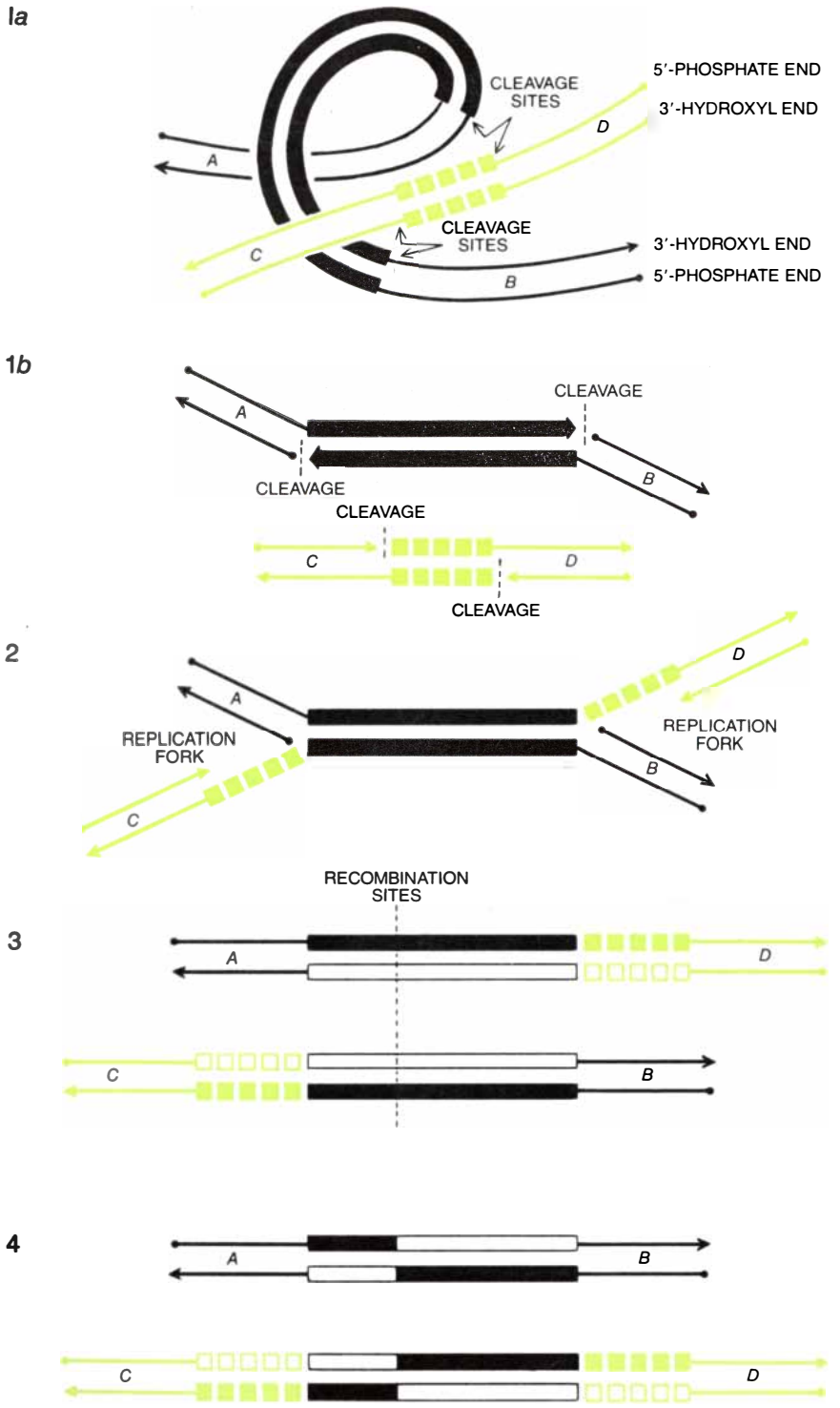
Subsequent reports from many laboratories have shown that similar duplications of a short DNA sequence result from the insertion of other transposable elements. Some elements generate nine-nucleotide duplications and others generate duplications five or 11 nucleotides long. As Calos and her colleagues and Grindley have pointed out, these observations suggest that a step in the insertion process involves staggered cleavage (at positions five, nine or 11 nucleotides apart) of opposite DNA strands at the target site for transposition. The filling in of the single-strand segments following such cleavage would require the synthesis of short single-strand stretches of complementary DNA and would result in the nucleotide-sequence duplication. Faelen and Toussaint had also concluded that DNA synthesis is required in the generation of chromosome rearrangements by Mu: they had noted that the rearranged bacterial chromosome often included two copies of the prophage, the inserted form of Mu.

On the basis of these observations one of us (Shapiro) has proposed a model to explain transposition, chromosome rearrangements and the replication of transposable elements such as phage Mu as variations of a single biochemical pathway. The pathway is such that transposable elements can serve two functions in the structural reorganization of cellular DNA: they specifically duplicate themselves while remaining inserted in the bacterial chromosome, and they bring together unrelated chromosomal-DNA segments to form a variety of structural rearrangements, including fusions, deletions, inversions and transpositions.

If this model is at all close to reality, then the nonhomologous recombination events associated with transposable elements are rather different from other types of illegitimate recombination, such as the integration of the phage-lambda DNA into the bacterial chromosome, that do not involve DNA synthesis. It seems likely that bacterial cells will turn out to have several different systems for carrying out nonhomologous recombination, just as they have multiple pathways for homologous recombination.

The potential for multiple mechanisms of illegitimate recombination is important to bear in mind when comparing phenomena that appear to be similar in bacteria and higher cells. Transposition phenomena that are analogous genetically may not be similar biochemically. There is some genetic evidence indicating that the movement of controlling elements in maize from one chromosomal site to another may be brought about by a mechanism different from that of transposition in bacteria.

Genetic rearrangements can have biological importance on two time scales: on an evolutionary scale, where the effects of the rearrangement are seen



POSSIBLE MOLECULAR PATHWAY is suggested to explain transposition and chromosome rearrangements. The donor DNA, including the transposon (*thick bars*), is in black, the recipient DNA in color. Arrowheads indicate the 3′-hydroxyl ends of DNA chains, dots the 5′-phosphate ends; the letters *A, B, C* and *D* identify segments of the two DNA molecules. The pathway has four steps, beginning with single-strand cleavage (*1a*) at each end of the transposable element and at each end of the "target" nucleotide sequence (*colored squares*) that will be duplicated. The cleavages expose (*1b*) the chemical groups involved in the next step: the joining of DNA strands from donor and recipient molecules in such a way that the double-strand transposable element has a DNA-replication fork at each end (*2*). DNA synthesis (*3*) replicates the transposon (*open bars*) and the target sequence (*open squares*), accounting for the observed duplication. This step forms two new complete double-strand molecules; each copy of the transposable element joins a segment of the donor molecule and a segment of the recipient molecule. (The copies of the element serve as linkers for the recombination of two unrelated DNA molecules.) In the final step (*4*) reciprocal recombination between copies of the transposable element inserts the element at a new genetic site and regenerates the donor molecule. The mechanism of this recombination is not known; it does not require proteins needed for homologous recombination, and at least in Tn3 it is mediated by sequences within element.

after many generations, and on a developmental time scale, where the effects are apparent within a single generation. It is known that transposable genetic elements can serve as biological switches, turning genes on or off as a consequence of their insertion at specific locations. In some instances the insertion of an IS element in one orientation turns off nearby genes, whereas an unexpressed gene can be turned on when the element is inserted in the opposite orientation.

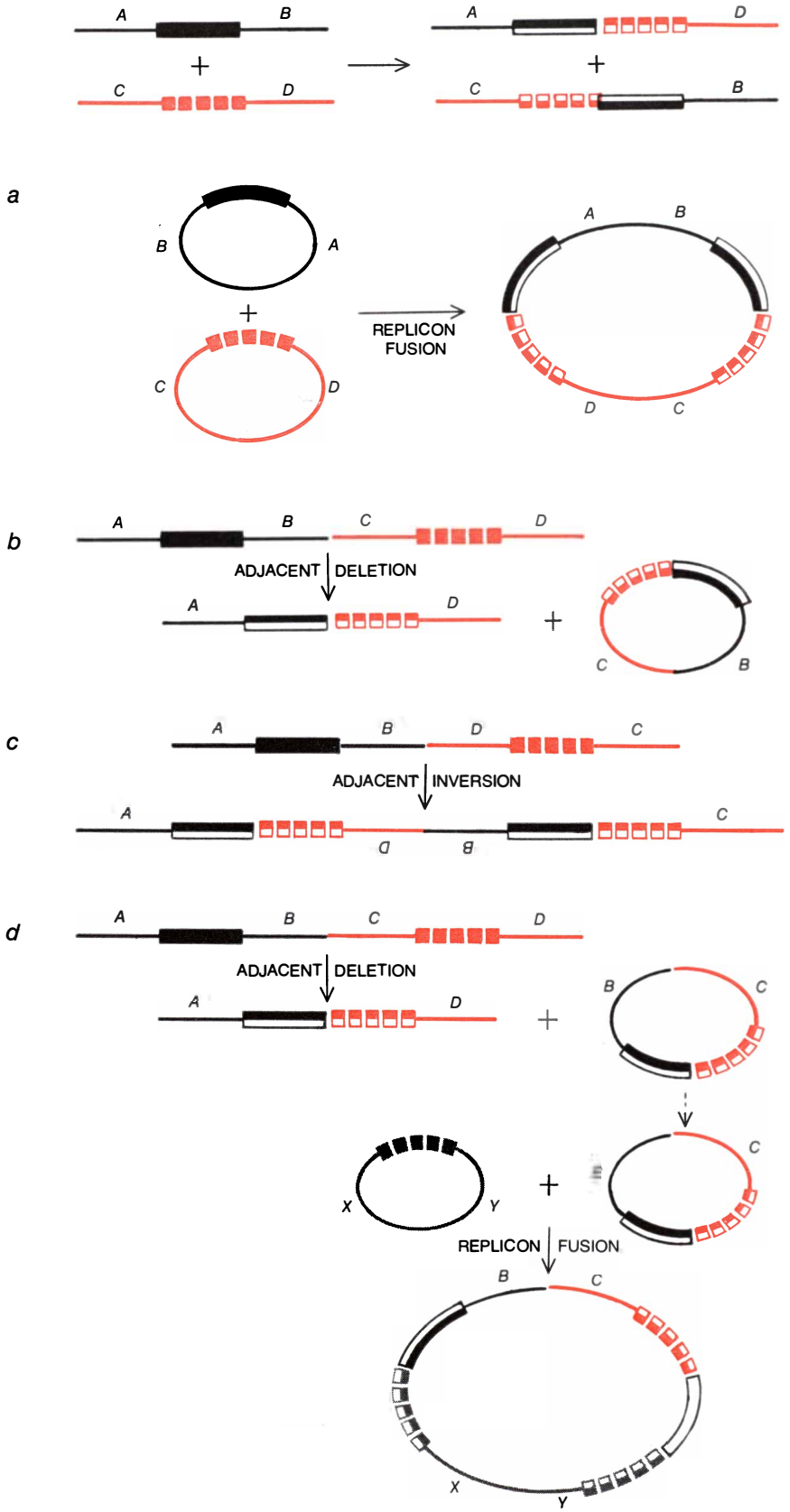
An analogous regulation of gene expression through chromosome rearrangement is "phase variation," which is seen in certain disease-producing bacteria that can invade the gastrointestinal tract. The phase, or immunological specificity, of a hairlike flagellum on these bacteria can change suddenly within a single bacterial generation. Melvin Simon of the University of California at San Diego and his colleagues have recently shown that the choice between the expression of one *Salmonella* flagellum gene and the expression of its counterpart, which specifies a different phase, is controlled by the inversion of a particular segment of the bacterial chromosome. The inversion takes place in the absence of proteins needed for homologous recombination, and so it appears to depend on recombination enzymes that recognize the ends of the invertible segment. Whether the switching mechanism responsible for phase variation operates by a molecular process similar to transposition remains to be determined, but the process clearly falls within the category of recombination events that were considered "illegitimate" a few years ago.

Although molecular studies on transposable elements have so far been carried out primarily in bacteria, there has been extensive genetic evidence for the existence of similar elements in higher organisms for years. The pioneering work of Barbara McClintock not only established the existence of transposable genetic elements in the corn plant but also showed by genetic analysis that the movement of a controlling element from one site to another in the maize chromosome depends on the action of genes on certain of the elements themselves, genes presumably analogous to those encoding the transposases of Tn elements and of phage Mu. McClintock also showed that some controlling elements (called regulators) regulate the expression of distant genes carrying insertions of other controlling elements (called receptors). Groups of genes are expressed synchronously at specific times during plant development, and McClintock suggested that the transposition of receptor elements could provide a mechanism for the rapid evolution of control mechanisms in situations in which several genes must be switched on or off at the same time, as they are in the course of development.

As often happens in science, the significance of McClintock's work was not entirely understood or appreciated until later studies carried out with the much simpler bacterial systems provided actual physical evidence for the existence of insertion sequences and transposons as discrete DNA segments and also established that transposition is brought about by a mechanism different from previously understood recombinational processes. Numerous other examples of transposable elements have now been recognized in higher organisms, such as the fruit fly *Drosophila* and the yeast *Saccharomyces cerevisiae*. The possible role of these elements in the generation of chromosome rearrangements is being actively investigated. Recent work on the control of immunoglobulin synthesis in mice by Susumu Tonegawa and his associates at the Basel Institute for Immunology has shown that the ability of mammalian cells to produce specific antibody molecules in response to injected foreign proteins also involves chromosome rearrangements. There is little doubt that additional instances will soon be found in which illegitimate recombination events play a major role in the expression of genes during cellular differentiation.

Even in bacteria much remains to be learned about the basic molecular mechanisms that accomplish the transposition of genetic elements and the associated rearrangement of DNA molecules. The various biochemical steps in the transposition pathway need to be more fully defined. What is the mechanism for recognition of the inverted-repeat ends of transposable elements? What proteins other than those encoded by the transposon play a role in transposition? What are the additional genetic aspects of the regulation of transposition? In a broader sense, what is the role of illegitimate recombination in the organization and expression of genes, not only in bacteria but also in higher organisms? Although the mechanisms that have been studied in bacteria provide a working model for the mechanisms of similar events in higher organisms, the parallels are probably incomplete.

It is already clear that the joining of structurally and ancestrally dissimilar DNA segments by transposable elements is of great importance for the production of genetic diversity and the evolution of biological systems. The discovery of such a fundamentally different recombinational process at a time when many molecular biologists believed virtually all the important aspects of bacterial genetics were understood in principle—with only the details of particular instances remaining to be learned—leads one to wonder whether still other fundamentally new and significant basic biological processes remain to be discovered.



FIRST THREE STEPS OF PATHWAY are summarized schematically at the top of this illustration. These steps achieve reciprocal recombination between unrelated DNA molecules and explain all rearrangements shown in the illustration on page 46, as follows. If the donor and recipient molecules are circular, the three steps result in replicon fusion (*a*). If the donor and recipient regions are part of a single molecule, the steps generate an adjacent deletion (*b*) or an adjacent inversion (*c*), depending on the positions of regions *A, B, C* and *D*. Two successive events (deletion and then replicon fusion) can result in the transposition to a plasmid of a DNA segment adjacent to the transposable element, along with two copies of the element (*d*).

Zapotec Writing

Among the high cultures of Mexico before the Spanish conquest was the Zapotec. Its hieroglyphs, mostly carved from 500 B.C. to A.D. 700, record the rise and decline of the Zapotec state

by Joyce Marcus

Among the pre-Columbian cultures of the New World the civilizations of Mesoamerica—the region from Mexico south to Guatemala and Honduras—were unique in their possession of a true form of writing: a series of hieroglyphs arranged in vertical columns and in many instances combined with numerals. The glyphs were at least indirectly related to a spoken language. Although there were many regional variations, the four major systems were those of the Maya of southern Mexico, Belize, Guatemala and Honduras, of the Aztec of central Mexico and of the Mixtec and Zapotec of southwestern Mexico.

Of the four the Zapotec system was the oldest. It appeared perhaps as early as 600 B.C. in the Valley of Oaxaca, some 550 kilometers south of Mexico City. The Zapotec system is also the least studied of the four, so that an understanding of its evolutionary relation to the later writings of the Maya, the Aztec and the Mixtec is still lacking. Early Zapotec writing is found primarily in the form of inscriptions on stone monuments and paintings on the walls of tombs in the Valley of Oaxaca. If the inscriptions could be deciphered, they might be combined with existing archaeological information to fill in part of the otherwise unrecorded history of the Zapotec people.

With this possibility in mind I have been working since 1972 to record the more than 500 stone inscriptions that have been found in the Valley of Oaxaca and to put them in context. My research has built on the pioneering work of two Mexican archaeologists, Alfonso Caso and Ignacio Bernal, and has been integrated with the recent work of two of my colleagues in the U.S.: Richard E. Blanton of Purdue University, who has carried out an analysis of the ancient Zapotec capital, Monte Albán, as an urban area, and Kent V. Flannery of the University of Michigan, who is studying the sequence of settlements in the Valley of Oaxaca that preceded the founding of Monte Albán.

Several previous studies of Zapotec writing have sought to interpret the inscriptions not in their own right but in terms of the better-known writings of the Aztec, the Mixtec and the Maya. This is unfortunate. Although some conventions are shared by the four systems, the languages the systems record belong to three different families: Zapotec and Mixtec belong to the Otomanguean family, Aztec to the Utoaztecan and Maya to the Macro-Mayan. To assign either Maya, Aztec or Mixtec names to Zapotec glyphs does little to advance understanding. Indeed, in some instances it serves to blur the interesting and significant differences among the four writing systems.

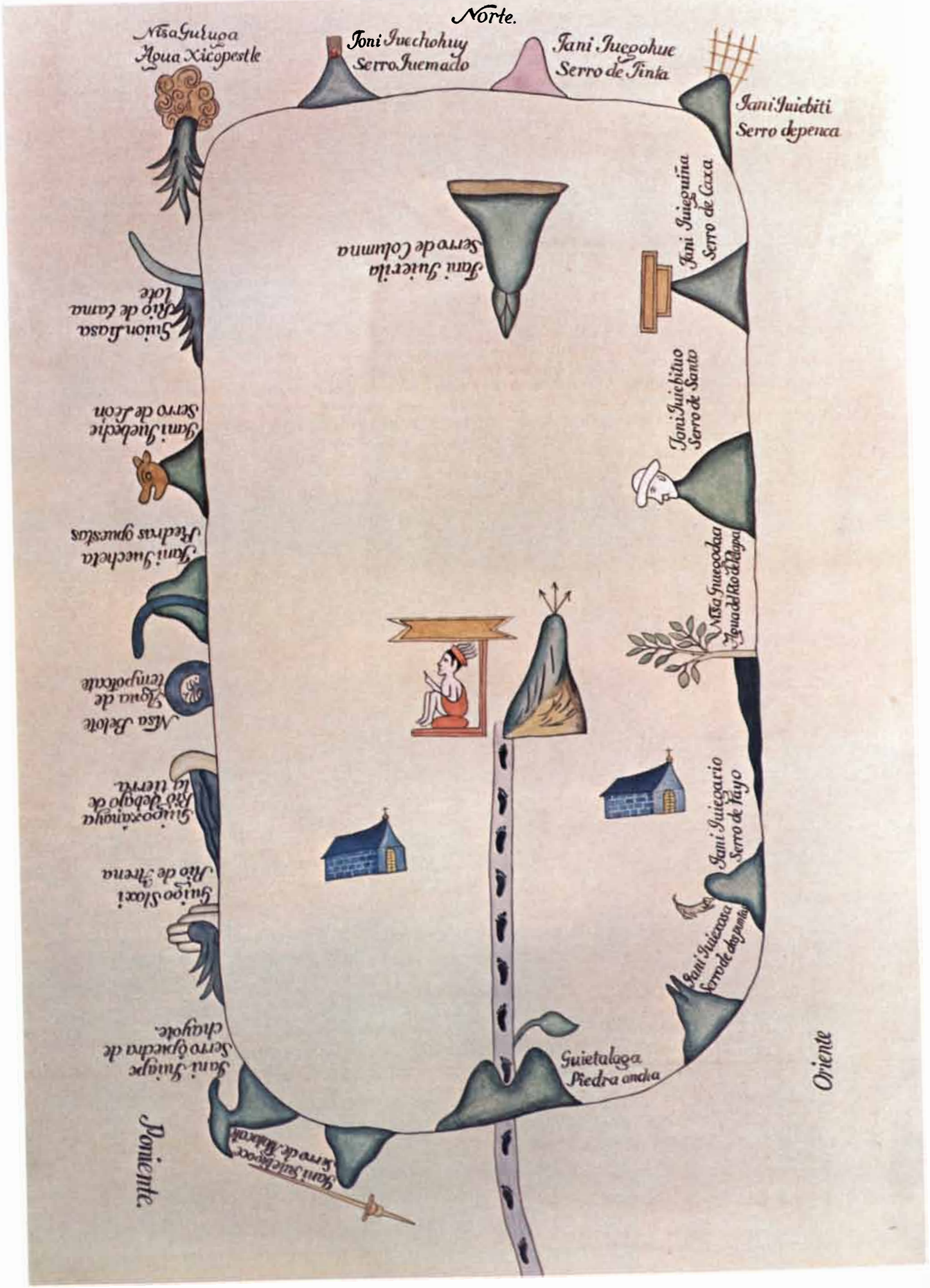
For my interpretive framework I have selected the extensive documents bearing on the Zapotec people that were compiled by their Spanish conquerors late in the 16th century. These include descriptions of the Zapotec calendar, the Zapotec political organization and religion and the grammar and vocabulary of the Zapotec language. Zapotec scribes, at the request of the Spaniards, also wrote down genealogies and prepared regional maps. Here I shall attempt to trace the evolution of Zapotec writing and simultaneously to reconstruct Zapotec political history. In doing so I shall combine information from the historical documents with what is known of the shared conventions of the four Mesoamerican writing systems and with the archaeological evidence from Oaxaca, in particular the inscribed monuments.

In the 16th century Zapotec society was divided into two classes that did not intermarry. The upper stratum consisted of the hereditary rulers (*coqui*) and their families, along with minor nobles (*xoana*). The lower stratum consisted of commoners and slaves. Great emphasis was put on the order of birth of noble children: rulers were frequently recruited from the elder offspring and priests from the younger. Military campaigns were fought by noble officers commanding commoner soldiers. Nobles frequently formed political alliances by marrying into the elite families of other communities; commoners usually married within their village. Royal ancestors were venerated and were thought to have considerable supernatural power over the affairs of their descendants.

The Zapotec of the 16th century kept two calendars, one secular and the other ritual. The secular calendar of 365 days (*yza*) was divided into 18 "moons" of 20 days and one period of five days. The ritual calendar of 260 days (*pije* or *piye*) was divided into four units of 65 days called "lightnings" (*cocijo*) or "great spirits" (*pitào*). Each 65-day period was further divided into five periods (*cocii*) of 13 days (*chij*).

Each day in the ritual calendar was designated by one of 20 day-name glyphs combined with a number between 1 and 13. The combination of day-name glyphs and numbers gave rise to the 260 days of the sacred cycle. Each day had its own ritual significance, and Zapotec rulers and nobles were named for the day on which they were born. Typical of the noble names that appear

ZAPOTEC PAINTING on the opposite page, prepared on Spanish command 19 years after the conquest of Mexico, shows the limits of the lands belonging to the municipality of Santiago de Guevea as an oval of 18 toponyms: hieroglyphic place signs for important landmarks. Next to each sign appear two translations. The first is the name of the landmark in the Zapotec spoken language, written in the Spanish alphabet; the second is the Spanish equivalent. Examples are "Hill with Two Peaks" (*at the clock position of five o'clock*), "Hill of the Spindle Whorl" (*left of six o'clock*), "River of the Tadpole" (*below nine o'clock*) and "Hill of the Puma" (*above nine o'clock*). The Zapotec ruler of Santiago de Guevea is shown seated in a temple near the center of the oval. The original painting, made in 1540, was copied in 1820; that copy, on which this painting is based, is now preserved in the Mexican National Museum of Anthropology.



on Zapotec stone monuments are "1 Tiger," "8 Deer," "5 Flower" and "11 Monkey."

The Zapotec people also used toponyms, glyphic "place signs" for important places or landmarks, mountains in particular. Several examples appear in an important pictorial document, the Lienzo de Guevea, that shows the lands belonging to the Zapotec town of Santiago de Guevea in 1540. Running around the edges of the picture are place signs accompanied by labels in Spanish (and in Zapotec, written in the Spanish alphabet) indicating the town borders; examples are "Hill of the Puma," "River of the Tadpole" and "Hill of the Spindle Whorl." Elsewhere in the picture is a genealogical list that presents the Zapotec rulers at Zaachila and on the Isthmus of Tehuantepec dating from the last century before the Spanish conquest.

Sixteenth-century documents such as this one provide a reasonable framework for efforts to interpret the ancient inscribed monuments of the Valley of Oaxaca. For example, many of the inscriptions evidently deal with the feats of ancient Zapotec rulers: their conquests, the sacrifice of their captives, their royal line of descent, their marriages and the names of their important dependencies and tributary districts. The names of many of the rulers are taken from the 260-day calendar, and their territories are defined by toponyms, usually the names of mountains.

Of the carved stone monuments in the Valley of Oaxaca the earliest may have been erected as long ago as 1000 B.C. The first monuments that include glyphs, however, do not appear until the interval between 600 and 200 B.C. This was a time of important political change. During what is known to archaeologists as the Rosario phase (700 to 500 B.C.) a number of regional and presumably competitive chiefdoms flourished in the valley. Each of these political units included one relatively large village with civic or ceremonial structures and smaller hamlets that lacked such public buildings.

In about 500 B.C. many of these valley chiefdoms disappeared or were greatly reduced, and a new kind of community was founded. The new community was on top of Monte Albán, a height near the center of the valley that rises some 400 meters above the valley floor. Blanton's study shows that the community, by far the largest in the valley, was initially divided into at least three separate residential areas. The arrangement suggests that the new stronghold may have been founded by previously competing groups that had come together in some kind of Zapotec confederacy.

During the initial phase of settlement, Monte Albán Period I (500 to 200 B.C.), the occupants of the mountaintop erected three kilometers of defensive walls. Most of this building was done late in the period. At the same time the settlers carved more than 300 stone monuments, the largest number known at any site in Mesoamerica. In none of the subsequent periods at Monte Albán were a fourth as many monuments erected. The Period I monuments, in keeping

MAIN PLAZA at Monte Albán dominates the most central of the five hills where the city stood; it measures 150 by 300 meters. Seen in the foreground is Structure J, erected during Monte Albán Period II. More than 40 inscribed "conquest slabs" were displayed on its walls.

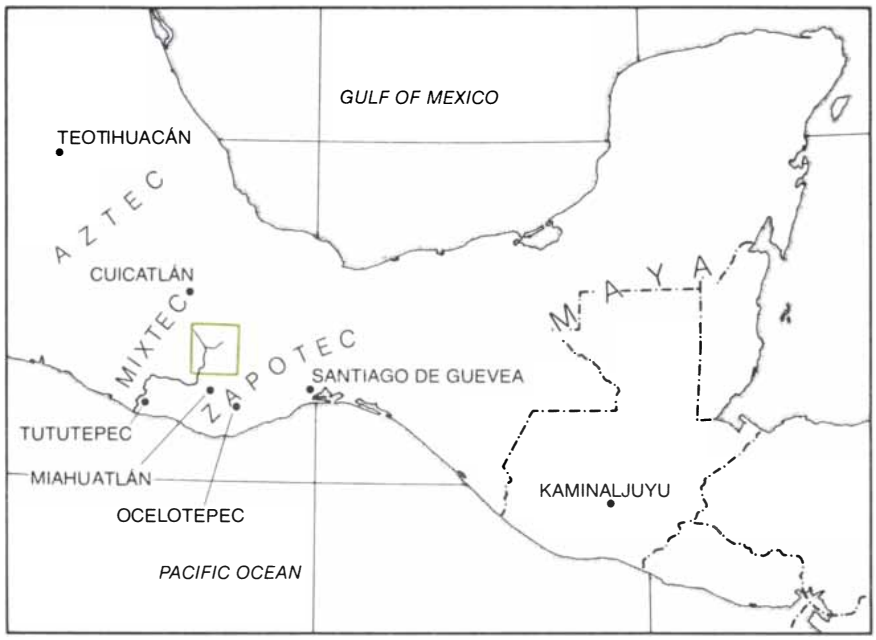
with the settlement's defensive walls, mainly portrayed military themes.

Of the shared conventions in Mesoamerican iconography some of the most widespread are those that depict captives. Prisoners are displayed in humiliation; they are stripped naked and bound, and their posture is awkward and distorted. Their captors, in contrast, are dressed in elegant regalia and are posed in rigid dignity. If a prisoner has been sacrificed, he is shown with his eyes closed and his mouth open, and in many instances with flowery scrolls, presumably representing blood, issuing from his wounds. To give one example, the Maya built many open galleries where prisoners were depicted in this way; the carvings were set into staircases so that the victors could figuratively "tread on the bodies" of the conquered when they were approaching the building at the head of the stairs, usually a temple. The Aztec built displays that served a similar purpose: the *tzompantli,* a rack or wall consisting of the skulls of enemy dead.

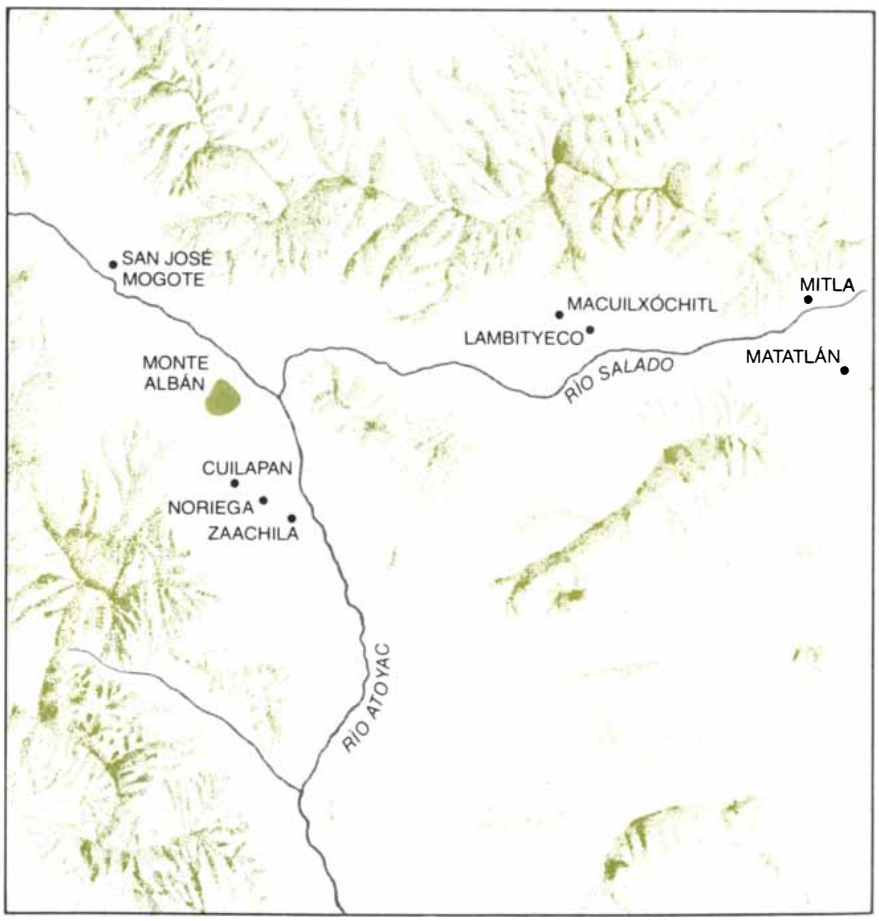
The earliest-known Zapotec carving representative of this convention was found some 15 kilometers north of Monte Albán at San José Mogote, a large civic and ceremonial center belonging to the Rosario phase. Known as monument No. 3, it depicts a sprawled naked human figure. Between the figure's legs an ornate dot (indicating the numeral 1) is accompanied by the Zapotec glyph *xoo,* meaning "earthquake" or "motion." The inscription is the oldest evidence known for the existence of the Zapotec 260-day calendar. It may record the name of the individual. Because San José Mogote appears to have been virtually abandoned at the end of the Rosario phase, presumably as part of the founding of Monte Albán, monument No. 3 was probably made sometime between 700 and 500 B.C.

The setting of Monte Albán is five interconnected hills, and the settlement covers an area of 6.5 square kilometers. A central hilltop is occupied by the Main Plaza, measuring 150 by 300 meters. Its principal structures are the North Platform, which held the royal residence and the temples of the Zapotec nobility, the South Platform, which held other temples, a large ball court along the east side of the plaza and a series of peripheral palaces and temples. Mound X, a temple site, lies northeast of the Main Plaza. Building L, a structure important to this discussion, stands in the southwest corner of the plaza. These various structures were built and rebuilt at different times. For example, Building L was erected during Period I, when the population of Monte Albán was at least 10,000. The two platforms and the ball court were built during subsequent periods.

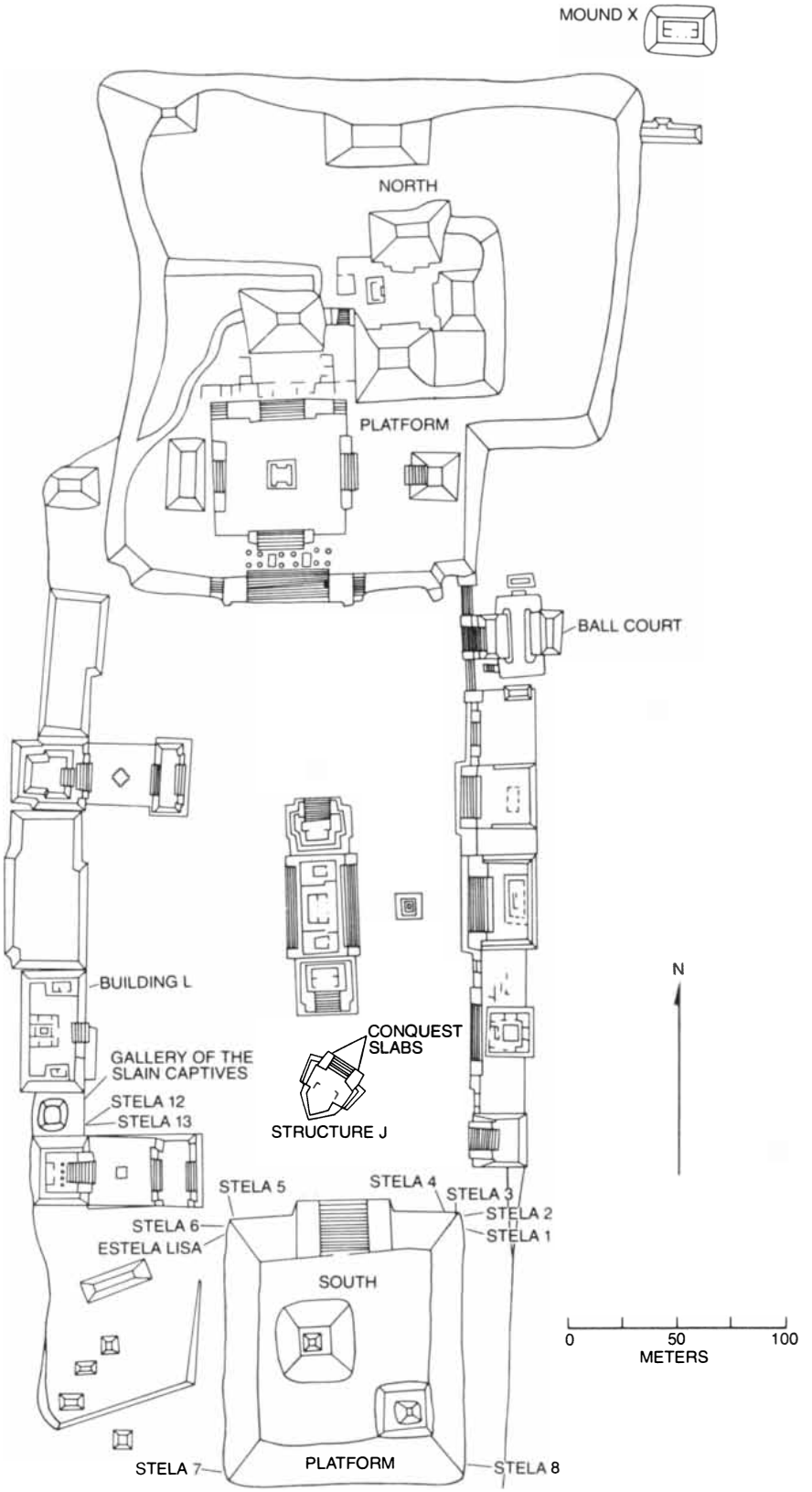
As one of the first public buildings



FOUR MAJOR SYSTEMS of hieroglyphic writing in the pre-Columbian New World were those of the Maya in eastern Mexico, Guatemala, Belize, Honduras and parts of El Salvador, of the Aztec of central Mexico and of the Mixtec and the Zapotec of southwestern Mexico. The influence of the Mexican city of Teotihuacán extended at least as far as Kaminaljuyú in Guatemala. The Valley of Oaxaca, inside rectangle, is shown in detail in the illustration below.



VALLEY OF OAXACA, centered on the confluence of the Río Atoyac and the Río Salado in the Sierra Madre del Sur, was the cradle of Zapotec civilization. From soon after 500 B.C. until A.D. 700 Monte Albán (*color*) was the capital of the then united valley. Before and after that period separate valley settlements were independent. The rulers of these districts in later times, mindful of their royal heritage, frequently entered into alliances by means of intermarriage.



PLAN OF THE MAIN PLAZA at Monte Albán shows the location of the two chief monument displays: the gallery of the slain captives along the east face of Building L and the 40-odd conquest slabs of Structure J. Of the stelae also located on the plan, No. 12 and No. 13 near the gallery of the captives carry the earliest Zapotec "text." Four of the nine stelae at the corners of the South Platform (*clockwise No. 1, No. 8, No. 7 and the* estela lisa) describe a visit by personages from Teotihuacán. Such a contact is also indicated on a monument found at Mound X. The stelae are shown where they were first found and not where they now stand. Building L was built during Monte Albán Period I (500 to 200 B.C.) and Structure J during Period II (200 B.C. to A.D. 100). The north and south platforms were built during Period III (A.D. 100–600).

erected by the founders of Monte Albán, Building L lay partially destroyed and buried under layers of later Zapotec construction until 1931, when its massive remains were first uncovered by archaeologists working at the site. The building was cleared between 1931 and 1936; photographs and drawings made at the time, along with the surviving parts of the structure, all indicate that the east face of Building L originally featured a great gallery of stone figures arranged in four rows and probably numbering in the hundreds. Each of the figures was a grotesquely sprawled naked human body with closed eyes. Some of the figures had blood scrolls issuing from one or more wounds.

In the lowest of the four rows each figure was upright and faced to the right. In the second row the figures were arrayed horizontally. In the third row the figures were again upright but faced to the left. In the top row they were again horizontal. The figures in the lowest row, those closest to observers, were the most elaborately carved. Many were adorned with necklaces, earplugs and complex hair arrangements; name glyphs are also common. The figures in the top row, those farthest away, were the least ornate.

For almost a century these Monte Albán figures have been the subject of almost every conceivable interpretation. Some of them, displaced from Building L, were among the first sculptures found at the site. Scholars have called them "dancers," "swimmers," "ecstatic priests" and even "medical anomalies." Indeed, Building L is still often called Los Danzantes, "the dancers." In 1962 Michael D. Coe of Yale University, who is familiar with the iconography of prisoner depictions throughout Mesoamerica, identified the Building L "dancers" as slain or ritually sacrificed captives. His interpretation might have been reached earlier if Building L had remained intact. Long before the Spanish conquest, however, the structure had been partially destroyed, and the inhabitants of Monte Albán had later used more than 100 of the figures as masonry for buildings in the plaza and elsewhere.

Attempts have been made to put the figures in chronological order on the basis of carving style, increasing degree of elaboration and so on. In my opinion the available archaeological evidence suggests that all the figures were carved at about the same time and were originally positioned as I have described them, with the more elaborate figures featured in the lower rows. The display, as it originally appeared, must have been one of the most impressive works of military propaganda in all Mesoamerica.

The figures were not necessarily the only elements in the display. At the south end of the gallery at Building L are two carved stones. Known as Stela

No. 12 and Stela No. 13, they bear one of the oldest glyph texts known at Monte Albán. Although the exact relation of the stelae to the gallery has never been worked out, some of the photographs made in the 1930's show the stones fitted so close together that they almost certainly once formed a single two-column inscription.

In the inscription both calendric and noncalendric glyphs appear. Of the calendric glyphs some seem to be day signs and others are possibly month signs. An example of a possible month-sign glyph is the last one in the second column [*see illustration on page 58*]. This glyph appears on monuments elsewhere at Monte Albán in association with numbers higher than 13. (In the 260-day calendar no day sign can be associated with a number higher than 13, but month signs in the secular calendar can be associated with numbers as high as 19.) One of the calendric glyphs is a year sign; within the surrounding raised area appears what is known as a year bearer.

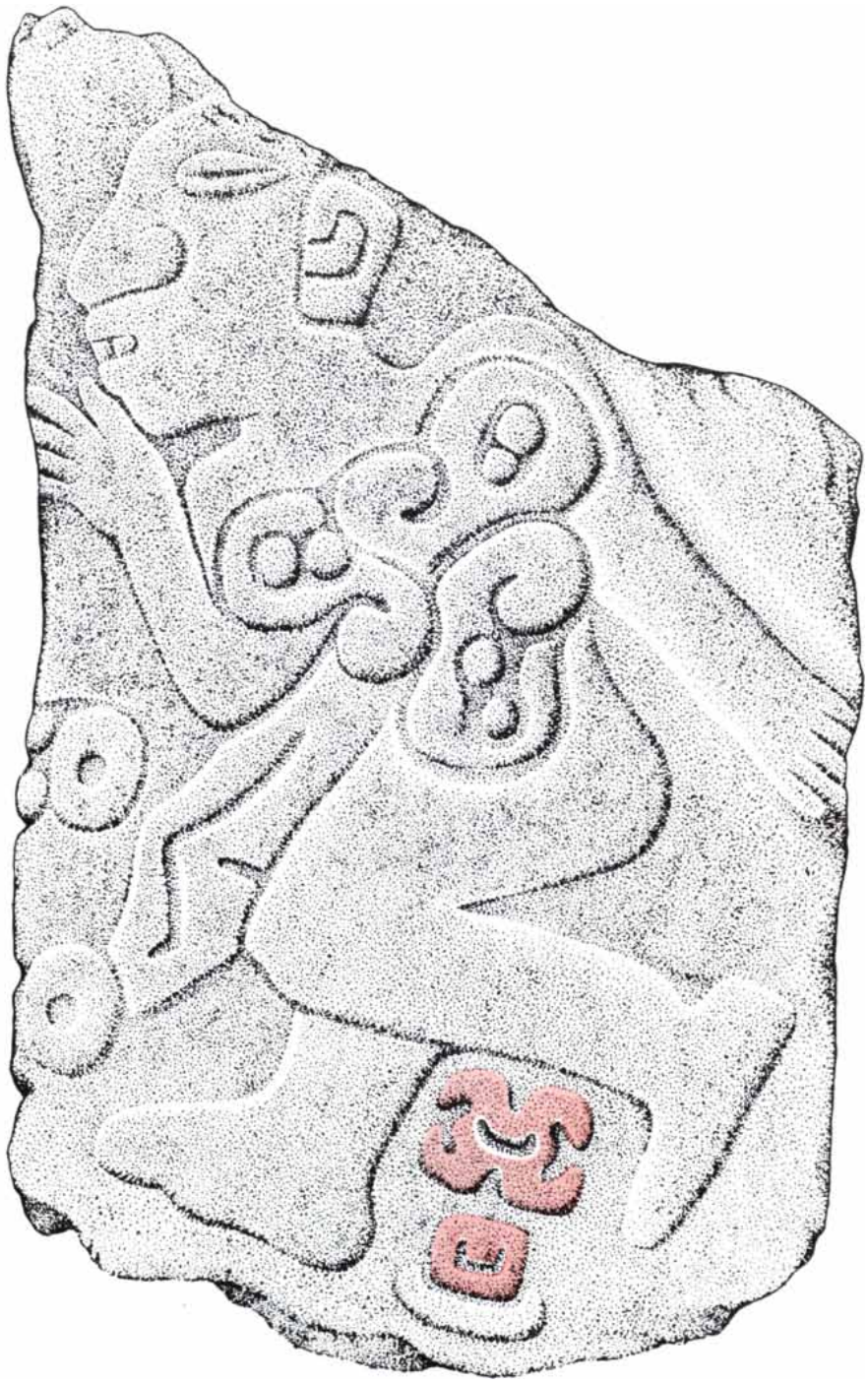
The noncalendric glyphs on the two stelae are sandwiched between the calendric glyphs. The third glyphs from the top seem to be the subjects of phrases or clauses. The second glyphs from the top evidently represent parts of hands. These glyphs are known as hand compounds. In the Maya and Aztec writing systems such representations of hands are parts of verbs; the Zapotec hand compounds at Monte Albán may be verbs of action.

Blanton's urban analysis has shown that during Period II at Monte Albán (200 B.C to A.D. 100) the population of the settlement grew to approximately 20,000. The settlers remained sheltered behind the three-kilometer wall, which stood as high as four meters along the gentler northern and western slopes of the site. During this period the Zapotec state also expanded its political, economic and military influence beyond the limits of the Valley of Oaxaca, reaching out into territories that had formerly been autonomous.

One of the major public buildings erected in the plaza during Period II was Structure J, notable for its arrowhead-shaped ground plan. Set into the walls of Structure J were more than 40 carved stone slabs. Caso has suggested that each of these "conquest slabs" represents a location subjugated by the rulers of Monte Albán in the period of expansion. All the slab carvings include the following elements: (1) a "hill" or "place" glyph, signifying "the hill of" or "the place of," (2) a glyph (or combination of glyphs) above the hill or place glyph, evidently representing the name of the hill or place, and (3) below the hill or place glyph an upside-down human head, the headdress of which varies from slab to slab.

Caso took these heads to represent the slain rulers of the subjugated areas and suggested that the various headdresses were regionally distinctive, thereby reinforcing the sense of the locational glyphs that appeared above them. A few of the slabs also bear glyphic texts. In their most complete form they include year signs, month signs and day signs along with noncalendric glyphs that are perhaps related to the time when a certain place was subjugated.

I consider Caso's interpretation of the conquest slabs to be essentially correct. This opinion is reinforced by the resemblance between the locational glyphs and the Zapotec descriptions of places that appear in later documents such as the Lienzo de Guevea. On this analogy it could be suggested that the 40 slabs rep-



SACRIFICED PRISONER appears on monument No. 3 from San José Mogote, a site north of Monte Albán. The monument was probably made between 700 and 500 B.C. The closed eye, the open mouth and the "scrolls" of blood emerging from the chest signify that the prisoner is dead. Between his legs appear (*color*) an ornate dot (representing the numeral 1) and a Zapotec glyph meaning "earthquake." The dual inscription may record the name of the prisoner.

resent 40 landmarks: for example, "Hill of the Rabbit," "Hill of the Bird" and "Hill of the Chili Plant." Such landmarks could have described the limits of Monte Albán territory in Period II. It is even possible that the original location of the slabs on the walls of Structure J reflected the sequence of these landmarks along the Zapotec frontier. This, however, can never be proved; many of the slabs had fallen out of place before Caso studied them.

It would obviously be useful to learn the location of the landmarks, even though it is unlikely that as many as a third of them could ever be precisely located. I have suggested, however, that a few of them might be traced by comparing them with the listing in a historical document, the Codex Mendoza. This codex is a 16th-century Aztec work listing 35 locales in Oaxaca that were paying tribute to Aztec overlords at the time. It depicts many locales by means of hill glyphs and I suspected that these glyphs might simply be Aztec versions of Zapotec place-names.

Since I made this suggestion I have found four codex place glyphs that closely resemble certain conquest-slab glyphs. The names of the four places, all of them within 140 kilometers of Oaxaca City, are Miahuapan (modern Miahuatlán), an Aztec name meaning "Place in the Water of the Maize Tassels"; Cuicatlán, Aztec for "Place of Song"; Tototepec (modern Tututepec), Aztec for "Hill of the Bird," and Ocelotepec, Aztec for "Hill of the Jaguar." The conquest-slab glyphs and the codex glyphs that are in close accord with these place-names respectively show maize tassels in an irrigation canal, a human head with a feathered speech scroll emerging from its mouth, a bird on the top of a hill and a jaguar on the top of a hill [*see illustration on page 59*].

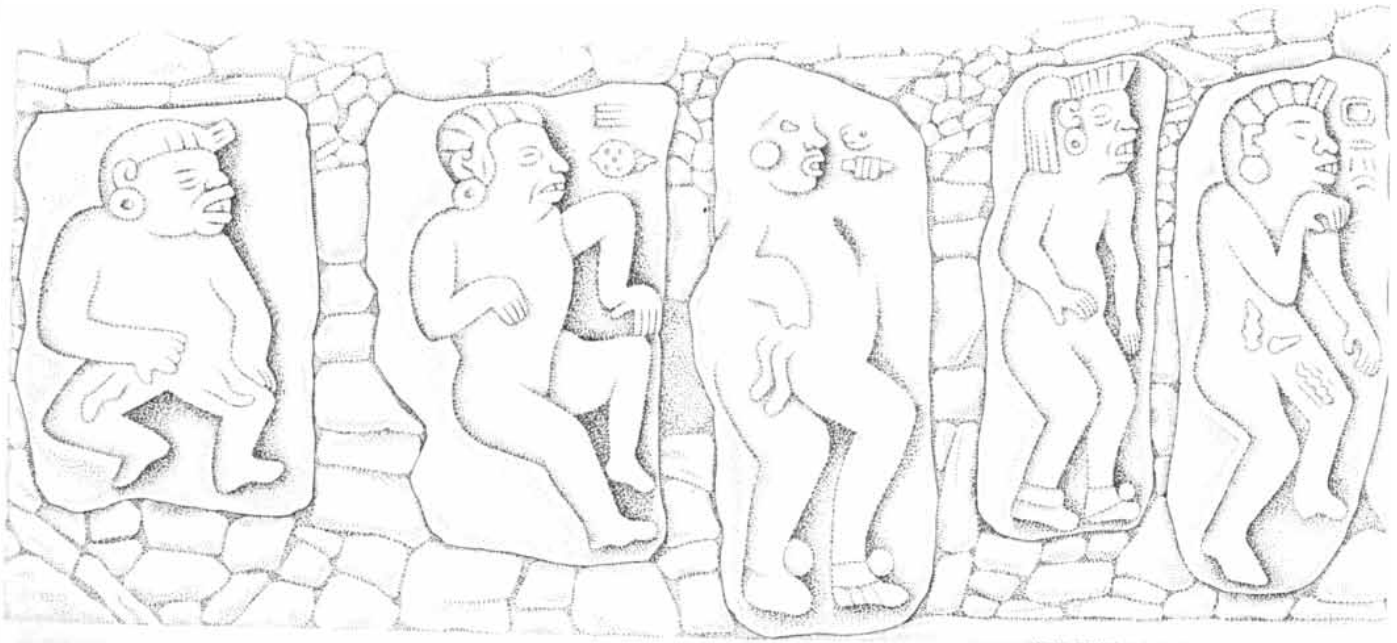
Such a correlation between a 16th-century Aztec codex and Zapotec glyphs of Period II implies some 1,500 years of place-name continuity. Hence my suggestion is no more than a hypothesis, subject to proof or disproof by future analysis. Recently, however, work by Charles Spencer of the University of Michigan and Elsa M. Redmond of Yale University in the vicinity of Cuicatlán, the "Place of Song," has provided a degree of confirmation. It appears that in this originally autonomous region control passed into Zapotec hands at about the end of Period I or the beginning of Period II. At one outlying Cuicatlán settlement the conquerors erected an edifice of skulls of the *tzompantli* type. Farther to the north they fortified a mountaintop, closing off the main route from Oaxaca to the neighboring Valley of Tehuacán. Spencer and Redmond find that pottery of Monte Albán Period II extends no farther than this mountain fort. Only pottery of Tehuacán style appears beyond it.

Similar archaeological tests of my hypothesis remain to be done at the other three towns. This should not be impossible. Tututepec and Miahuatlán in particular include the remains of substantial Monte Albán II settlements. It would also be heartening to discover the identity of still other conquest-slab place glyphs.

During Period III at Monte Albán (A.D. 100 to 600) the settlement grew to cover more than six square kilometers; Blanton estimates that the population reached some 30,000. The five centuries of Period III are divided into two subphases (IIIa and IIIb), and the settlement reached its maximum size during the second subphase. Throughout the period, however, Zapotec territorial expansion seems to have slowed, perhaps because Monte Albán was now competing economically with an even larger metropolis.

That metropolis was Teotihuacán, 500 kilometers to the north in the basin of Mexico. During the same 500-year interval Monte Albán's northern competitor had expanded to cover 25 square kilometers; René Millon of the University of Rochester estimates that its population was then more than 100,000. Although the region tributary to Teotihuacán is still not well defined, it must have been many times larger than that of Monte Albán, and its zone of influence must have been larger still. For example, there is evidence of Teotihuacán influence at the Maya site of Kaminaljuyú, 900 kilometers to the south in Guatemala. Clara Millon of the University of Rochester has suggested that one particular kind of head ornamentation at Teotihuacán, the "tassel headdress," is associated with the representation of certain personages who evidently traveled to distant parts of Mesoamerica, perhaps in some kind of ambassadorial capacity. Support for this suggestion is found at the Guatemala site in portrayals of the tassel headdress on painted pottery.

The Millons find evidence of a special



GALLERY OF THE CAPTIVES at Building L in the Main Plaza of Monte Albán had this appearance when it was discovered under later levels of construction in 1931. The alternating courses of vertical and horizontal representations of sacrificed prisoners may once have in-

relationship between Teotihuacán and Monte Albán. For example, a Zapotec colony apparently existed for a century (from about A.D. 200 to 300) on the western outskirts of Teotihuacán. The Zapotec enclave extended over more than a hectare (2.5 acres); its remains include residences, graves, funerary urns and other pottery of the Monte Albán style. The stone doorjamb of one tomb is inscribed with a Zapotec glyph.

No corresponding Teotihuacán colony has been found by Blanton at Monte Albán. Some stone monuments of subphase IIIa, however, give evidence of relations between these two great cities of Mesoamerica. Perhaps the most impressive single structure built at Monte Albán during phase IIIa is the South Platform of the Main Plaza. It is a truncated pyramid 15 meters high and more than 100 meters on a side at the base. A number of stone monuments stood at the four corners of the pyramid.

Eight of the monuments echo the militaristic themes of Period I and Period II. Six show captives, evidently prisoners of superior status, with their arms tied behind their back. Below each captive is a hill glyph, presumably indicating his place of origin. The figures on the other two monuments contrast vividly with the six captives; they are elegantly

cluded more than 300 figures. More than 100 of the carved stones were removed to be reused as masonry elsewhere in Monte Albán.

When the display was first erected, it must have been one of the most impressive works of military propaganda anywhere in Mesoamerica.

costumed and armed with lances. They presumably represent Zapotec leaders.

When these monuments were discovered early in this century, along with a ninth stela that bore no figure and was therefore called the *estela lisa* (plain stela), they did not appear to bear any inscriptions other than the human figures and hill glyphs. Later work on the South Platform in the 1950's revealed, however, that four of the monuments were also inscribed on their edges and elsewhere. The four were stelae No. 1 (northeast corner), No. 7 (southwest corner), No. 8 (southeast corner) and the *estela lisa* (northwest corner). In the course of investigating these inscriptions Jorge Acosta of the Mexican National Institute of Anthropology and History found that stone offering boxes had been placed at three of the platform's four corners. The boxes contained seashells, jade and pottery of the Monte Albán IIIa style.

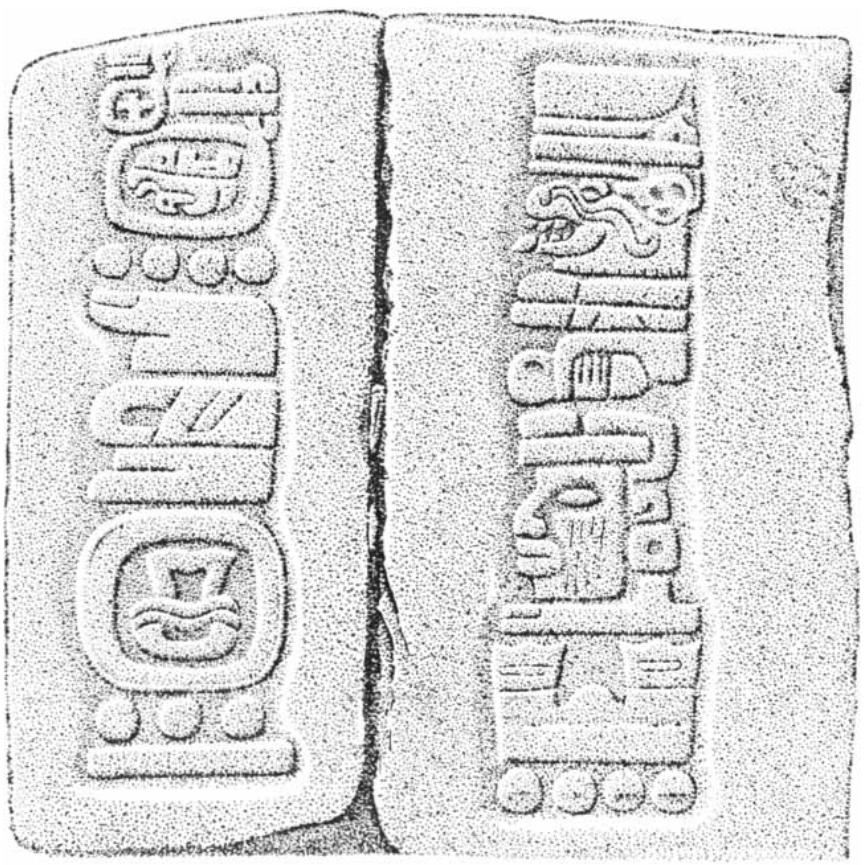
The edge inscriptions of the four monuments all present much the same information. Eight named individuals in two groups of four are depicted in all. They are shown leaving a place where temples are decorated in the style of one district of Teotihuacán: Tetitla. All the travelers are wearing the kind of tassel headdress identified by Clara Millon as being possibly ambassadorial. The eight are then seen arriving at a place named "Hill of 1 Jaguar," where they are greeted by an official wearing a typical Zapotec headdress. In view of the physical association between the stelae and the offering boxes, it is not unlikely that the visit of the eight travelers coincided with the dedication of the South Platform. "Hill of 1 Jaguar" could be the name of all or part of Monte Albán.

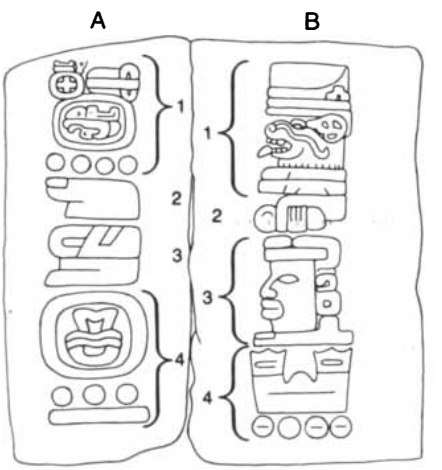
Although each of the inscriptions presents the same information, the inscriptions vary in detail. For example, Stela No. 7 shows four of the travelers, accompanied by their name glyphs. On Stela No. 8 the same four travelers are presented in a different manner. Each is represented by a tassel headdress, an incense burner of the Teotihuacán style and then a calendric name and a nickname. Three of the calendric names can be read as follows: "5 Turquoise," "12 Skull" and "7 [?] *N*." (The question mark indicates that the identification of the number is not certain, and the letter *N* is Caso's designation for this still undeciphered Zapotec glyph.)

The other four travelers are named on the underside of the *estela lisa*. These names are easier to read: "13 Knot," "9 Monkey," "1 Owl" and "Treble Scroll." (The last designation is a common iconographic symbol at Teotihuacán.) The four travelers are seen being greeted by a Zapotec ruler whose name is given as "8 [followed by an undeciphered glyph]" and whose residence is given as "Hill of 1 Jaguar." Inscriptions on the upper and lower edges of Stela No. 1 make reference to the same four travelers in abbreviated form; the travelers' footprints are also shown leading away from a temple of the Tetitla style.

As the Millons have pointed out, no depiction of a Teotihuacán personage on a Zapotec monument shows him in military garb or bearing weapons. For example, the tassel-headdress figures on the South Platform monuments are dressed in ceremonial costumes and are carrying pouches of copal, the incense burned in Mesoamerican ritual. One may conclude that whereas the relations between Monte Albán and some of its other neighbors were often hostile the visit of the Teotihuacán personages to "Hill of 1 Jaguar" constituted peaceful foreign relations.

Further information on relations between Monte Albán and Teotihuacán came to light in 1936, when a carved slab of polished travertine was discovered on Mound X, to the northeast of the Main Plaza. Two figures are depicted on this slab, known as the Lápida de Bazán. One figure, on the left, is dressed in Teotihuacán style and holds a pouch of copal in one hand. The other is costumed as a jaguar in the style of the lords of Monte Albán. Caso, who was the first to recognize the figure on the left as a





TWO-COLUMN TEXT, almost certainly once a single inscription, is one of the earliest inscriptions known at Monte Albán. It is untranslated, but many of the glyphs can be interpreted (*see plan at right*). A-1 is a calendric glyph, specifically the year sign "4 Serpent." A-2 is noncalendric; a hand with the thumb prominent, it may be a verb. The meaning of A-3 is not known. A-4 is calendric; its reading is "8 Water," and it may be a day sign. B-1 is calendric; its reading appears to be "10 Jaguar." It may be a month sign or a calendric name. B-2, a hand grasping an object, is noncalendric; like A-2, it may be a verb. B-3, a profile head with a finger below it, may be a personal name. Part of the reading of B-4, a calendric glyph, is "4"; the other part is undeciphered. Its use on other monuments shows it is a month sign.

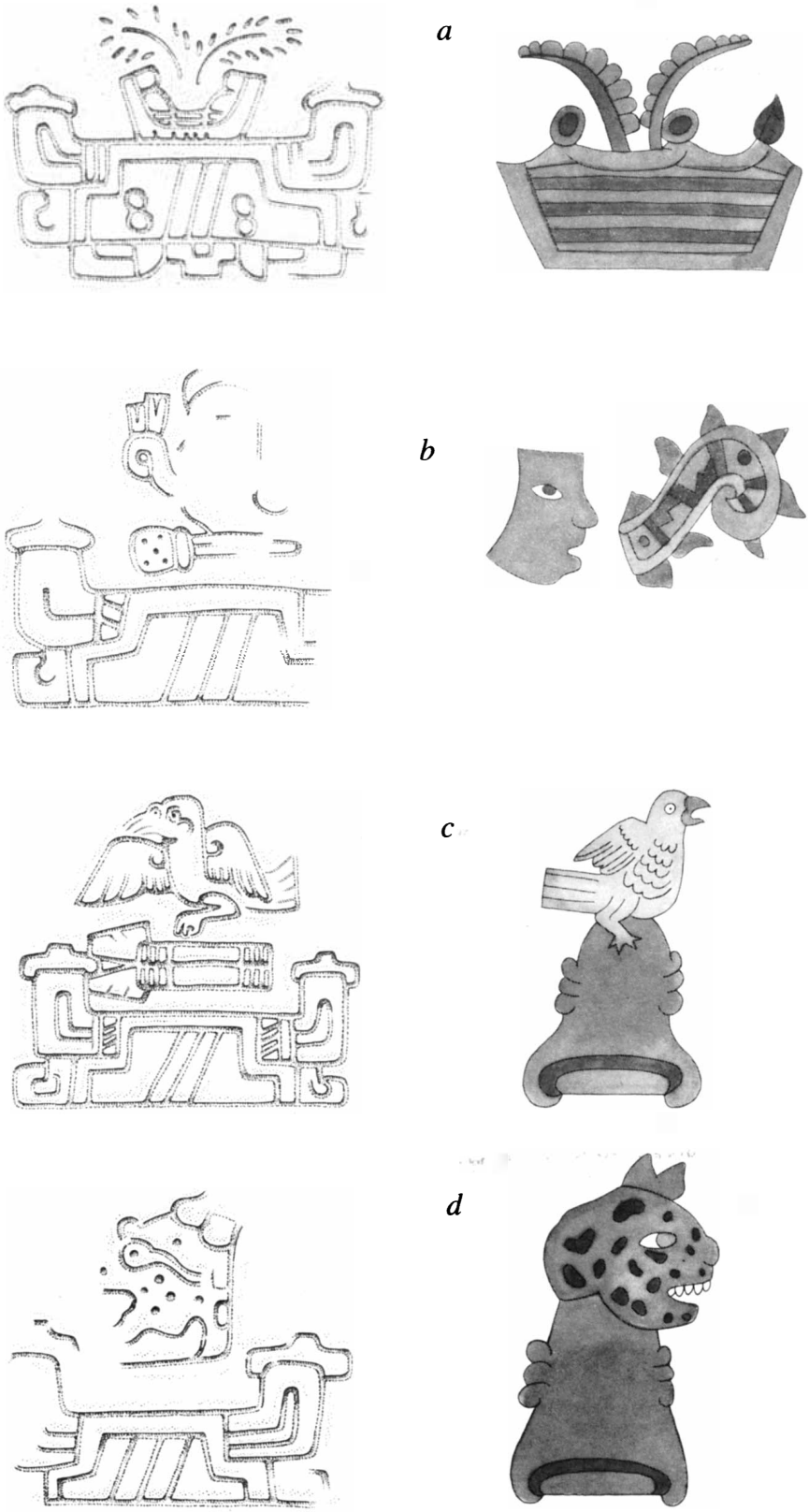
Teotihuacán personage, read his calendric name as "8 Turquoise." The name of the jaguar lord is "3 Turquoise."

Accompanying each figure is a column of glyphs. Neither "text" contains any calendric signs, and so it seems plausible that the inscriptions are essentially narrative ones and that they are probably historical and political in character. Teotihuacán is alluded to twice: by the depiction of a tassel headdress (column A, glyph 6, or A-6) and by the depiction of a foot wearing a Teotihuacán-style sandal (B-4). Travel is indicated by footprints (A-7 and B-6) and flowery speech by scrolls issuing from a head (A-5) and from a "jaguar nose" (B-7). An incense burner of Zapotec style is shown (A-8), as is a hand holding a single bean (A-4). According to 16th-century accounts, beans were used by Zapotec diviners to help decide important issues. Here the depiction of a single bean may indicate that after beans had been removed from a pile by twos, fours and so forth in the manner prescribed in the 16th century, this remaining "odd number" decided whatever was at issue. The inscriptions also include a number of hand-gesture glyphs, the kind I have suggested were possibly verbs of action. Finally, the series of glyphs A-5 through A-7 might be read: "Representative from Teotihuacán came to confer."

Pending a complete decipherment of the Lápida de Bazán I regard it tentatively as being a record of an agreement between representatives of the two cities. In my interpretation the representatives traveled, met, spoke, consulted diviners and burned incense. This last action would have established the binding quality of their agreement by putting it in a sacred context. It was probably through diplomatic encounters such as this one that Monte Albán and its far larger neighbor Teotihuacán maintained a healthy social distance, regulated their tributary boundaries and preserved their special relationship.

In about A.D. 600 the great metropolis of Teotihuacán was virtually abandoned. Many of its temples and major buildings were burned. In theory this crisis might have given the rulers of Monte Albán a favorable opportunity to expand the Zapotec realm. For reasons unknown, however, at about this same time Monte Albán also began to decline. Although the Zapotec capital was never burned and never entirely abandoned, public construction around the Main Plaza came to an end with the close of Period III in about A.D. 700.

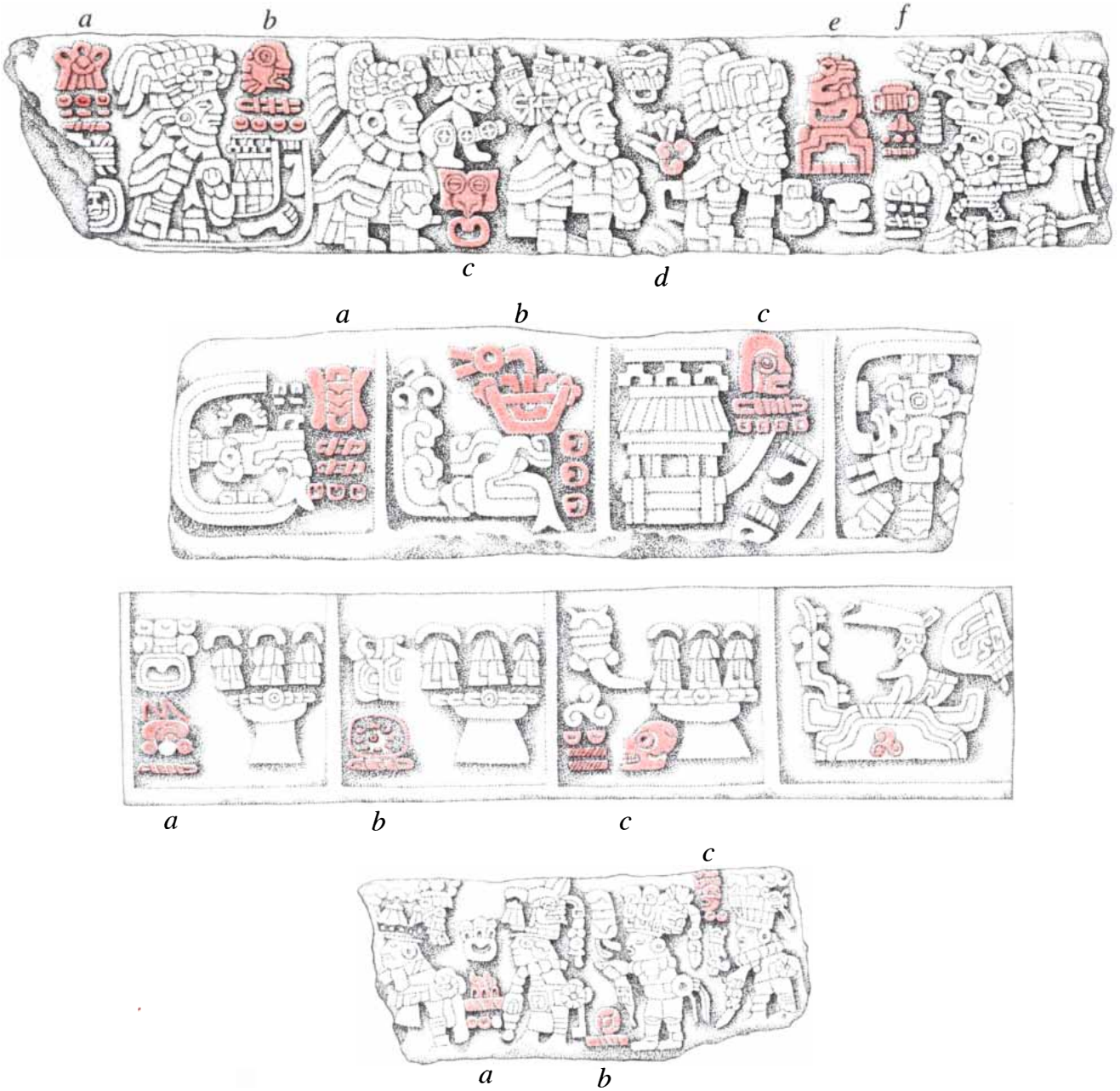
From a peak of some 30,000 in subphase IIIb the population of Monte Albán shrank rapidly during the succeeding periods: Period IV (A.D. 700 to 1000) and Period V (1000 to 1520). By the year 1300 only 4,000 to 8,000 inhabitants still remained. What had hap-



FOUR TOPONYMS, glyphs descriptive of geographical locations, appear at the left; they are selected from the more than 40 such glyphs carved on the conquest slabs of Structure J at Monte Albán. At the right are four matching toponyms from a painted Aztec document that lists locales in Oaxaca that were paying tribute to the Aztec in the 16th century. The Aztec names associated with the toponyms are (*a*) Miahuapan, "Place in the Water of the Maize Tassels," (*b*) Cuicatlán, "Place of Song," (*c*) Tototepec, "Hill of the Bird," and (*d*) Ocelotepec, "Hill of the Jaguar." The resemblance between the Aztec toponyms and Zapotec glyphs suggests that the Aztec overlords may simply have translated long-standing Zapotec place-names. The four locales, all within 140 kilometers of Oaxaca City, are now known by their Aztec names.

pened? Blanton has suggested that one motive for maintaining a large population during Period III was to provide a deterrent to possible Teotihuacán expansion into the Oaxaca region. If that was the case, the collapse of Teotihuacán would have removed a major incentive for maintaining an urban center at Monte Albán. In any event the confederacy centered on Monte Albán for more than 1,000 years began to dissolve as the urban population drifted away to various competing civic and ceremonial centers on the floor of the valley. Not until the arrival of the Spaniards in 1529 was the Valley of Oaxaca again united.

Many of the competing centers (Cuilapan, Zaachila, Macuilxóchitl, Mitla, Matatlán, Lambityeco and others) had already existed as villages when Monte Albán was first founded. Some had begun to grow again toward the end of subphase IIIb, as if anticipating the decline of the mountain city. During Peri-



"VISITOR" INSCRIPTIONS appear on four monuments at the corners of the South Platform in the Main Plaza of Monte Albán. The inscriptions convey the same information in different ways: Eight personages have come from Teotihuacán on a peaceful visit. The top inscription appears on a monument known as the *estela lisa*. Four of the personages appear, all facing to the right. Their names, marked in color from left to right, are (*a*) "13 Knot," (*b*) "9 Monkey," (*c*) "1 Owl" and (*d*) "Treble Scroll." Directly before "Treble Scroll" appears the toponym "Hill of 1 Jaguar" (*e*). Facing the four personages is a Zapotec ruler in full regalia; his name (*f*) is given as "8 [unknown]." The second inscription appears on Stela No. 1. The visitors are not seen but are identified by name; the names are (*a*) "13 Knot," (*b*) "3 [Caso's glyph *C*]" and (*c*) "9 Monkey." A fourth name probably appeared at the far right, but that part of the carving is missing. Associated with "9 Monkey" is a reference to Teotihuacán in the form of a temple facade characteristic of one city district and a reference to travel (*lower right*) in the form of ascending footprints. The third inscription appears on Stela No. 8. The names but not the figures of the visitors seen in the fourth inscription appear in the same order, left to right (*color*). To the right of each name is an incense burner with a "tassel headdress" on top. The inscription includes the toponym known as a hill sign. Within it is the treble-scroll sign prominent in Teotihuacán iconography (*see* d *in top inscription*); the toponym may therefore refer to the city. The fourth inscription is on Stela No. 7; four visitors appear, all facing to the left. Three are named: (*a*) "7 [?] [Caso's glyph *N*]," (*b*) "5 [Caso's glyph *D*]" and (*c*) "12 Skull." All four are wearing the tassel headdress that identifies them as Teotihuacán envoys; the three whose hands are shown carry pouches of copal.

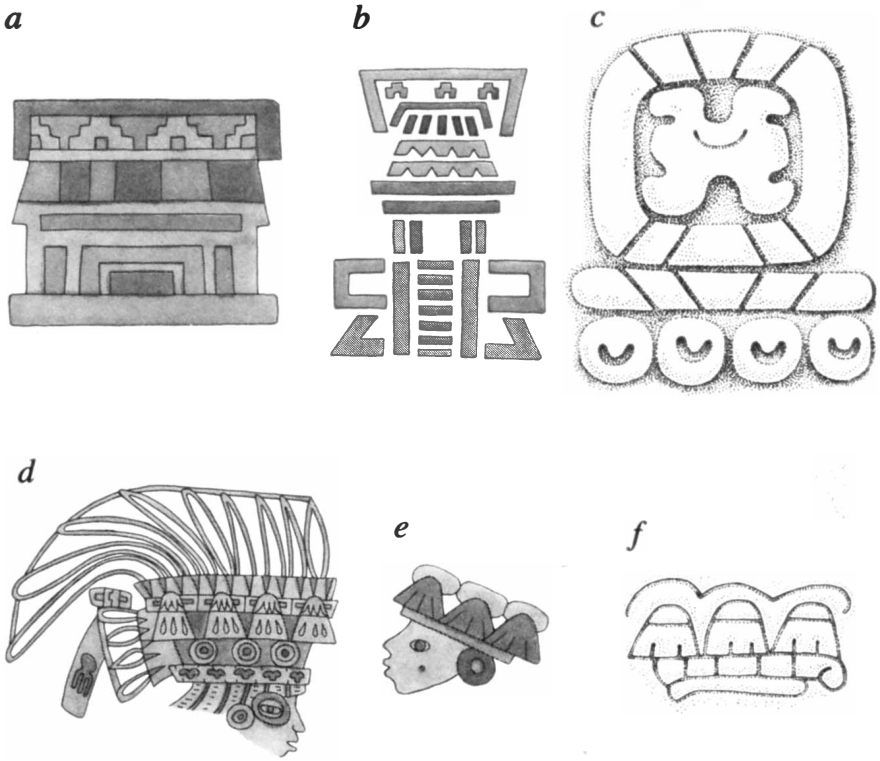
od IV all these valley centers expanded rapidly; this was perhaps in part the result of simple internal growth, but the expansion must also have come partly from the absorption of immigrants from Monte Albán. Many of the valley centers were still important politically, economically and religiously when the Spaniards set down the first extended descriptions of the Zapotec people in the period from A.D. 1579 to 1581.

As Period III ended and Period IV began at Monte Albán one innovation was the appearance of a new kind of stone monument I call a genealogical register. Unlike the large stone monuments of the preceding periods, which were obviously meant to be viewed from some distance, the genealogical registers are small and can only be read close up. Many that I have measured are only from 50 to 60 centimeters high and from 30 to 40 centimeters wide. Instead of being set up in public buildings these small stones appear to have been installed in the residences of the Zapotec elite or (as at Cuilapan and Lambityeco) placed in their tombs. The inscriptions on the registers do not echo the militaristic themes of the earlier periods at Monte Albán; they record the births, ancestry and marriages of the Zapotec rulers and nobles of the time.

Particularly common on the registers are depictions of royal marriages. After the decline of Monte Albán such unions were one of the chief means by which the Zapotecs established political alliances between important communities. The royal husband and wife are usually shown facing each other, seated on woven mats or poised above hill glyphs; in some instances their calendric names are included. The couple may be shown burning incense or sharing a cup of chocolate or pulque. Above them appears a glyphic element Caso has named the "Jaws of the Sky," along with other iconographic elements indicative of royal descent.

On the more elaborate genealogical registers one can trace a record of events affecting the royal personage. For example, the register may begin with the marriage of the subject's parents, then continue with the subject's own birth and perhaps conclude with the subject's marriage. The events are displayed in panel form, one above the other. I believe they are meant to be read from the bottom, where the older events are depicted, to the top, where the most recent events appear. Moreover, they should be read alternately from left to right and from right to left in the reading system known as boustrophedon (from the Greek meaning "as the plow ox turns").

Both the order of reading of these registers and their content are highly significant. First, it may seem surprising that a reading system known in Europe in classical Greek times should have been invented independently in the pre-Columbian New World for the display of genealogical information. The fact is that there is a New World precedent for the system among the Mixtec, who were close neighbors of the Zapotec. Living immediately to the north and west, the Mixtec in the 15th and 16th centuries painted genealogical and other records on screen-folded deer hide, and these codices are meant to be read in boustrophedon style. The origins of this Mixtec painted-record tradition remain obscure, but the possibility that Zapotec genealogical registers, carved on stone between A.D. 700 and 900, were meant to be read in alternate directions suggests that the concept is an ancient one in the New World.



RELATIONS BETWEEN MONTE ALBÁN AND TEOTIHUACÁN are reflected in the art of both cities. The mural painting of a Teotihuacán temple facade in the Tetitla district (*a*) is elaborated in a Teotihuacán pot decoration (*b*). A Tetitla-style temple facade appears on Stela No. 1 at Monte Albán (*see illustration on opposite page*). The Zapotec calendric glyph "9 Earthquake" (*c*) appears on the jamb of a tomb entrance in the Zapotec enclave at Teotihuacán; the same element appears on monument No. 3 at San José Mogote. Mural paintings at Teotihuacán (*d*) provide the details of the tassel headdress associated with important travelers from Teotihuacán. These personages evidently impressed the Maya of Guatemala, to judge from a simplified representation of the headdress (*e*) on a bowl from the site of Kaminaljuyú. The same Teotihuacán-style headdress appears on such monuments at Monte Albán as Stela No. 8 (*see illustration on opposite page*) and the Lápida de Bazán (f *and illustration on next page*).

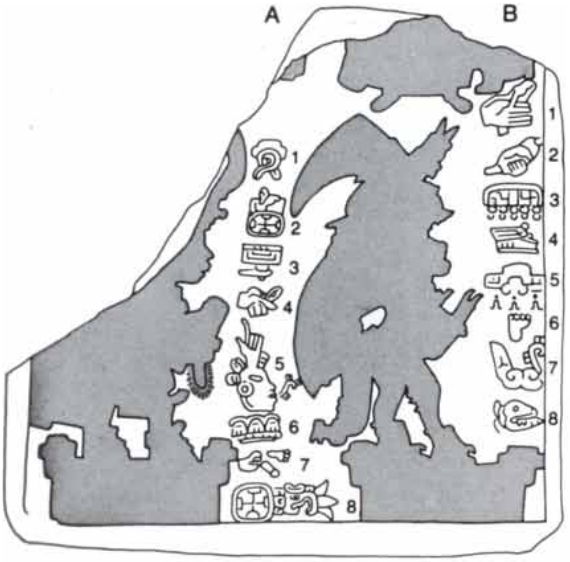
It will be instructive to examine a Zapotec genealogical register in detail. I have selected as an example one that is now preserved in the National Museum of Anthropology in Mexico City. It is said to have come from Zaachila, a valley-floor site that rose to prominence as Monte Albán declined, and it appears to record two generations of a royal family. In its upper panel is a typical wedding scene. A man is seated on a woven mat and a woman is kneeling; each is holding a pottery vessel. The woman's calendric name is "3 Serpent" and the man's is "6 Earthquake." (The serpent glyph is Caso's glyph *M;* the earthquake glyph is his glyph *L.*) Above the couple are the "Jaws of the Sky," flanked by stylized conch shells. Descending from the "Jaws of the Sky" is a personage, perhaps ancestral or perhaps mythical, holding in one hand a strand of beads.

In the lower panel an older couple are seen, seated on hill signs. In my order of reading they are presumably ancestral to either the husband or the wife in the upper panel. The woman's name is "11 Monkey." (The monkey glyph is Caso's glyph *O.*) The man's name, depending on whether or not the two dots behind his back are included with the dot and bar on his knee, is either "6 Flower" or "8 Flower." (The flower glyph is Caso's glyph *D.*)

One striking feature of this register is a series of 13 day signs and numerical coefficients that begins at the top right and runs down the right side of the small stone. They are all calendric glyphs taken from the 260-day ritual calendar, but

they are in an order that makes no calendric sense. Are they perhaps a list of personal names? Supporting such an interpretation is the fact that the series includes the names of the couple shown in the upper panel, "3 Serpent" and "6 Earthquake." I suggest that the vertical series records the names of the ancestors of the husband or of the wife (or of both) in the upper panel.

The vertical series is accompanied at



LÁPIDA DE BAZÁN, a slab of polished travertine, was unearthed in 1936 at Mound X, to the northeast of the Main Plaza at Monte Albán. The figure at the left, "8 Turquoise" (*colored glyphs*), is evidently a visitor from Teotihuacán. The figure at the right, "3 Turquoise," dressed as a jaguar lord, is presumably the ruler, or some high official, of Monte Albán. The two columns of glyphs (A *and* B *on plan at top left*) include no calendric glyphs; it thus seems plausible that their intention is narrative. Teotihuacán is alluded to twice: by a tassel headdress (*A-6*) and by a Teotihuacán-style sandal (*B-4*). Travel is indicated by footprints (*A-7, B-6*) and flowery speech by two scrolls (*A-5, B-7*). Ritual is suggested by an incense burner (*A-8*), divination by a hand holding a single bean (*A-4*). Hand glyphs (*B-1, B-2*) may be verbs. The monument may well commemorate a time when representatives of the two powers met to ratify an agreement.

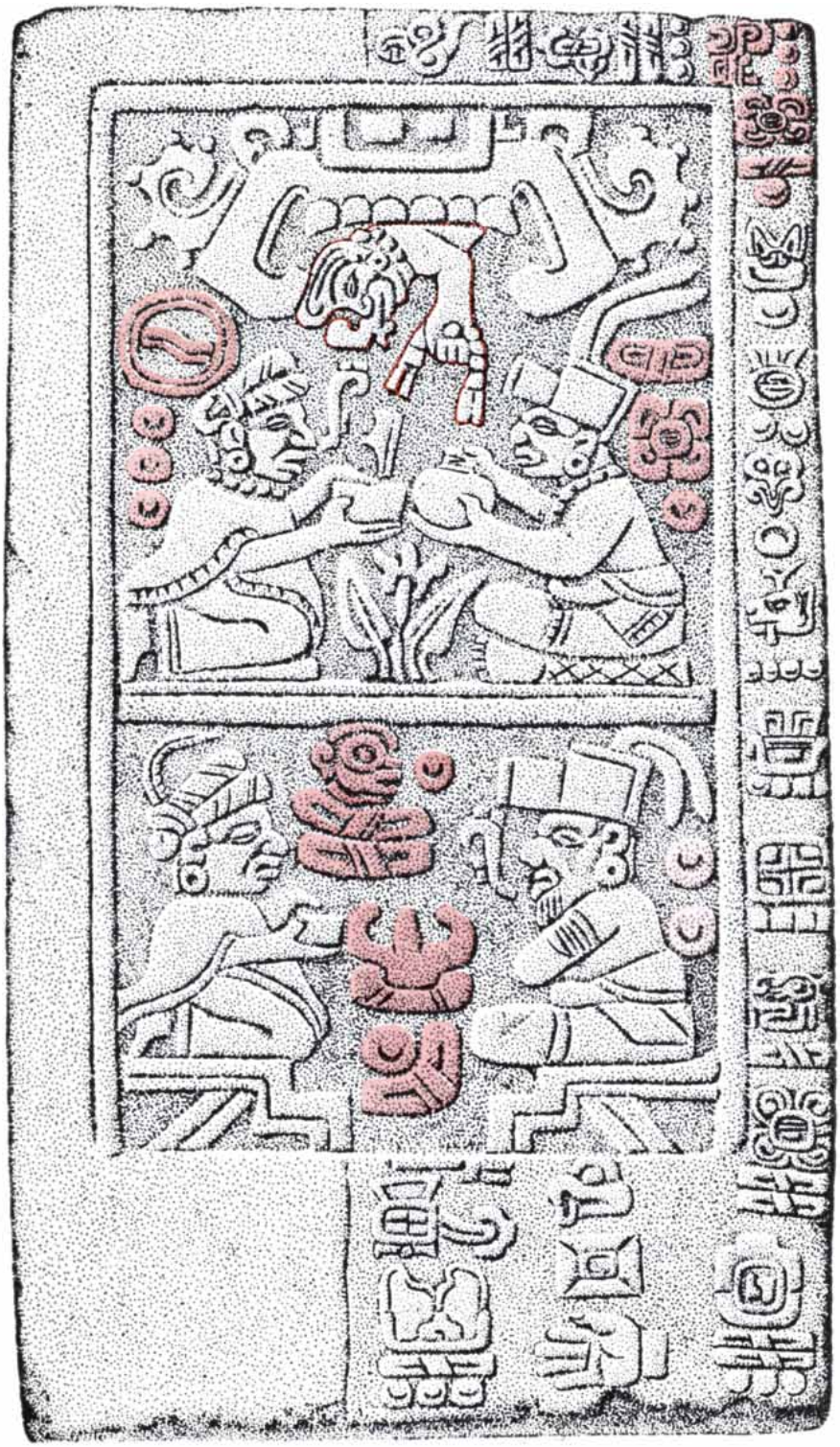
the bottom of the register by two shorter columns of glyphs that are not fully interpretable. One column includes the image of an open right hand, which again may represent a verb of action. The other column must record a date; it includes the calendric expression "8 [followed by Caso's glyph *N*]," above which is a glyph Caso has identified as a year sign. The date may be when the couple in the upper panel were married.

A second example is a famous genealogical register found in a tomb at Noriega, not far from Zaachila. Its inscription occupies three panels. The top and middle panels seem to trace the life of a young noble from birth to later childhood. The bottom panel again bears the "Jaws of the Sky," appearing above a hill sign that is flanked by two reptilian heads. In what may be an ancestral or mythical scene a man named "10 Vessel [?]" and a woman named "9 Serpent" appear on each side of the "Jaws of the Sky."

The middle panel is evidently meant to be read from left to right. Proceeding in that order, one sees at the left a woman, "2 Water," giving birth to a child, "2 Vessel [?]." At the center is a large male figure with a distinctive headdress; he is presenting something to the child. At the right the child, now old enough to sit up, faces a male figure, perhaps its father. If one now reverses the reading order and starts at the right side of the top panel, one again sees the child's mother. She holds a staff similar to the ones, known as "manikin scepters," that appear on contemporaneous Maya monuments. At the center the child, now still older, reappears; its head band is being adjusted by an unidentified adult. At the left appears the man, again possibly the child's father, who was seen before at the right of the middle panel.

Dominating the top panel is another Zapotec iconographic element: a "flying turtle." It bears the name "5 Skull." The turtle's head is similar in appearance to the other reptilian heads in the bottom panel. Historical documents suggest that the Zapotec sometimes visualized the "sacred clouds" from which their rulers were descended as having the appearance of flying turtles. Thus both of the iconographic elements of the Noriega register, the "Jaws of the Sky" and the "flying turtle," are consistent with the concept of a genealogical record.

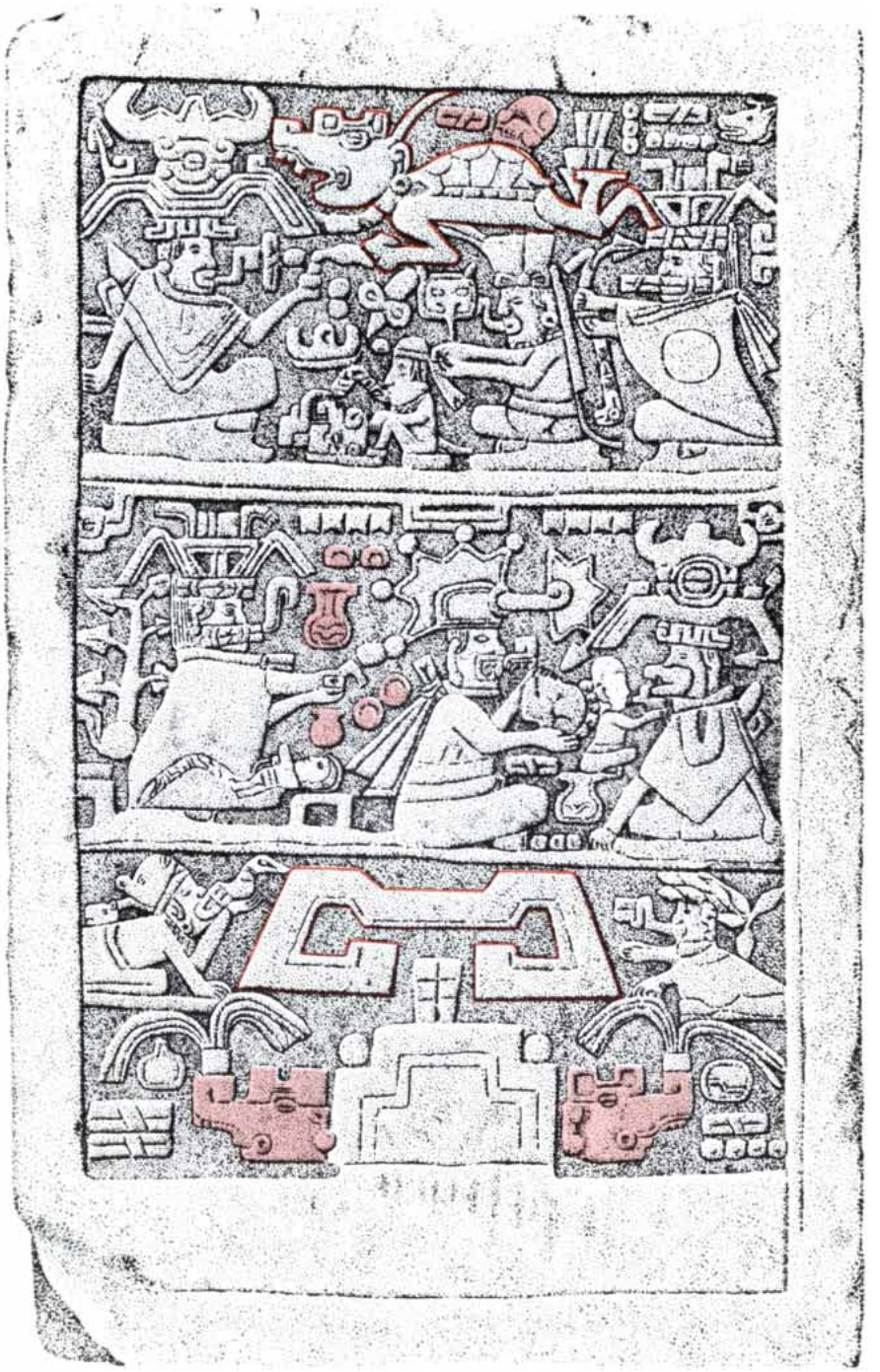
This review of the later Zapotec inscriptions brings my discussion to the point where an overall summary is possible. First, I believe it is clear that all Zapotec inscriptions, early or late, are associated with Zapotec political history. Can evolutionary trends be identified? I believe progress is evident from an early phase, when the "message" of an inscription was conveyed very simply in a mainly pictorial way, to a later



GENEALOGICAL REGISTER from Zaachila, in the Valley of Oaxaca, portrays two generations in a royal family after the decline of Monte Albán. A long inscription occupies three of the four sides of this small monument. The royal couple in the lower panel are "11 Monkey" (*upper colored glyphs*) and "6 [perhaps 8] Flower" (*lower glyphs*) depending on whether the two numeral dots behind the man's back are added to his name glyphs. The upper panel evidently records the marriage of a royal couple. Emerging from the "Jaws of the Sky" (*top*) is a figure (*colored outline*) holding a string of beads. The couple's names (*color*) are "3 Serpent" (*left*) and "6 Earthquake" (*right*). The names also appear in the inscription (*color at top right*).

phase, when more complex glyphic displays served to elaborate the pictorial message.

For example, it was in Period I that the largest number of monuments at Monte Albán, the 300-odd "dancers," were created. The overall impact of this display must have been powerful, but the individual monuments conveyed relatively little information. Far fewer monuments are known from Period II, but some of these 50 or so works carry double rows of glyphs, and the individual monuments convey much more information than any "dancer" monument does. Indeed, many Zapotec glyphs make their first appearance in Period II. Finally, the first subphase of Period III is almost monument-poor: only 15 or so monuments were raised at Monte Albán. The number and variety of the glyphs on these few monuments, however, represent a further substantial increase in the amount of information conveyed.



REGISTER FROM NORIEGA, another Valley of Oaxaca site, includes in its bottom panel the "Jaws of the Sky" (*colored outline*) and two reptilian heads (*color*). In the middle panel, reading from left to right, a woman, "2 Water" (*upper colored glyphs*), gives birth to a child, "2 Vessel" (*lower glyphs*). A male with a headdress is at the center; at the right the child is now old enough to sit up. It faces a male figure, possibly its father. In the top panel, reading from right to left, the child's mother appears again; she holds a "manikin scepter." At the center the child appears again, still older; an unidentified adult adjusts the child's headband. The child faces a man at the far left, again possibly its father (the headdresses are alike). At top center is seen a "flying turtle" (*colored outline*): its head resembles the reptilian heads in the bottom panel. It bears the name "5 Skull" (*colored glyphs*). The image of the turtle, like the "Jaws of the Sky," reinforced the genealogical context of the inscription: the royal descent of a newborn heir.

To recapitulate, early in Zapotec history the common themes of the monuments were scenes of captives and lists of conquered places. This is the kind of propaganda one associates with an emerging state that is fighting to take control over previously autonomous regions and wants to discourage resistance. Once Monte Albán had become a major urban center, the capital of what was unquestionably the most powerful state in the highlands of southern Mexico, its monuments begin to deal with diplomacy. The Lápida de Bazán and the four stelae at the corners of the South Platform reflect peaceful Zapotec dealings with Teotihuacán. With the decline of Monte Albán after Period III and the rise of smaller competitive centers in the Valley of Oaxaca, one of the major concerns of the new Zapotec elite became the affirmation of their royal status.

As far as monumental inscriptions are concerned, that affirmation was achieved by means of the genealogical registers: displays that recorded the ruler's marriage and ancestry and in some instances were even placed in the antechamber of the royal tomb, where the record could be consulted by future generations. Even after the Spanish conquest, as the Lienzo de Guevea demonstrates, the Zapotec people were still greatly concerned with the ancestry of their rulers and with the named landmarks that defined their territory.

We are still a long way from being able to "read" Zapotec writing in the way that Egyptian and even Maya hieroglyphs can be read. Major topics for further study are the lists of places mentioned as important landmarks, the "hand gestures" that may represent verbs of action, the noncalendric glyphs, which appear to be related to political and ritual information, the correlation between the Zapotec and the European calendars, the correspondences between Zapotec writing and the Zapotec spoken language and finally the evolutionary relation between the Zapotec system of writing and the systems of the Mixtec, the Aztec and the Maya. Only when progress has been made in these topics will it be possible to appreciate fully the contribution of this remarkable people to pre-Columbian literacy. And it is a contribution that must be understood in its own terms and not simply in terms of later and better-known systems.

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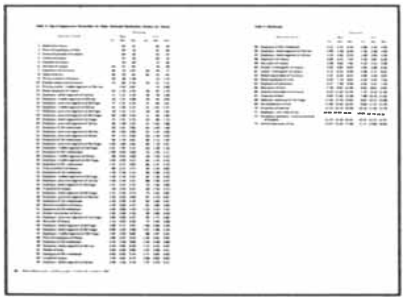
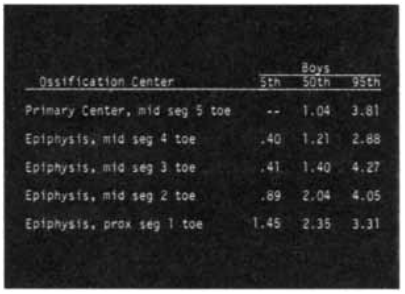


Only when you are in front of the audience does it hit you that this was not a good idea. A better idea would have been to select a part of the table that makes a memorable point and yet contains no more than can be read without optical aid from the slide held in the hand. This calls for retyping within a 2″ x 3″ (or at most a 3″ x 4½″) rectangle, which in itself sets the limit on how much to pack into a single slide. Photograph the typing with KODALITH Ortho Film, Type 3.



Ossification Center	Boys 5th	50th	95th
Primary Center, mid seg 5 toe	--	1.04	3.81
Epiphysis, mid seg 4 toe	.40	1.21	2.88
Epiphysis, mid seg 3 toe	.41	1.40	4.27
Epiphysis, mid seg 2 toe	.89	2.04	4.05
Epiphysis, prox seg 1 toe	1.45	2.35	3.31

Now those who need to know about the ossification of the human toe can see that males reach the 50th percentile for the third toe at age 1.4 years. (The editors and artists of *Scientific American* would probably have brought it out more vividly with a clever graph, but the rest of us work under sterner limitations.) It's in black-and-white, though. Since most photographs seen on a screen are in color, interposition of a black-and-white slide like this can act as a hidden cue to turn off the audience's attention. Watercolor dye applied to your black-and-white slide with a small brush or cotton swab will help.

There are more directly functional uses for added color in diagrams and tables, as this magazine aptly demonstrates. This is beginning to be widely understood. A large number of the questions we get at meetings of professional societies concern nothing more profound than tips and techniques for preparing more eloquent slides. They are asked by folks whose operating budgets don't allow for calling in professionals who do such work. They find it wise to take time from their own professions to learn the details for doing it well.

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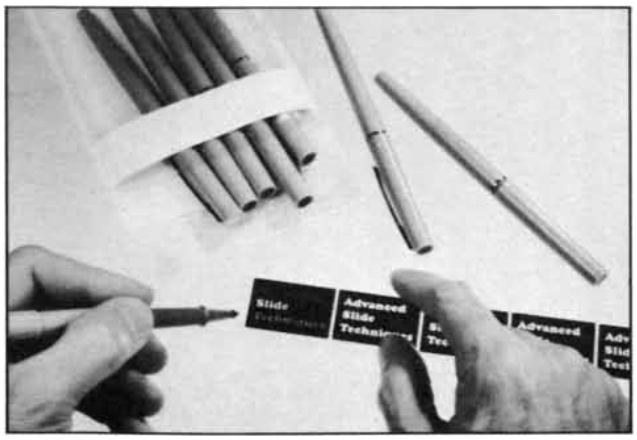

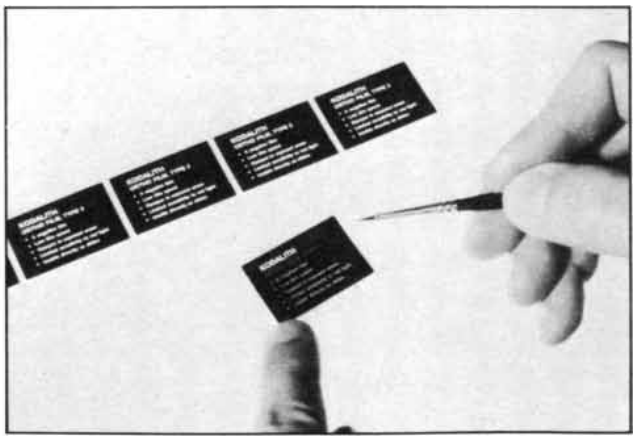

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Projections

In the summer of 1978 the electric-power industry in the 48 contiguous states of the continental U.S. was capable of generating a total of 545,700,000 kilowatts of electricity; the actual peak load for that year was 408,050,000 kilowatts, leaving a "capability margin" of 137,650,000 kilowatts available to provide for scheduled maintenance, emergency outages, system-operating requirements and unforeseen loads. By the summer of 1988, according to the latest 10-year forecast made by industry representatives, it is estimated that the total capability of the industry will be 813,300,000 kilowatts, an increase of 49 percent. The corresponding figure for the anticipated peak load is 655,600,000 kilowatts, and for the capability margin it is 157,700,000 kilowatts.

The combination of energy sources responsible for the total amount of electric power is expected to shift significantly over the decade: in 1988 coal-fired generating units will be up from an actual share of 44.7 percent in 1978 to a projected share of 49.2 percent; oil-fired units will be down from 16.3 percent in 1978 to 12.8 percent; gas-fired units will be down from 13.5 percent in 1978 to 3.4 percent; nuclear units will be up from 12.8 percent in 1978 to 27.3 percent; hydroelectric generators (under adverse conditions of precipitation) will be down from 13.3 percent in 1978 to 7.5 percent, and all other sources will be up from .1 percent in 1978 to .7 percent. (A sum of 100 percent is obtained for both years by deducting a nationwide energy expenditure for pumped-storage systems of .7 percent in 1978 and .9 percent in 1988.)

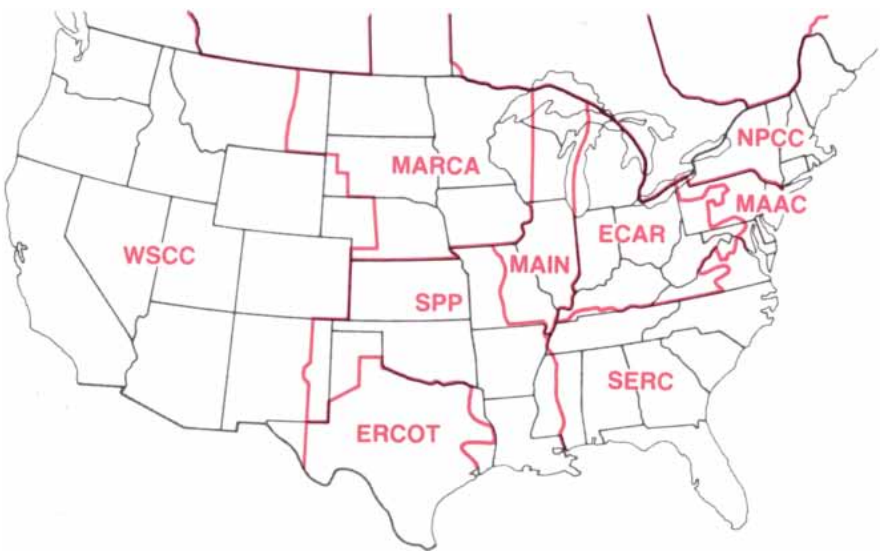
Geographically the breakdown by energy source among the nine regions constituting the National Electric Reliability Council (NERC) varied widely in 1978 and will undoubtedly continue to do so for the rest of the decade. For example, in 1978 coal was the predominant energy source for the generation of electricity in most of the north-central, mid-Atlantic and southeastern states, accounting for the largest share of the output of electric power in the regions served by the Mid-Continent Area Reliability Coordination Agreement (MARCA), the Mid-America Interpool Network (MAIN), the East Central Area Reliability Coordination Agreement (ECAR), the Mid-Atlantic Area Council (MAAC) and the Southeastern Electric Reliability Council (SERC). The greatest reliance on coal was in the ECAR district, where coal burning accounted for 89 percent of the electric power generated in 1978.

The emphasis on coal burning in each of these regions is expected to persist through 1988, although on a percentage basis the share of the total electric-power generation attributable to coal will give way somewhat to the more rapid expansion of nuclear-generated electric power in all but one of the areas. The largest contribution from the nuclear source will come in the regions represented by the MAIN, MAAC and SERC groupings; in each of these areas the nuclear share of electric-power generation is scheduled to increase by 1988 to more than 40 percent.

In the states represented by the Northeast Power Coordinating Council (NPCC) oil burning was the most important source of electric power in 1978, accounting for 49.4 percent of the electric power generated, followed by nuclear-generated power (25.1 percent), hydroelectric-generated power (16.6 percent), coal-generated power (10.5 percent) and gas-generated power (.1 percent). In terms of percentages the dependence of the New England states on oil burning for electric-power generation is projected to decrease by 1988 to 39.9 percent; the rest of the region's electric power will then be supplied by nuclear reactors (36.8 percent), coal-burning units (13.9 percent) and hydroelectric generators (11.9 percent). The use of gas for generating electricity will be terminated in the NPCC states by 1984.

The gradual phasing out of gas as a source of electricity, a nationwide trend that will carry through the decade, will have the largest impact on the state of Texas, most of which is encompassed by the Electric Reliability Council of Texas (ERCOT). In 1978 gas supplied 78.9 percent of the electric power generated in the ERCOT area, with coal (18.6 percent), oil (2.3 percent) and hydroelectric (.2 percent) bringing up the rear. In 1988 the combination of energy sources in the area will be coal, 46.9 percent; gas, 20.5 percent; oil, 16.7 percent; nuclear, 15.7 percent, and hydroelectric, .1 percent. Much the same effect will be seen in the neighboring region of the Southwest Power Pool (SPP), where in 1978 gas accounted for 59.2 percent of the total electric-power generation, with oil (18.7 percent), coal (16.8 percent), hydroelectric (2.8 percent) and nuclear (2.7 percent) making up the remainder. The 1988 projections for the SPP region call for an even greater reliance on coal (55.5 percent), complemented by nuclear (15.9 percent), gas (15.4 percent), oil (11.4 percent), hydroelectric (1.7 percent) and other sources (.3 percent).

The combination of energy sources in the largest geographical division in the country's electric-power network, the Western Systems Coordinating Council (WSCC), will reflect a special set of trends between 1978 and 1988: hydroelectric, down from 46.7 percent to 24.6



NINE REGIONAL DIVISIONS of the National Electric Reliability Council (NERC) are outlined in color on this map of the U.S., adapted from the Edison Electric Institute's *Annual Electric Power Survey* for 1979. The NERC network encompasses essentially all the electric-generating utility systems in the contiguous states of the U.S. and in four adjacent Canadian provinces; data presented in the survey, however, cover only systems in the U.S. The abbreviations stand for East Central Area Reliability Coordination Agreement (*ECAR*), Electric Reliability Council of Texas (*ERCOT*), Mid-Atlantic Area Council (*MAAC*), Mid-America Interpool Network (*MAIN*), Mid-Continent Area Reliability Coordination Agreement (*MARCA*), Northeast Power Coordinating Council (*NPCC*), Southeastern Electric Reliability Council (*SERC*), Southwest Power Pool (*SPP*) and Western Systems Coordinating Council (*WSCC*).

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percent; coal, up from 22.6 percent to 31.5 percent; oil, up from 16.3 percent to 18.1 percent; gas, down from 10.6 percent to 2.2 percent; nuclear, up from 3.3 percent to 20.3 percent; other (mainly geothermal), up from .7 percent to 3.6 percent.

The 10-year forecasts of the electric-power industry, which are contained in the *1979 Annual Electric Power Survey,* a report published late last year by the Edison Electric Institute, are said to be based on "the best information available as of April 1, 1979." The narrowness of the capability margins available in some areas to deal with emergencies and unforeseen loads is presented most strikingly in one of the report's tables, in which the net-capability margin is calculated for the nine NERC districts after planned and forced outages are excluded from the gross margins. In the summer of 1978 the net-capability margin in four of the regions was less than 10 percent; the narrowest net margin of all, in the MAIN area, was a mere 3.6 percent.

Death Certificate

On October 26, 1977, Ali Maow Maalin, a 23-year-old cook in the town of Merka in Somalia, came down with smallpox. He recovered, and with his recovery smallpox died. After a two-year period of active search and surveillance prescribed by the World Health Organization had failed to turn up another case, a WHO commission last October certified that Somalia was free of smallpox. The same finding was made for three other countries in the Horn of Africa (Djibouti, Ethiopia and Kenya, whose last cases had been recorded earlier than Somalia's) and for the region as a whole. The certifications marked the end of smallpox in the last pocket of resistance worldwide. In May the World Health Assembly is expected to declare formally that smallpox has been eradicated from the earth, the first such achievement in the history of medicine.

The eradication is the culmination of a WHO campaign that began in 1967, when smallpox was endemic (an indigenous, ever-present disease) in 33 countries and another 11 countries had "imported" cases. In the Western Hemisphere, Brazil was the only endemic country; the other major reservoirs of the disease were the Indonesian archipelago, a region of Asia extending from what is now Bangladesh through India to Afghanistan, and Africa south of the Sahara. Essentially the campaign was an effort to break the thread of transmission of the disease (which spreads only from person to person), first by mass vaccination programs and later, as the incidence was reduced and techniques were improved, by the strict isolation of patients and the vaccination of any possible contacts (see "The Eradication of Smallpox," by Donald A. Henderson; SCIENTIFIC AMERICAN, October, 1976). The last case was recorded in western and central Africa in 1970, in Brazil in 1971 and in Indonesia in 1972; the Asian reservoir region was clear by the end of 1975. Just when the disease seemed to have been eliminated in eastern Africa, it flared up again in 1977 among nomads and then in Mogadishu, the capital of Somalia. The outbreak peaked in June, when there were 1,388 cases, and finally died only after a determined nationwide drive by a small army of Somalian health workers supported by WHO personnel.

The defeat of the most devastating pestilence in human history is a major triumph of public health and preventive medicine. It had long been clear that vaccination could control smallpox; Edward Jenner himself had predicted when he developed the procedure that "the annihilation of smallpox must be the final result of this practice." The annihilation took a long time, however, and was achieved only by an unprecedented international effort. Now the wheel has come full circle: the WHO believes the small risks attending vaccination outweigh any possible benefits, so that there is no longer any justification for routine vaccination. The very efficacy of Jenner's procedure has outmoded it.

Bad Bits

The computer error has become legendary for its mindless disregard of plausibility and common sense. Most such errors can of course be traced to mistakes made by those who program or operate the computer; now and then, though, the machine itself blunders. Parts fail or malfunction; extraneous signals are introduced into the circuitry; legitimate signals go unrecognized. Even if each component is highly reliable, the computer has so many parts that errors are not infrequent.

One intriguing mode of computer failure was recognized only about two years ago. It is characterized by elusive and evanescent errors, which appear at random and immediately disappear, only to show up again somewhere else. For example, a pattern of bits, or binary digits, is stored in a semiconductor memory; when the pattern is read out again some time later, it is found that a single bit has been altered, changed either from a 0 to a 1 or vice versa. When the memory cell that held the erroneous bit is tested, it works perfectly, but an apparent fault may then appear in some other cell. The transitory defects are called soft failures.

The alteration of a single bit can have grave consequences. If the bit happens to represent stored data, a calculation in progress may reach a wrong answer. If the bit is part of a program, then the sequence of operations to be carried out by the machine can be changed. Again the result may be an incorrect answer, but more often the altered instruction is simply unintelligible and execution of the program comes to a halt.

A clue to the nature of the soft failures is that they are commonly observed only in the newest semiconductor components, those where the circuit elements are crowded onto a "chip" of silicon at the highest possible density. Of necessity the individual transistors and other electronic devices on such a chip are minute, and it turns out that the cause of the errors is closely related to the small size of the circuit elements. The soft failures are brought about by radiation derived from the decay of radioactive nuclei in materials near the chip and from cosmic rays. The radiation does not permanently damage the chip, but it can change the state of a circuit element, thereby altering the stored information.

The densest random-access memories available today will store 64,000 bits on a single chip. (The exact number is 2^{16}, or 65,536, but memory capacity is commonly expressed in units of 2^{10}, or 1,024, bits.) Each bit is represented by the presence or the absence of an electric charge on a small capacitor, which is built into the pattern laid down on the surface of the silicon. By convention a charged capacitor stores a logical 1; a discharged capacitor represents a 0.

A single memory cell on such a chip occupies only about 100 square micrometers. The electric charge that determines the logical state of the cell consists of about 1.5 million free electrons and an equal number of "holes," which are vacancies in the crystal lattice that mark the absence of an electron. Certain specialized semiconductor memories store information even more densely, although they do not provide random access, and so the information cannot be retrieved as quickly. Called charge-coupled devices, these memories can fit as many as 256,000 bits on a single chip (actually 2^{18}, or 262,144, bits). In a charge-coupled device a single bit is represented by only about 50,000 electrons and holes.

When a fast-moving electrically charged particle passes through a solid material, it ionizes atoms along its path. This process is particularly efficient in semiconductors, where the ionization of an atom is equivalent to the creation of a free electron and a hole. A single alpha particle, or high-energy helium nucleus, can give rise to as many as three million electrons and holes in silicon. That is clearly enough to alter the information stored in a high-density random-access memory, where a bit is represented by only half as many charges. Even less ionization could disrupt the operation of a charge-coupled device.

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important cause of soft failures; their source is the package in which the chip itself is encapsulated. The chief emitters of alpha particles are decaying atoms of uranium, thorium and some of their daughter nuclei, traces of which are found in many ceramics and even in plastics. As little as one part per million may give rise to a significant rate of soft failures.

Another ubiquitous source of ionizing radiation is the flux of high-energy particles created in the earth's atmosphere by the solar wind and by cosmic rays. The effects of this radiation on computer performance were recently assessed by James F. Ziegler of the Thomas J. Watson Research Center of the International Business Machines Corporation and William A. Lanford of Yale University. Their evaluation of the problem is published in *Science*. They find that the error rate depends strongly on the design of the semiconductor device and on the nature of the irradiating particles. Muons, for example, have negligible effects on the present generation of random-access memories, but they are the most important cause of soft failures in charge-coupled devices. For all forms of radiation taken together, Ziegler and Lanford estimate that a 64,000-bit random-access memory is subject to about seven soft failures per million hours of operation. For a 256,000-bit charge-coupled device the rate is about 3,000 errors per million hours.

There is probably no simple or direct cure for the problem of radiation-induced soft failures (other than setting a larger minimum size for semiconductor circuit elements). The concentration of alpha emitters in packaging materials might be reduced somewhat, but they cannot be eliminated entirely; shielding is not the answer because it is effective only against some kinds of cosmic rays. There is, however, a strategy for eliminating the effects of the errors. When a "byte" of eight bits is stored in a computer memory, a code made up of a single bit or of two bits can be appended to it. When the information is retrieved, the code is checked against the numerical value of the byte. If a single bit has been altered, the error can be identified and corrected; if two bits have changed, the error can at least be detected. Because soft failures are both rare and random they are not likely to affect more than one bit in a single byte.

Error-correcting codes have been employed for some time in large computers. The introduction of high-density memories susceptible to soft failures may now compel their adoption in small computers as well. Of course, there is an economic penalty to be paid: storing a given amount of information along with an error-correcting code requires a memory of larger capacity. In this regard, however, the high-density memory chips are both the problem and the solution. When semiconductor memories were introduced in the early 1970's, they cost about one cent per bit; the 64,000-bit devices should eventually bring the price down to about .01 cent per bit.

Misplaced Migrants

The reliance of rich countries on workers from poor ones has reached the point where some 20 million people are thought to hold jobs outside their native countries. In the traditional view the flow of emigrants benefits both the sending country (by relieving unemployment and by bringing in money in the form of remittances sent by the migrants to their families) and the receiving one (by plugging holes in the work force). Lately this "brain and brawn drain" has come to be seen on both sides as a mixed blessing, according to a paper ("International Migration: The Search for Work") written for the Worldwatch Institute by Kathleen Newland, a researcher with the institute.

One problem for the sending countries, Newland writes, is that many of their citizens working abroad are skilled professional people such as physicians and engineers, who stay in the country where they received their professional education even though their skills are sorely needed at home. In addition many of the nonprofessional emigrants are skilled at various trades, and their loss creates "serious gaps in the domestic labor market that can lead to bottlenecks in the development process." Emigration from the Philippines, for example, "has created shortages of welders, computer operators, cable splicers and oil-refinery workers, to name only a few." Then there is the question of remittances, which "have become as crucial a part of national [budgets as they have] of household budgets." The problem is that in times of economic stress the sending countries are vulnerable because their citizens working abroad are usually among the first to be laid off, so that the remittances are curtailed.

The receiving countries also tend to find the migrant workers a mixed blessing. On the one hand they are spared the cost of raising, educating and training the foreign workers. On the other "the inadequacies of professional training in rich countries are perpetuated when foreigners can be plugged into the holes left by the educational system." Moreover, foreign workers are an easy target for discrimination and even violence because it is thought they take jobs away from citizens of the receiving country.

In Newland's view "massive labor migration is a symptom of a world economy that is fundamentally askew, an economy in which gross income disparities both within and among countries persist. In the sending countries the chronic need to migrate signals a failure of economic planning, population policy or both. In the receiving countries migration can perpetuate anachronistic economic and social structures and can create a class of subcitizens whose civil liberties, economic security and human rights are tenuous. Long-term solutions to these basic problems of migration depend on a restructuring of economic relations so that people can earn a decent living in their home countries."

Codebreaker

An interesting exception has been found to the generalization that all living systems have the same "dictionary" for translating into proteins the genetic code embodied in DNA. The hypothesis of a universal genetic code became widely accepted after investigations of translation systems ranging from the one for the protein capsule of the tobacco mosaic virus to the one for human hemoglobin. It was assumed that the genetic code was frozen early in evolution because any change in it would have created a sort of genetic Babel.

Discrepancies in the genetic-code dictionary have now been revealed by investigations of the genetic system of the mitochondrion, the organelle of the living cell whose enzymes engineer the reactions of biological oxidation. The instructions for synthesizing these mitochondrial proteins are coded in a small circular molecule of DNA that is within the mitochondrion and therefore separate from the DNA embodying the bulk of the cell's genetic message.

A genetic-code dictionary has in effect two columns: the first column lists the 64 codons, or "words," that can be represented in the chain of nucleotides that comprises DNA; the second column lists the 20 words that represent the chain of amino acids that comprises a protein. Sixty-one of the DNA codons, each three "letters" long, specify one amino acid. In most instances several different codons can specify the same amino acid. Three of the 64 codons serve as "punctuation," telling the protein-synthesizing machinery to stop. As the codons in the first column of the genetic-code dictionary are usually written, they are formed from the letters *U, C, A* and *G,* which respectively stand for the nitrogenous bases uracil, cytosine, adenine and guanine in RNA, the chain of nucleotides into which the DNA message must first be transcribed before it can be translated into protein.

The universality of the genetic-code dictionary can be tested by comparing the sequence of codons in a particular length of DNA with the sequence of amino acids in the protein the organism constructs from the DNA message. This has now been done in a number of laboratories for the DNA and the corresponding proteins found in the mitochondria of yeast, cattle and human be-

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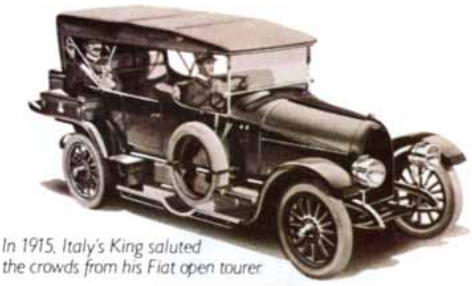

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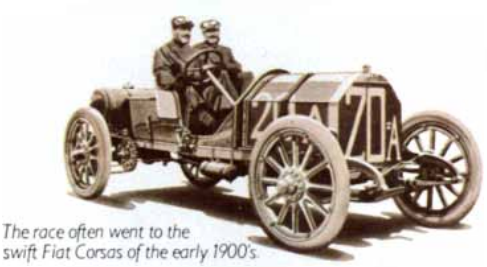

The race often went to the swift Fiat Corsas of the early 1900's.

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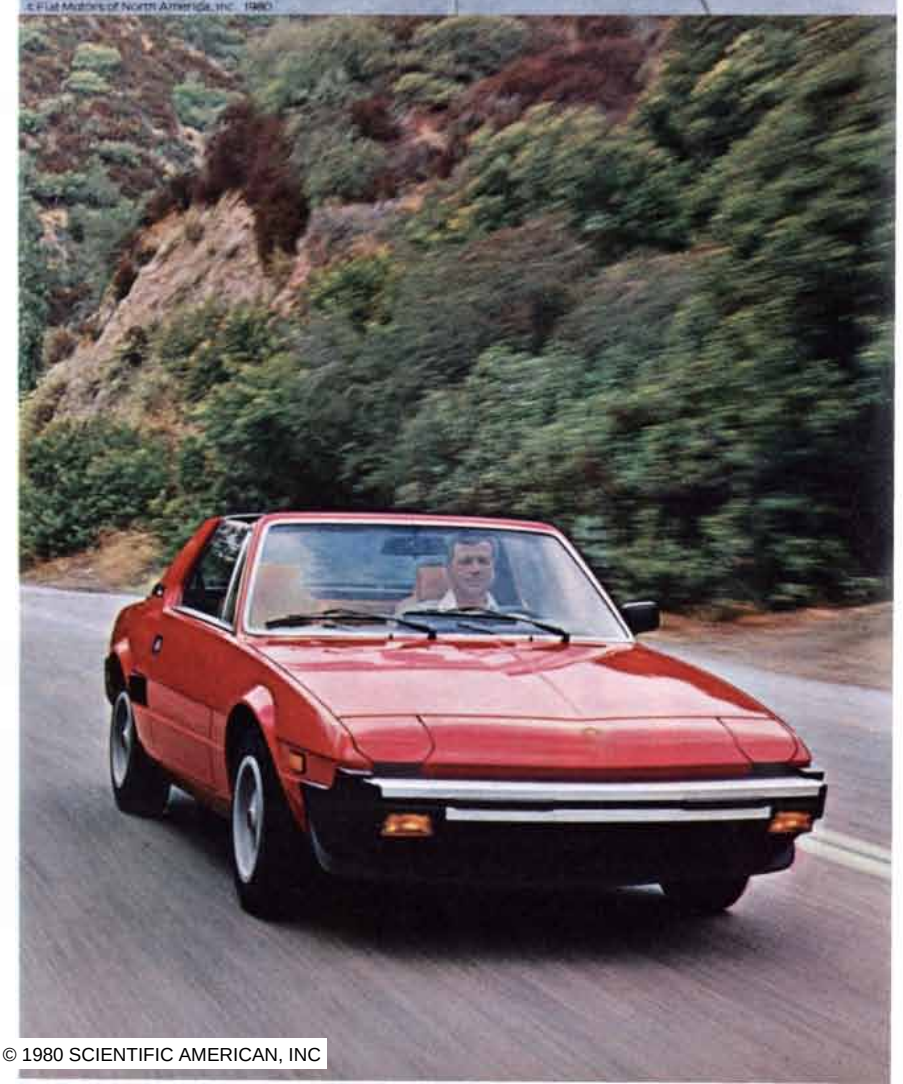
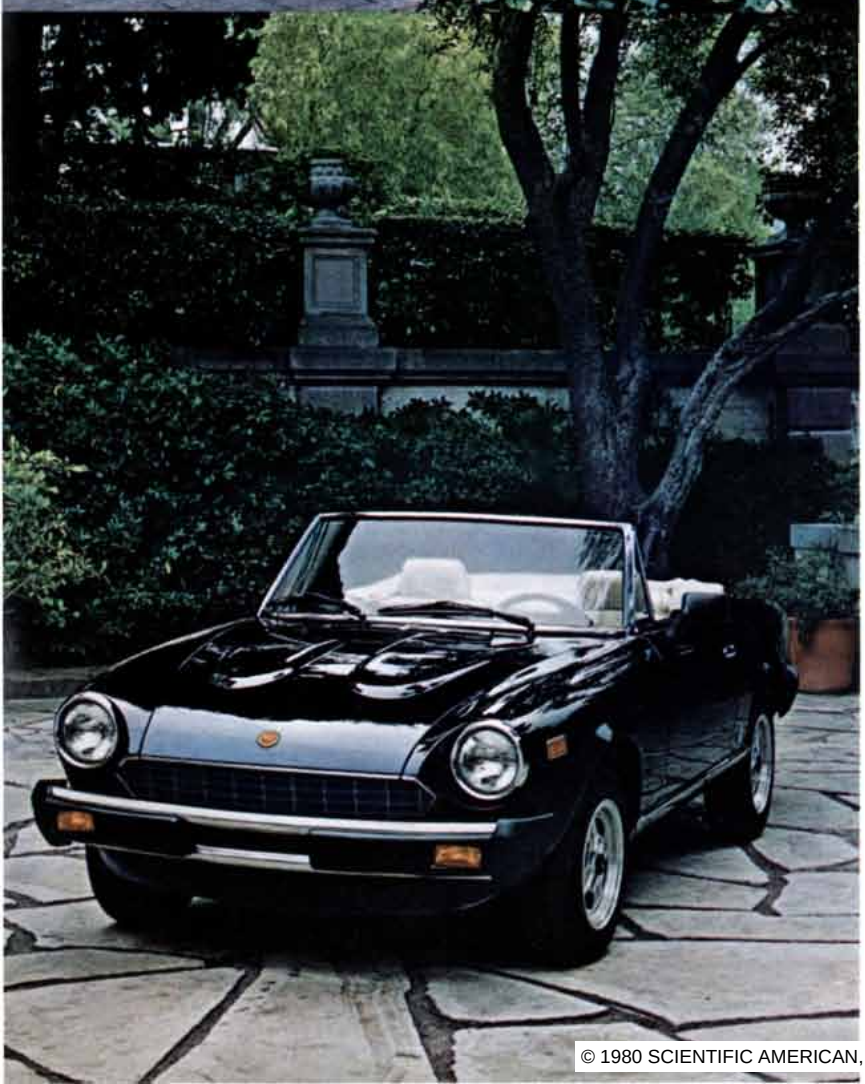
THE FIAT X1/9. PERFORMANCE IN THE EUROPEAN TRADITION.





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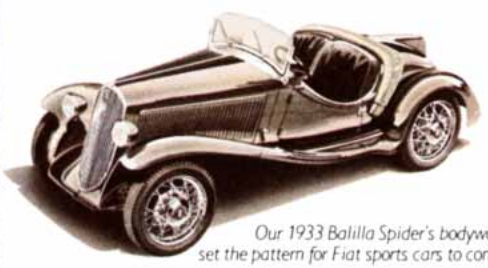

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ings. The techniques for establishing the amino acid sequences of proteins go back three decades. Efficient techniques for establishing the base sequence in DNA are more recent. The basic techniques were developed by Frederick Sanger's group at the Medical Research Council Laboratory of Molecular Biology at Cambridge in England.

In order to get enough pure DNA to study one can splice a selected strand into the DNA of the bacterium *Escherichia coli*. The bacterial cells then make multiple copies of the inserted DNA as they divide and redivide. When the desired DNA is extracted and purified, it is in the normal form of a double helix: two twisted chains each carrying the genetic message. Either chain can be isolated to serve as a template for the synthesis of a complementary chain in laboratory glassware.

In the Sanger technique the copying is done in quadruplicate with slight variations in the supply of bases needed to form the copies. Each batch is "doped" with a radioactively labeled base of a different type: one that stops the synthesis of the new DNA chain at sites containing an *A,* another that stops the chain at sites containing a *G* and so on. The stopping occurs statistically, so that chains of all possible lengths are produced, but each fragment ends with a known base determined by the dopant. On being subjected to separation on four separate strips of electrophoretic gel the fragments become distributed according to their length. The termination points reveal themselves in an autoradiogram: a photographic emulsion that records the position of the radioactively labeled bases. By correlating all the termination points on the separate strips one can assign a base to each site and thereby determine the complete sequence of codons. When the codon sequences of the mitochondrial DNA are compared with the amino acid sequences of the corresponding mitochondrial protein, the genetic code of the mitochondrial DNA can be deduced.

In a recent issue of *Nature* three of Sanger's colleagues, B. G. Barrell, A. T. Bankier and J. Drouin, report that the genetic code of human mitochondria differs in at least two respects from the code previously thought to be universal. The triplet *UGA,* normally one of the three termination codons, is translated by mitochondria as the codon for the amino acid tryptophan. The triplet *AUA,* normally the codon for the amino acid isoleucine, serves as the codon for the amino acid methionine.

The deviations found in the genetic code of mitochondria would seem to lend support to the hypothesis that mitochondria were originally independent organisms that entered into a symbiotic relation with a host cell of a different kind. "If the endosymbiotic theory is correct," Barrell and his colleagues observe, "the different genetic code may represent a 'frozen,' more primitive code, for it is unlikely that once mitochondria became essential to their 'host' the code would [have been] able to change."

Force v. Guile

In the past year computer programs have defeated the best human players at backgammon and blitz chess (in which each side has only five minutes for the entire game). How are the automatons faring at other games, such as Othello, 4-by-4-by-4 three-dimensional ticktacktoe, checkers, go, bridge and matching pennies? Because of their high speed and capacious memory computers have an edge over people when it comes to investigating an unwieldy number of game possibilities. For example, the fastest chess-playing program, Belle, developed by Ken Thompson and Joe Condon of Bell Laboratories, looks at 5,000 positions per second and is being upgraded to look at 15,000. The strength of Belle's play is not as awesome as these numbers suggest because most of the time it is pursuing foolish continuations that a human chess master would never even begin to explore. Moreover, to make a good move the computer must evaluate the strength of the positions it investigates, but there are no simple algorithms for such evaluations, so that Belle sometimes makes inferior moves.

In games where algorithms exist for reliably evaluating a position or where the computer can follow a tree diagram of possibilities through to the end, human opponents are at a considerable disadvantage unless the game is so simple (like ticktacktoe) that they too can see ahead to the end. Computer programs are particularly good at Othello (also known as reversi), in which two contestants take turns putting stones on an 8-by-8 board. When one player's stones surround those of the other, they become his own. The winner is the player who fills the entire board with his stones.

Positional judgment is required only in the earliest stages of Othello. After a few moves the computer is able by brute calculation to follow the tree diagram far enough to choose a winning line of play. The Othello program at Carnegie-Mellon University has never lost to a human player. Applied mathematicians at Carnegie-Mellon are convinced it can be proved that the game can always be won by the second player, but they have not yet found a complete proof. Computer programs are also strong at three-dimensional ticktacktoe on a 4-by-4-by-4 board, which Oren Patashnik of Bell Laboratories has proved can always be won by the first player to make a move.

Although the strength of computers clearly lies in brute calculation, it is not obvious how best to tap this strength in more complex games such as checkers. The possible continuations are so numerous in checkers that the fastest computers could not come close to following the tree diagram to the end, as they do in Othello. To deal with the complexity of checkers two competing programming philosophies have emerged: the exhaustive approach of looking at all possible continuations to a certain depth and the restrictive approach of looking at a few continuations to a great depth. The restrictive search mirrors what the best human players do, but it requires the computer to have extensive positional knowledge so that it can intelligently choose the few moves it will investigate deeply.

The best restrictive-search checkers program was designed in the 1950's by Arthur L. Samuel, who is now at Stanford University. The program, which includes a list of important properties of checkers positions, analyzes games between human masters and on the basis of the outcome decides for itself what strategies succeed and what kinds of positions are the strongest ones. Then in its own games it makes use of what it has learned from the experts.

Samuel's learning program was the best checkers program in the world until 1977, when it was defeated in two games by the program Paaslow, developed by Eric C. Jensen and Tom R. Truscott of Duke University. Paaslow, which is probably stronger than all but the top 10 human players, is an exhaustive-search program. Investigating about a million positions every two minutes, it typically looks ahead seven moves in the middle game and 10 moves in the end game. The remarkable thing about the program is how little checkers strategy is built into it. About all Paaslow knows is that it is good to win material, good to make kings and good to keep men in the back rank to prevent the opponent from making kings. Nevertheless, its ability to explore all possible continuations from a given position for at least seven moves enables it to beat restrictive-search programs that by their nature incorporate much more checkers strategy.

Go, a surround-and-capture game in which two sides stake out territory on a huge 19-by-19 board with black and white stones, is one game that seems to be too complex to yield to exhaustive-search techniques. In go about 10^{700} unique games are possible, as opposed to only about 10^{120} unique games in chess. A typical game of go lasts for 200 moves, with an average of 250 possibilities per position. For a program to look ahead exhaustively for only three moves it would have to investigate eight million positions, which it cannot do. As a result the best program, designed by Walter Reitman and Bruce Wilcox of the University of Michigan, is a restrictive-search one that tries to mimic the

thought processes of a human go master. The program breaks down the board into units and relations that correspond to what is known about how a go master perceptually represents the board in his mind. Although the program is the best one, it plays only slightly above the novice level, apparently because it is the result not of an effort to develop a master-strength program but of artificial-intelligence work to simulate human thinking.

In bridge the best programs, which are available in microcomputers sold in department stores, are no match for most of the 200,000 people who compete in tournaments sanctioned by the American Contract Bridge League. Bridge has two distinct phases: the bidding phase, in which a player and his partner exchange information about their hands as they compete with their opponents for the right to declare, or play, the hand, and the declaring phase, in which the cards are actually played. The low level of computer declarer play seems to be due not to any novel programming problems but to lack of work in this area.

Computer experts believe they could easily develop a program that would outclass most human competitors at declarer play. Although declarer play involves some degree of psychological deception, such as "false carding" (making an unnatural or even an objectively inferior play in order to mislead the opposition), a computer could probably more than make up for what it lacks as a psychologist by what it gains as a powerful precision calculator. Even as psychologists computers are bound to get better. Hans Berliner of Carnegie-Mellon is designing a mechanism by which his world-class backgammon program will develop a profile of an opponent's overall playing style so that it can second-guess his moves and play accordingly. The same kind of mechanism could be incorporated in a bridge program.

In addition to being good at games requiring brute calculation, computers are good at those requiring totally random play. In the simple game of matching pennies, where a player tries to guess his opponent's secret choice of heads or tails, the Sequence Extrapolating Robot (SEER) developed by D. W. Hagelbarger of Bell Laboratories wins from 55 to 60 percent of the time against all human comers. The machine makes its choices totally at random because such a strategy has been proved to be the best one. It seems impossible for people to play completely at random, and so the machine has an edge. Moreover, in the course of the game the machine spends much time analyzing its human opponent's play. If SEER detects a deliberate or unconscious pattern in the opponent's choices, such as heads on the prime-numbered rounds and tails on the remaining ones, it can do even better by abandoning its random strategy and taking advantage of that pattern.

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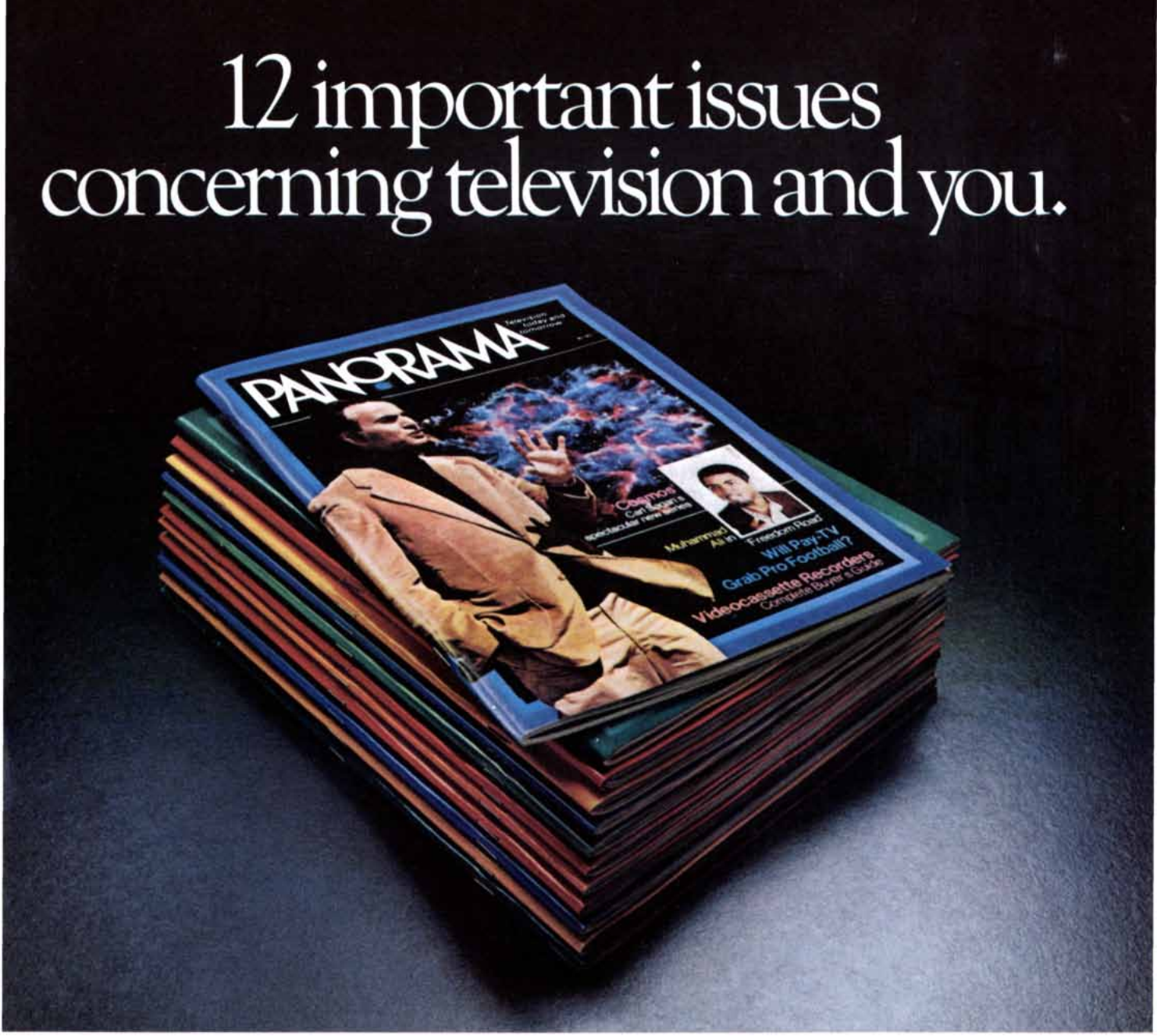

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The Einstein X-Ray Observatory

This satellite, carrying an X-ray telescope of unprecedented size and sensitivity, has been aloft for more than a year. It has yielded dramatic new views of high-energy phenomena in the universe

by Riccardo Giacconi

The launching in November, 1978, of *HEAO-2,* the second high-energy astronomical observatory, has provided astronomers for the first time with a telescope whose sensitivity to X rays matches the sensitivity of instruments operating in the optical and radio regions of the spectrum. *HEAO-2,* also known as the Einstein Observatory, carries a 58-centimeter X-ray telescope that has succeeded in recording at X-ray wavelengths every major class of astronomical objects whose optical and radio emission can be detected by the largest ground-based telescopes. This instrument represents as great an advance in sensitivity over the early X-ray detectors carried above the atmosphere by rockets in 1962 as the 200-inch Hale telescope on Palomar Mountain represents over Galileo's telescope of 1610. In both cases the increase in sensitivity has been roughly a millionfold.

Every day, from an orbit some 500 kilometers above the earth's surface, the Einstein Observatory records the X-ray emission from 10 to 12 regions of the sky selected by the mission team and relays the observations to large radio dishes operated in different parts of the world by the National Aeronautics and Space Administration. Ultimately all the data are transmitted to the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory in Cambridge, Mass., which played a principal role in developing the Einstein Observatory and schedules its daily operations. The Center for Astrophysics group has made the observatory's services available to guest observers in a score of countries. The observatory's X-ray telescope can be pointed with an accuracy of one minute of arc and provides an X-ray resolution of about four seconds of arc, which compares favorably with the resolution of ground-based optical telescopes under average seeing conditions.

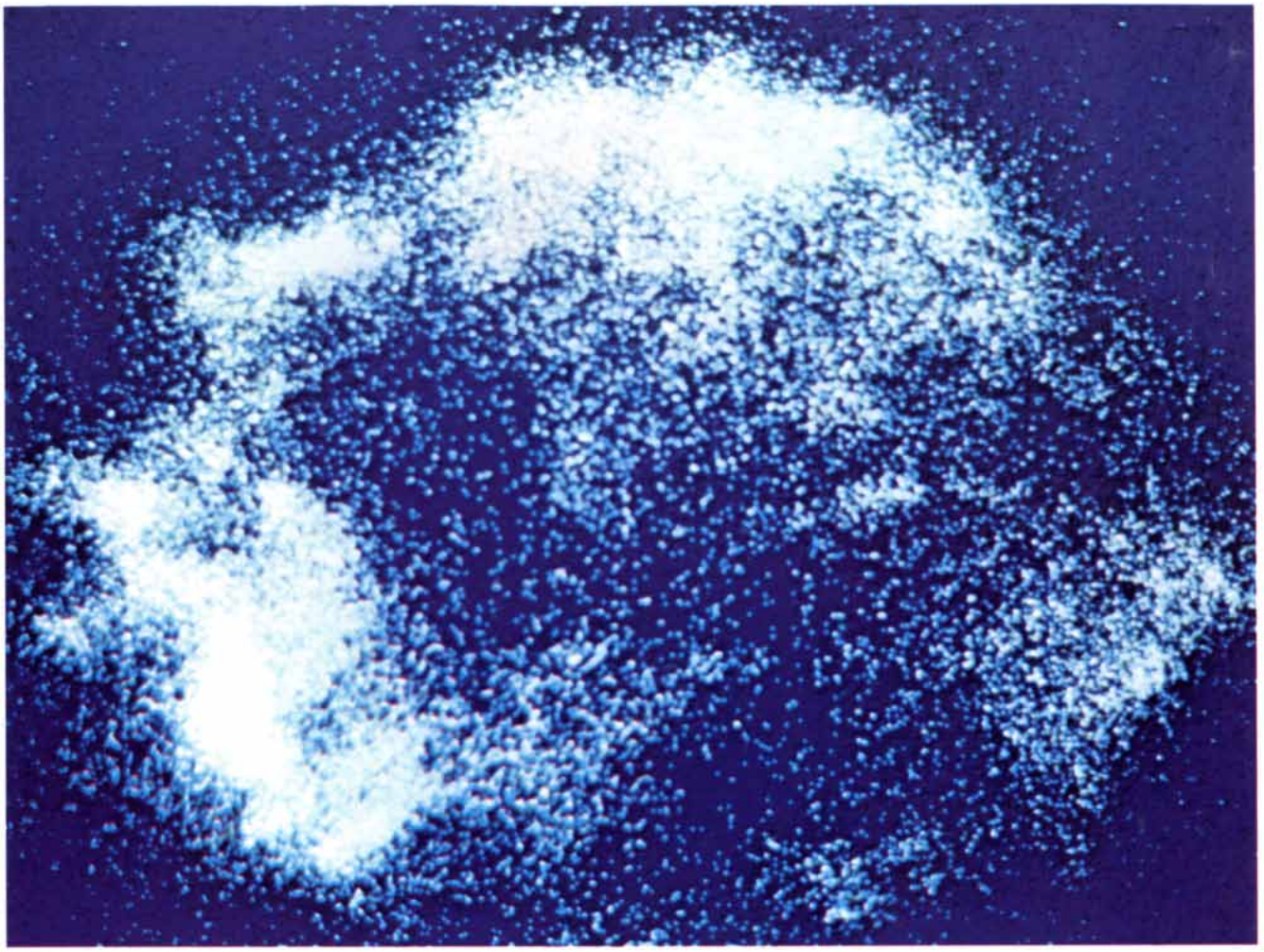
During its brief but busy existence the Einstein Observatory has examined more than 3,000 celestial fields. In each field at least one X-ray source has been recorded, and the great majority of the sources were previously unknown. The wealth of new information being gathered about the X-ray sky will keep astronomers occupied for years to come. The first results are now beginning to appear in the scientific literature.

It would be virtually impossible to summarize the investigations in all their rich variety, and so I shall limit myself to some of the highlights. The Einstein Observatory has disclosed, for example, that normal stars emit far more X-radiation than had been predicted. It has greatly increased the known number of binary systems in which mass is being transferred from a large star to a small ultradense companion, either a neutron star or a black hole. Where previous X-ray satellites had been able to detect only a handful of X-ray sources in galaxies other than our own, the Einstein Observatory X-ray telescope has uncovered more than 80 X-ray sources in one galaxy alone: the Great Nebula in Andromeda (Messier 31, or M31). When the instrument has been directed at clusters of galaxies, it has yielded surprises in the way X-ray-emitting gas is distributed in the space between the galaxies. At one extreme the gas is distributed more or less randomly, in clumps; at the other it is concentrated near the center of the cluster and falls off smoothly in all directions. The gas distribution as revealed by the X rays therefore provides a way to classify clusters that was not possible with observations at other wavelengths. The Einstein Observatory has also recorded X-ray emissions from the most distant of the known quasars, the starlike objects whose enormous red shifts signify they are receding at up to 90 percent of the speed of light. Indeed, the evidence from the observatory suggests that most if not all of the X-ray background radiation arises not from diffuse hot gas, as had been proposed, but from quasars too distant to be recorded individually.

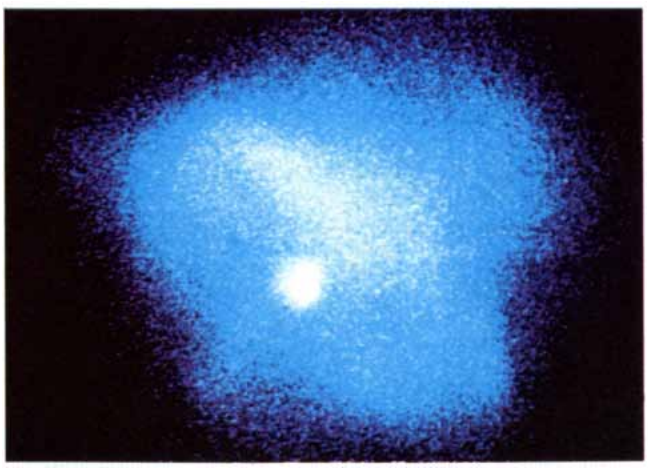
The Dynamic New Universe

Many of the most remarkable discoveries about the universe in the past few decades have resulted from observations of radiation not visible to the eye. Radio telescopes first revealed the existence of quasars and of the universal background radiation at microwave wavelengths. The latter radiation provides the most convincing evidence for the big-bang theory of the origin of the universe apart from the recession of the galaxies. Radio observations also led to the discovery of pulsars, thought to be rapidly spinning neutron stars. Such objects had been theoretically predicted as the end point of stellar evolution for stars of medium mass. With the aid of infrared detectors mounted on optical telescopes astronomers have recorded the emission of objects at the center of our galaxy, which is totally shrouded by dust at visible wavelengths. With the advent of rockets and artificial satellites instruments have been carried aloft to record the emissions of celestial objects at ultraviolet and X-ray wavelengths, which would be absorbed by the earth's atmosphere.

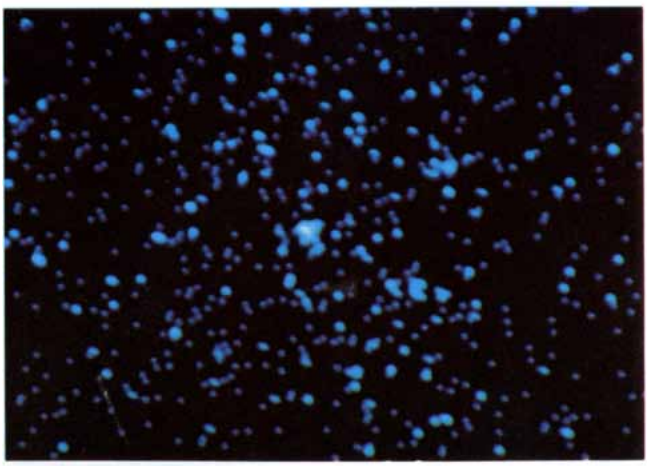
Even astronomers were slow to appreciate that important information about the universe might be contained in wavelengths invisible to the eye, although they were fully aware that natural physical processes give rise to characteristic radiations shorter and longer than visible light by factors of millions. Radiation in the visible and infrared range arises from changes in the energy state of atoms and molecules that involve only the most weakly bound electrons. Such radiations carry most of the energy emitted by bodies at temperatures of a few thousand degrees, such as the filament of a light bulb or the surface of the sun. Changes of energy state involving more tightly bound electrons give rise to increasingly energetic and shorter-wavelength radiation from ultraviolet radiation to X rays. Substances heated to millions of degrees emit most of their energy in the form of X rays and only a negligible fraction at visible wavelengths. Gamma rays, the wavelengths of which are still shorter than those of X rays, are generated by physical processes that involve changes in the



SUPERNOVA REMNANT in the constellation Cassiopeia, Cas A, was imaged at high resolution with the X-ray telescope in the High Energy Astronomical Observatory 2 (*HEAO-2*), also known as the Einstein Observatory. The telescope's resolution of four seconds of arc is 1,000 times higher than the resolution of the X-ray detectors used previously; the Einstein Observatory instrument is also 1,000 times more sensitive. Cas A measures 5.5 minutes of arc across. The image confirms that Cas A does not contain a pulsar, a rapidly rotating neutron star of the type found in other supernova remnants. Pulsars are strong X-ray emitters (*see illustration at left below*).



PULSAR IN THE CRAB NEBULA, part of the remnant of a supernova described by Chinese observers in A.D. 1054, made the bright central spot in this image recorded by the Einstein Observatory X-ray telescope. The extended nebulosity around the pulsar is about two arc minutes in its longest dimension. The picture is at the same scale as the image of Cas A at the top of the page. Unless otherwise indicated the images in this article were supplied by the author's group at the Center for Astrophysics of the Harvard College Observatory and the Smithsonian Astrophysical Observatory in Cambridge, Mass.



MOST DISTANT QUASAR KNOWN, OQ 172, was readily imaged by the X-ray telescope. About 60 photons from the quasar made the central cluster of dots. According to current theory, the photons were emitted by the quasar some 15 billion years ago. Surrounding the dots are background events. OQ 172 has a red shift, designated Z, of 3.53. This means that the wavelength of the electromagnetic radiation emitted by the object is lengthened by a factor of 3.53, the largest red shift known. This image was prepared from Einstein Observatory data by workers in the Astrophysical Laboratory of Columbia University.

energy state of atomic nuclei. At the opposite end of the spectrum wavelengths extending from the infrared region through the microwave region to the longest radio wavelengths are produced when the trajectories of energetic free electrons are deflected by magnetic fields or when individual atoms or molecules "flip" from a higher energy state to a lower one.

The consequence of observing the universe through these various spectral "windows" in the past quarter century has been a profound revolution in astronomy. It is now recognized that in the universe at large violent processes are the norm rather than the exception in the evolution of stars and galaxies. The new view is in sharp contrast to the one that had prevailed earlier. In that view the universe was filled with majestically rotating galaxies slowly evolving over billions of years at the measured pace of the nuclear burning processes in the core of stars.

To cite only one example of how this view has changed, the study of supernovas has shown that although a star radiates only a few percent of its total rest-mass energy in the course of its evolution, at the end of its evolution it can liberate most of the remaining energy within a few seconds of an abrupt gravitational collapse. Many of the heavy elements found in the universe and in the solar system (including the metallic elements in our own bodies) must have been created by nucleosynthesis in the seconds preceding such a collapse. The heavy elements are part of the outer shell that is violently blown into space by the dying star and dispersed into the interstellar medium. Heated to high temperatures by these ejecta, the gases of the interstellar medium copiously emit X rays, and so does the collapsed stellar remnant left behind: a pulsar. Whenever such an explosive event occurs, gases are heated to very high temperatures and electrons and protons are usually accelerated to high energies. Most of the radiation emitted by gases heated to 10 million to 100 million degrees Kelvin lies in the X-ray region of the spectrum. High-energy particles emit X rays by interaction with magnetic fields or with photons: the quanta of electromagnetic radiation.

In summary, high-energy events are dominant in the dynamics and evolution of the universe. When such events take place, X rays are emitted. Therefore in order to learn about dynamic and explosive events in the universe the astronomer must learn how to observe X rays.

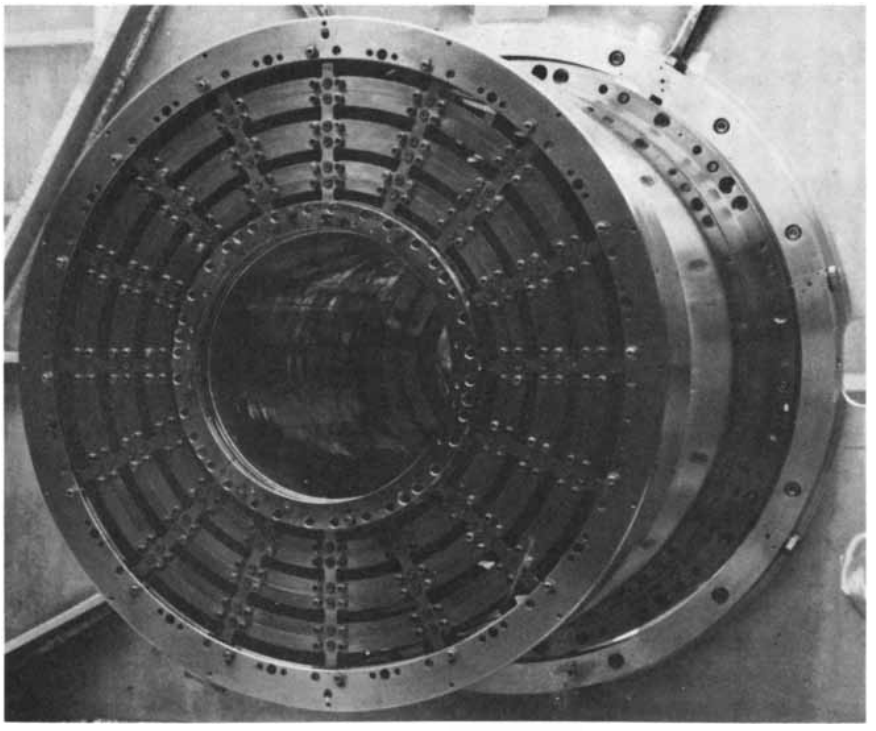
History of X-Ray Astronomy

X-ray astronomy is concerned with photons whose energies fall in the range between 100 and 100,000 electron volts. (The energy of photons of light is two or three electron volts.) Since X-ray photons are absorbed by the atmosphere, X-ray astronomy had to await the development of rocket engines capable of lifting instruments above the atmosphere. When the necessary vehicles were available, attention was at first directed to the sun. Solar X rays were detected in 1948 with a rocket-borne instrument by T. Robert Burnright. Subsequently Herbert Friedman and his colleagues at the Naval Research Laboratory used rockets to monitor the sun's X-ray output over an entire 11-year sunspot cycle. Friedman's group tried to detect X-ray emission from stars other than the sun but failed. The failure was not unexpected: the sun was found to emit only a millionth part of its total energy in the form of X rays. If the rate of X-ray emission had been roughly the same for all stars, the X-ray flux above the earth's atmosphere would have been too weak for detection with the instruments then available.

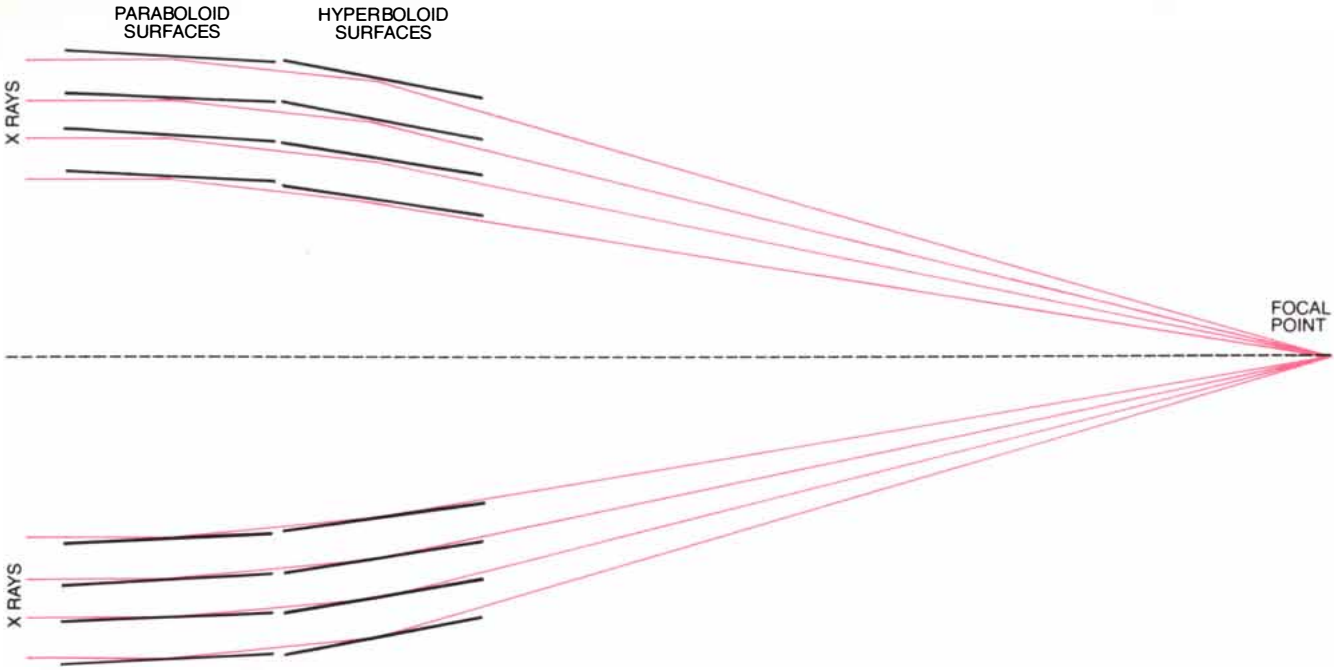
Nevertheless, there was a growing awareness that X-ray observations could provide a new and potentially rewarding window on the universe. Several groups therefore sought to improve the existing X-ray detectors. Our group at American Science & Engineering, Inc., which included Herbert Gursky and Francis R. Paolini, succeeded by 1962 in developing a detector with a hundredfold greater sensitivity as a result of a research program I had initiated in 1959 following a suggestion by Bruno Rossi of the Massachusetts Institute of Technology. After two unsuccessful rocket flights with the new instrument we were fortunate enough to discover in June, 1962, the first source of X-radiation outside the solar system, a star in the constellation Scorpio that we named Sco X-1.

In retrospect we can see that nature was kind to us. Although the pessimistic predictions about the flux of X rays emitted by sunlike stars appeared to hold quite true, we had discovered the first of a new class of stellar systems in which the X-ray emission exceeded the emission of visible light by a factor of 1,000. In succeeding years rocket flights by many groups, including those at the Naval Research Laboratory and the Lockheed Aircraft Corporation and our own group at American Science & Engineering, confirmed our initial results, increased the sample of galactic X-ray sources to about 30 and identified the first extragalactic X-ray sources: M87, a giant elliptical galaxy that is also a powerful radio source, and 3C 273, earlier recognized as the first quasar. In spite of these early successes, however, rocket-borne instruments could not study the X-ray sources in sufficient detail to provide clues to the physical processes responsible for their powerful emissions.

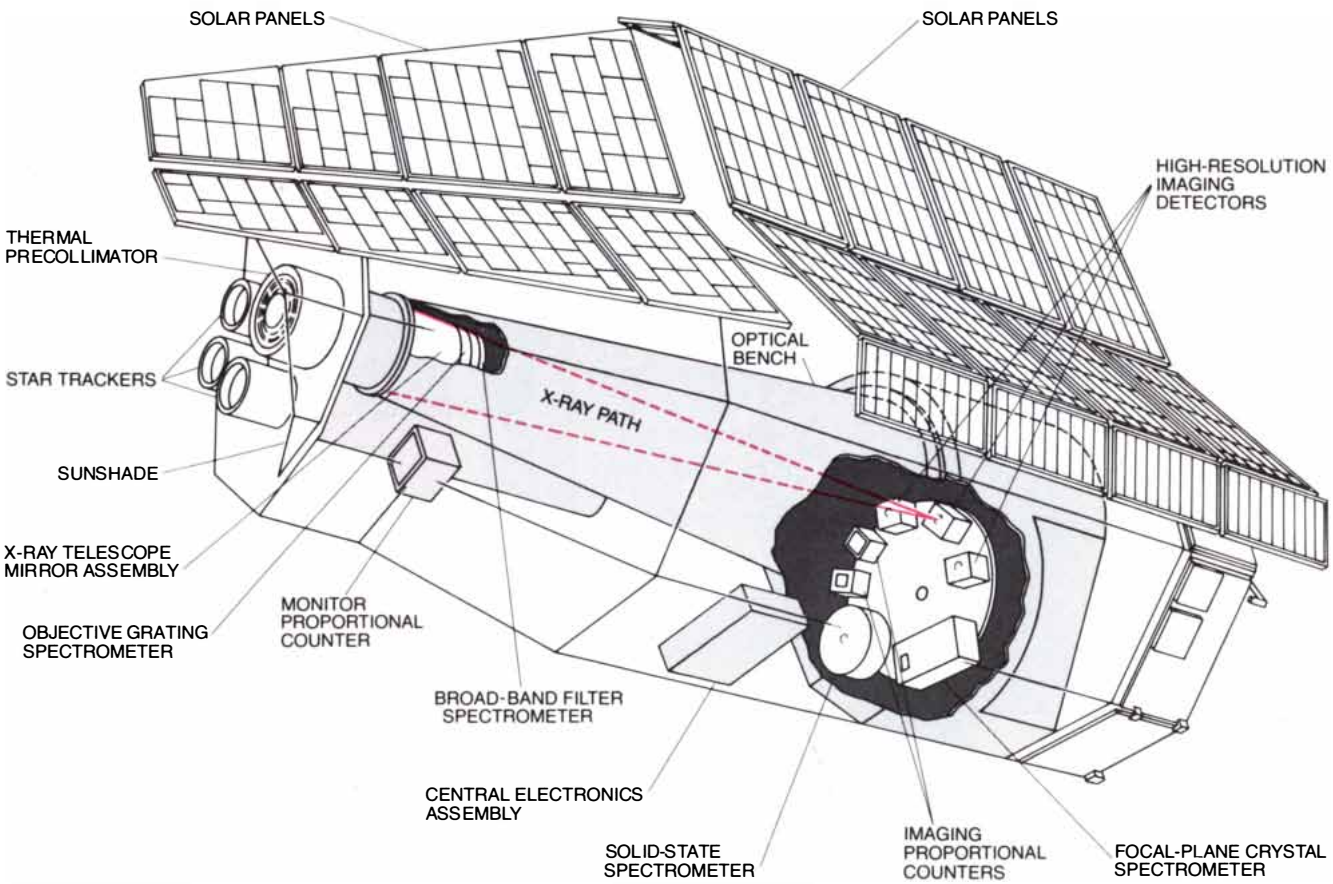
A solution to the problem had to await the next major step in instrumentation, which was taken with the launching in 1970 of *Uhuru,* the first satellite



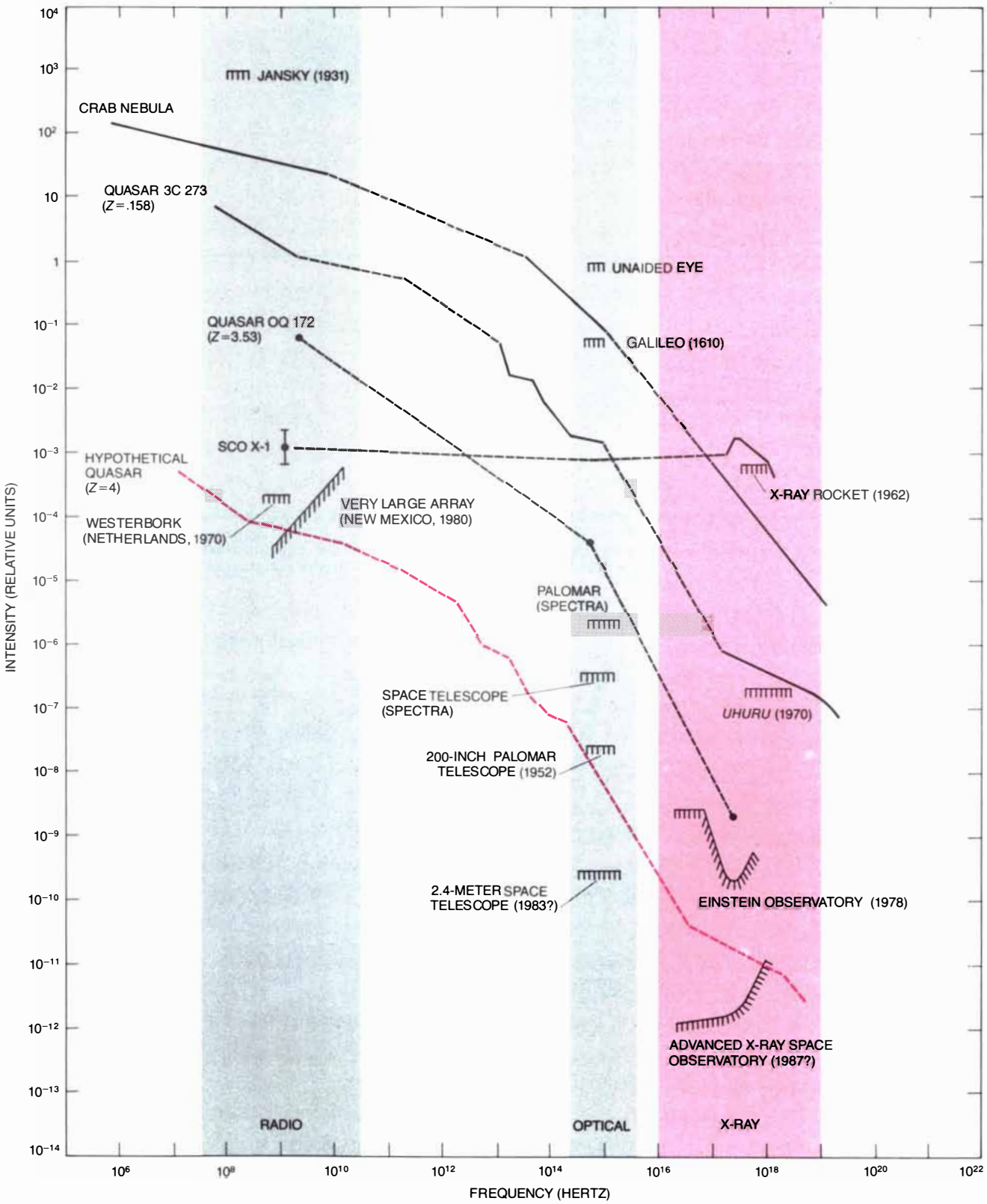
EINSTEIN OBSERVATORY X-RAY TELESCOPE, with an aperture of 58 centimeters, is the largest instrument of its kind that has ever been built. The X-ray photons enter the telescope through the four segmented rings and come to a focus after grazing reflections from two aspherical surfaces (*see top illustration on opposite page*). Instrument was built by Perkin-Elmer Corporation with guidance from Leon P. Van Speybroeck of Center for Astrophysics.



X RAYS CAN BE FOCUSED by causing them to reflect from specially shaped surfaces at small angles of incidence. In an X-ray telescope the rays are reflected first from a paraboloidal surface and then from a hyperboloidal one. The Einstein Observatory telescope has four nested surfaces of each type. Each surface is figured and polished from a single cylinder of low-expansion glass. The surfaces are coated with a thin film of nickel. The focal length of the telescope is 3.4 meters; its maximum effective collection area is 300 square centimeters.



EINSTEIN OBSERVATORY, financed by the National Aeronautics and Space Administration and built by American Science & Engineering, Inc., and TRW Inc., was launched on November 13, 1978. It is 6.7 meters long, 2.4 meters in diameter and weighs 3,175 kilograms. The altitude of its original orbit was 537 kilometers. A turntable at the focal point of the X-ray telescope carries instruments for making four different kinds of observations and measurements. The pictures accompanying this article were made by the high-resolution imaging detectors and the imaging proportional counters. The several spectrometers provide detailed information on the energy of the X-ray photons. Spacecraft's observations are scheduled by the Center for Astrophysics. Author is the principal investigator for the mission.



SENSITIVITIES OF ASTRONOMICAL INSTRUMENTS operating in various parts of the electromagnetic spectrum can be compared on the basis of their ability to detect the radiation from typical astronomical objects. In general the objects represented here radiate more power per unit of frequency in the radio region of the spectrum than they do in the X-ray region. X-ray binaries such as Scorpio X-1 (Sco X-1) are a notable exception. The increase in sensitivity of radio telescopes from Karl G. Jansky's first instrument to the Westerbork radio telescope in the Netherlands and the Very Large Array in New Mexico is a factor of about 10 million. The improvement in optical instruments from Galileo's telescope to the 200-inch Hale telescope on Palomar Mountain is nearly as great. With the Einstein Observatory X-ray astronomy has made a comparable leap in sensitivity from the early rocket measurements of 1962. It is this sensitivity that has enabled the Einstein Observatory X-ray telescope to detect the quasar (OQ 172) with the largest red shift known ($Z = 3.53$). A more powerful X-ray observatory, now on the drawing boards, should be able to record quasars with Z equal to 10, possibly beyond the limit of detectability by the Hale telescope. The spectrum needed to establish the red shift of such an object, as distinct from detecting it, may exceed the capability of an even more powerful instrument: the 2.4-meter Space Telescope, scheduled for launching in December, 1983.

fitted out for X-ray observations. Our group had been working on the design and development of such a satellite since I had proposed it to NASA in 1963. *Uhuru* was the first of a series of similar satellites that provided most of the results in X-ray astronomy in the 1970's: the *ANS* satellite of the Dutch group, *SAS-3* of the M.I.T. group, *Ariel V* of the British group, *OSO-8, Copernicus* and finally in 1977 the first of the High Energy Astronomical Observatory series: *HEAO-1*.

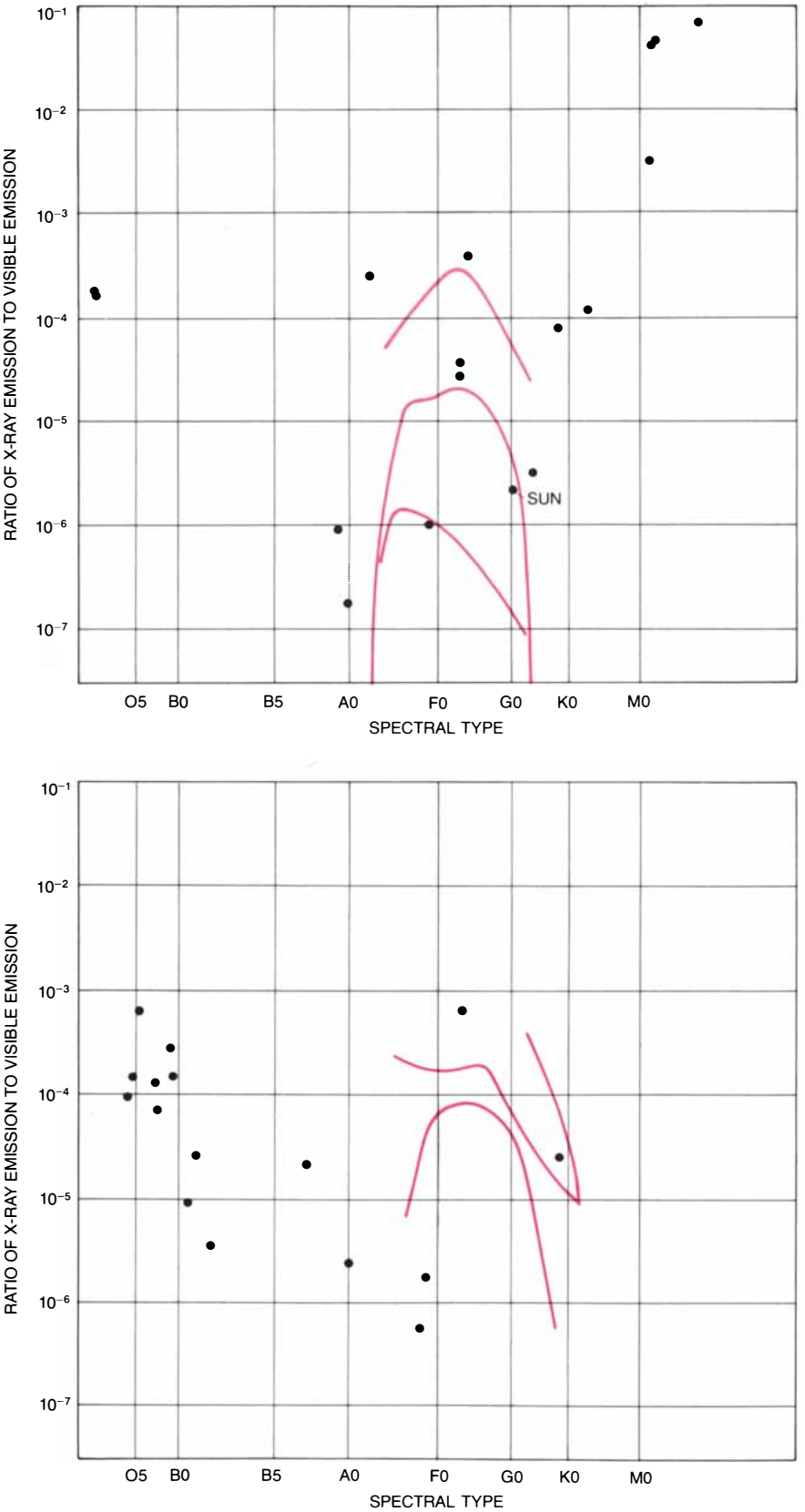
The First X-Ray Observatory

Among the most important findings of *Uhuru,* subsequently confirmed and extended by other satellites, was the identification of many X-ray sources within our galaxy as binary systems in which X rays were emitted in the transfer of mass from the larger member of the pair to the smaller. In a sequence of exciting discoveries following rapidly on each other regular pulsations were discovered in two of the sources: one in Hercules, Her X-1, and one in Centaurus, Cen X-3. Close examination of the period of pulsation showed that in both objects a Doppler shift in frequency was produced by the motion of the X-ray-emitting star as it circled its companion. Long-term study of the period revealed that the rotation of the X-ray star was speeding up rather than slowing down. This surprising finding meant that the energy for the emission could not come from rotation, as it does with pulsars. The only remaining plausible source of the energy was gravitational energy released by the accretion of material from the companion star onto the X-ray-emitting object. The infall of material could also account for the acceleration in rotation.

The identification of Her X-1 and Cen X-3 at optical, or visible, wavelengths became possible with the improved locations supplied by *Uhuru*. The combination of X-ray and optical measurements made it possible to infer the mass of the emitting object. From the change in the speed of rotation the moment of inertia could also be calculated. The conclusion was that the X-ray-emitting object is a neutron star with a mass equal to that of one or two suns. This was the first direct measurement of the mass of a neutron star.

In another system, Cyg X-1, we found a compact object that flickered on time scales as brief as milliseconds but without regular pulsations. Following the optical identification of the system the mass of the X-ray-emitting object could be estimated as greater than six solar masses. The fact that it is compact and has a mass too large for a neutron star gave the first strong evidence for the existence of a black hole.

Since these early discoveries astronomers have concluded that mass-ex-



RATIO OF X-RAY EMISSION TO VISIBLE EMISSION for a wide variety of stars has been determined for the first time with the Einstein Observatory. The spectral classification is correlated with a star's surface temperature, ranging downward from 50,000 degrees Kelvin for O5 stars to 3,600 degrees for M0 stars. The sun, with a temperature of 5,700 degrees, is a member of the dwarf and subdwarf family (*top*). Subgiants, giants and supergiants are put in a separate category (*bottom*). The smooth curves are based on stellar models developed before the Einstein Observatory was launched. The dots show the range in the ratio of X-ray to visible emission now known from Einstein Observatory measurements. A surprise is that subdwarfs cooler than the sun emit nearly a tenth as much energy in X rays as they do in visible radiation.

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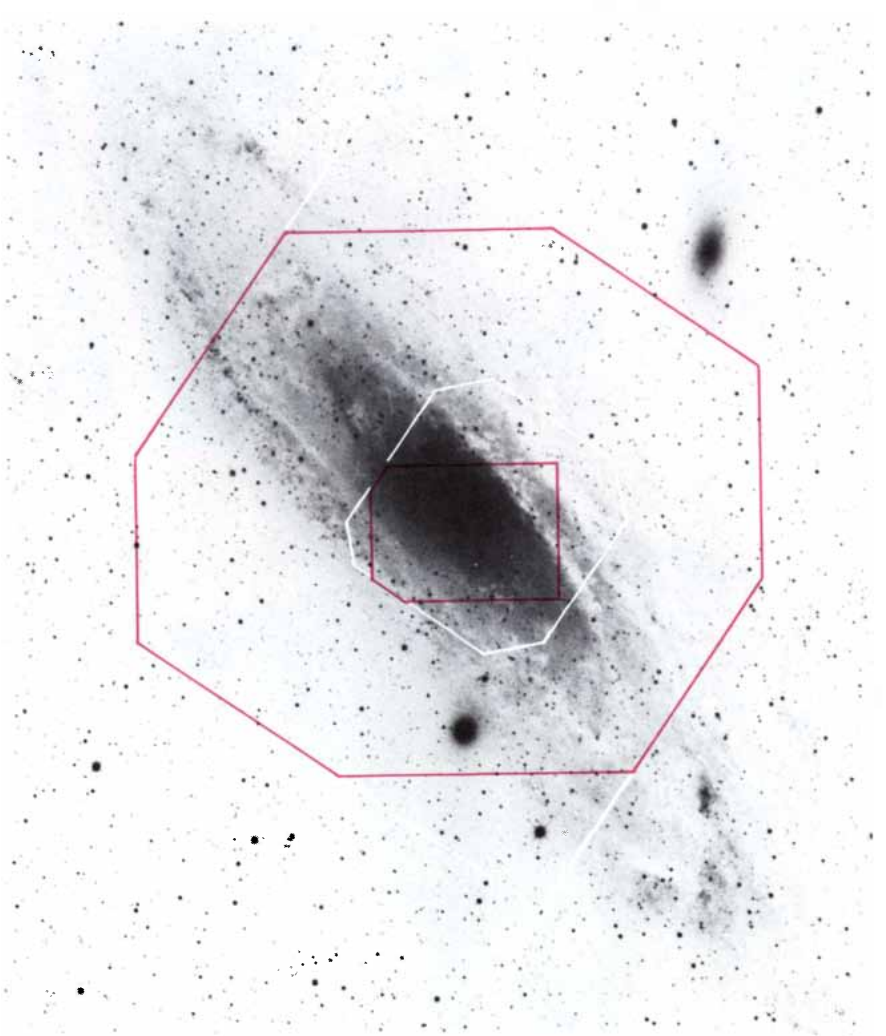
change binary systems are the source of many and perhaps all of the most bizarre high-luminosity phenomena detected by the X-ray satellites. The different classes of pulsating X-ray sources, "bursters" and transient sources all seem only varied manifestations of one underlying energy source. The mass-exchange systems serve as exotic astrophysical laboratories in which one can study the behavior of matter at extremely high densities as it is reflected in the properties of neutron stars. The orbital changes observed in systems in which large masses are traveling at high velocity also provide tests of theories of general relativity that are difficult to conduct in more typical systems.

Another important and far-reaching discovery from the *Uhuru* observations is that gas at a temperature of 10 million to 100 million degrees K. fills the space between galaxies in clusters of galaxies. Such clusters are the largest gravitationally bound aggregates of matter known in the universe. Their origin and evolution remain a mystery. It is not known, for example, whether galaxies first formed and then came together to form a cluster or whether a great cloud of gas already existed as a distinct entity before the galaxies formed. The X-ray observations should help to solve the problem. Although the mass of the gas in a cluster equals the mass of all the visible galaxies in it, the existence of the gas was previously unknown and could have been revealed only by X-ray measurements.

The X-ray observations of the half-dozen satellites from *Uhuru* of 1970 through *HEAO-1* of 1977 expanded the catalogue of galactic and extragalactic X-ray sources to more than 400. Yet the sensitivity of these observations still fell quite short of what was necessary to realize the full potential of X-ray astronomy. The instruments placed in orbit up to that point could study only the most luminous and unusual systems in our own galaxy and only the nearest and most powerful of the extragalactic sources. For X-ray astronomy to join the mainstream of astronomical research it was necessary for the sensitivity of X-ray-detecting instruments to be increased by a factor large enough to make possible the study of the X-ray emission from a much broader class of objects within our own galaxy and to extend the X-ray observations of extragalactic objects to the most distant clusters and quasars known. Unless such an improvement in instrumental sensitivity could be achieved urgent questions about stellar evolution and cosmology would remain unanswered.



NEGATIVE PRINT OF THE ANDROMEDA GALAXY, M31, is marked to show two areas imaged by the Einstein Observatory X-ray telescope. The larger area outlined in white was recorded by an imaging proportional counter, which covers a field of 60 arc minutes with a resolution of one arc minute. The smaller area outlined in white, 20 arc minutes on a side, was recorded at the telescope's maximum resolution. Areas within the colored boundaries appear on page 92. The optical image is from the Harvard College Observatory plate collection.

Focusing X-Ray Optics

From the early rocket flights of 1962 to the launching of *HEAO-1* in 1977 the basic X-ray detector had remained unchanged. It was a contemporary version of the venerable Geiger counter, a gas-filled tube with a thin window that would block visible and ultraviolet photons but would pass X-ray photons in the energy range of interest. The detector was rugged, not difficult to construct and had the great virtue of being able to detect each incoming X-ray photon. Its main disadvantages were a lack of directionality and a high background noise resulting from gamma rays and cosmic rays. The problem of determining the direction of X-ray sources was solved with increasingly complicated systems of baffles that provided an angular resolution of half a degree when the detector was used for all-sky surveys. Higher angular resolutions, down to one arc minute, could be achieved by special apertures but only at the cost of a severe sacrifice in sensitivity. The basic problem remained: when observations are limited by background noise, sensitivity improves only in proportion to the square root of the area of the detector.

HEAO-1 was already one of the largest scientific satellites ever built: about six meters high, 2.4 meters in diameter and 2,700 kilograms in weight. Yet because of physical constraints its X-ray detectors, although they were 50 times larger in area than those of *Uhuru,* were only seven times more sensitive. To have improved the sensitivity of the *HEAO-1* instruments by a factor of 1,000 would have called for detectors several hundred acres in extent. Clearly what was needed for further progress was an instrument built on entirely different principles. The importance of the Einstein Observatory is that it brought about this major advance in technology.

In other regions of the spectrum, such as the optical region and the radio region, sensitivity is increased by the straightforward method of gathering larger numbers of photons and concentrating them to form an image. In small-

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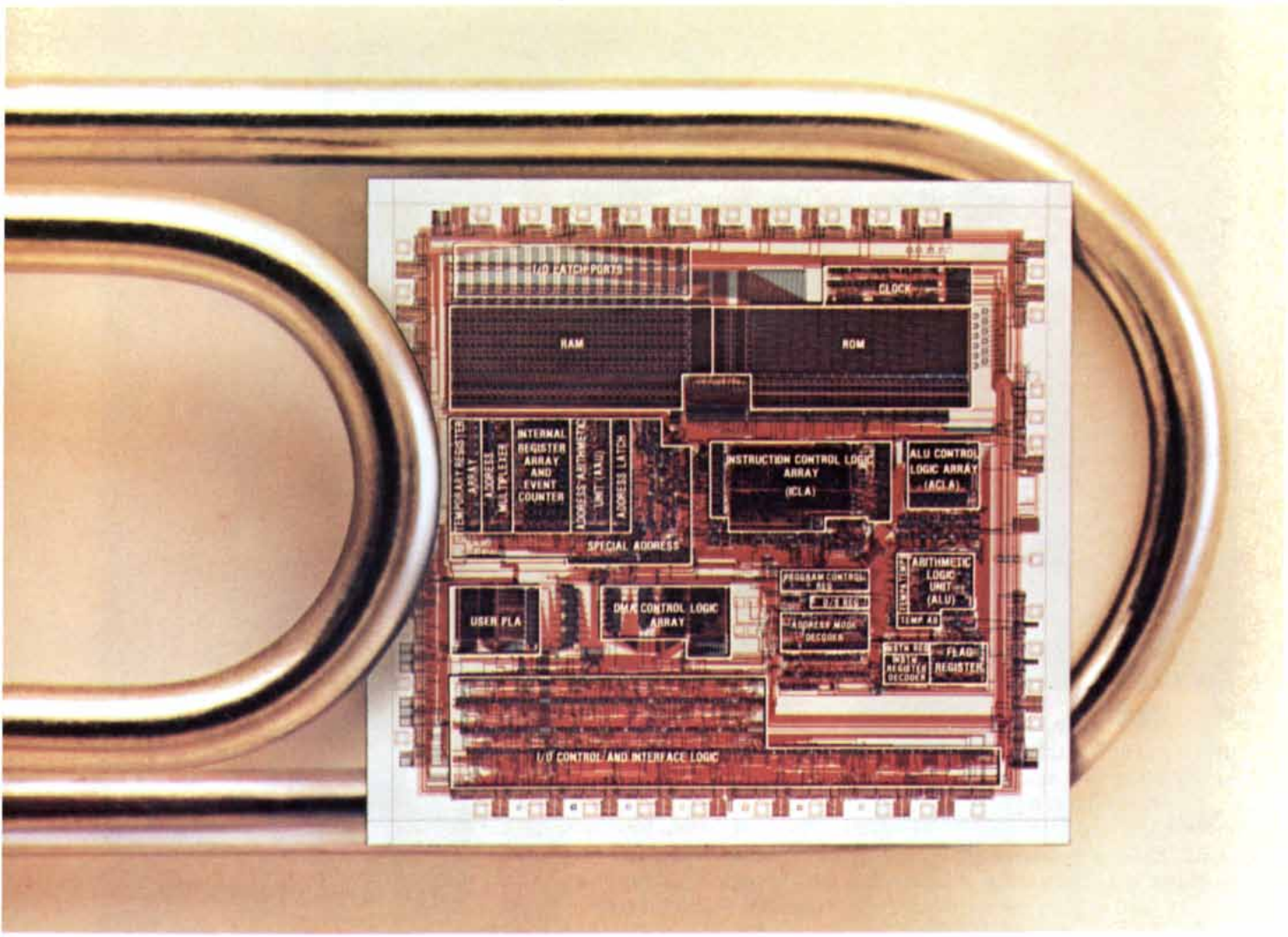
The one-chip computer: offspring of the transistor



The MAC-4 one-chip computer, developed for a variety of telecommunications applications, is compared to a standard-sized paper clip. The chip's numerous functional areas are labeled.

One of the transistor's latest descendants is the Bell System's 30,000-element MAC-4 "computer-on-a-chip." It's another in a long line of microelectronic developments that have come from Bell Laboratories.

The MAC-4 is so efficient that a program written on it takes 25 percent less storage space than that required by most other microcomputers. Its assembler language, C, also developed at Bell Labs, has features that make MAC-4 easier to program, debug and maintain. And the MAC-4 can handle anything from nibbles to bytes to words with its 4-, 8-, 12-, and 16-bit operations capacity.

Like other one-chip computers, the MAC-4 has sufficient memory to support its varied tasks—3000 nibbles of read-only memory and 200 nibbles of random access memory coupled to 34 input/output ports.

Fabricated with the latest CMOS technology, the MAC-4 needs little power. Thus it is well matched to a variety of telecommunications applications.

It started with the transistor

MAC-4 is just one current example of the many microelectronic devices to come from Bell Labs since we started the solid-state revolution with the invention of the transistor in 1947.

Over the past three decades, our advances in materials, processing, and devices have been vital to solid-state technology. These include:

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- Charge-Coupled Device
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- Electron-Beam Exposure System

Today and tomorrow

Today, we continue to make important contributions to solid-state technology. For example, we've developed a rugged 65,536-bit RAM that can tolerate processing faults. Corrections can be made on the chip itself, so we can get more usable chips out of each manufacturing batch—and thus lower unit costs.

In materials processing, we've developed a technique for precisely controlling the growth of successive atomic layers of single crystal materials. This "molecular beam epitaxy" process is finding increasing use within Bell Labs and elsewhere in the electronics industry. We've used it to fabricate a device that permits us to double the speed of electrons by channeling them into crystal layers where they meet less resistance.

Other advances, in X-ray lithography and new resist materials, for example, promise to help place more elements on microelectronic devices and thus enhance their ability to perform important tasks.

As the solid-state revolution continues, these and other developments from Bell Labs will play an important part in it. What's important to us is the promise these advances offer for new telecommunications products and services. Like the transistor, MAC-4 and its solid-state relatives will find more and more applications in the nationwide telecommunications network.

For further information, or to inquire about employment opportunities, write: Bell Laboratories, Room 3C-303, 600 Mountain Avenue, Murray Hill, N.J. 07974.

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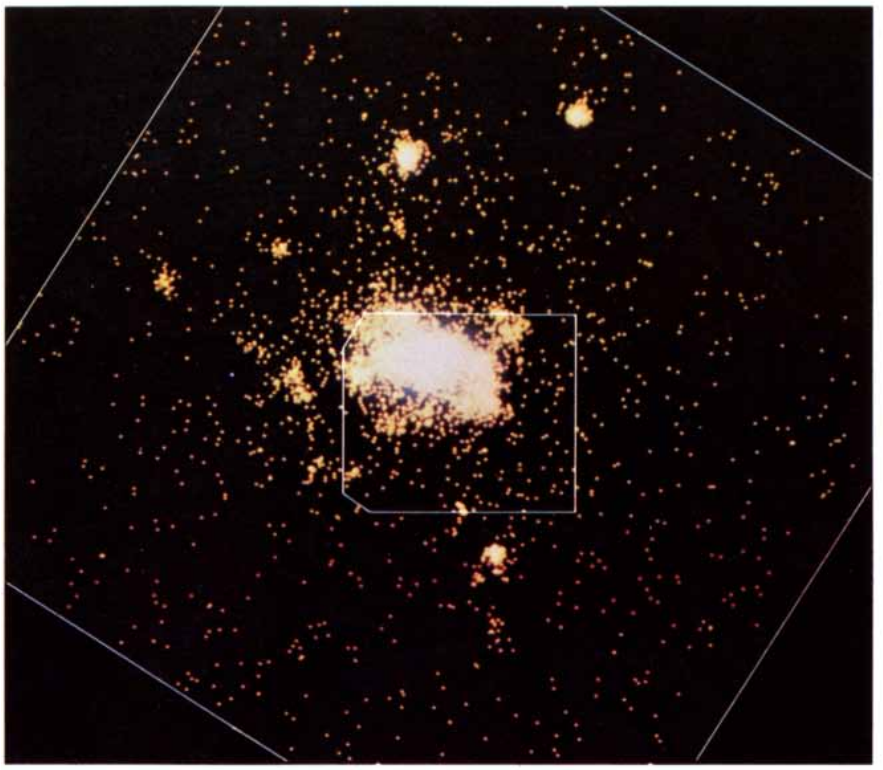
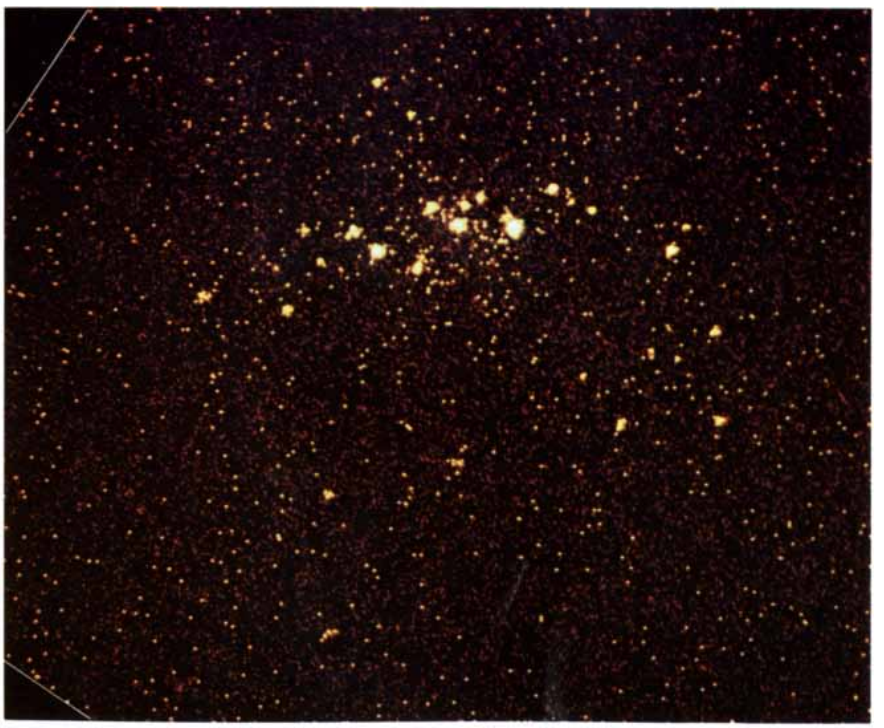


WIDE-ANGLE X-RAY VIEW OF M31, when it is analyzed closely, reveals at least 20 discrete X-ray sources outside the overexposed nucleus of the galaxy. Most of the sources are thought to be similar to the X-ray binary star systems found in our own galaxy. Such binaries consist of a large star that is transferring mass to a small dense companion, either a neutron star or a black hole. X rays are emitted by disk of matter that accretes around small companion.



NARROW-ANGLE X-RAY VIEW OF M31 shows the center of the galaxy, the area outlined in white in the view at the top of the page. The nucleus of the galaxy harbors about 18 discrete X-ray sources. The number is surprising because fewer sources have been detected in the nucleus of our own galaxy. Narrow-angle view is at the telescope's maximum resolution.

er optical telescopes glass lenses can be used for the purpose, but they would not work in the X-ray region because the glass would absorb the radiation without focusing it. In larger optical telescopes and in radio telescopes the preferred collector is a dish-shaped reflector, but it too is ruled out for X rays because virtually none of the rays that strike a mirror perpendicularly or at steep angles are reflected.

It had been discovered in the 1930's, however, that X rays can be reflected if they are allowed to strike a smooth surface at very shallow angles, a phenomenon known as grazing reflection. Optical designs based on grazing reflection from paraboloidal surfaces were studied in the early 1950's, notably by Hans Wolter of the University of Kiel, who was seeking to develop an X-ray microscope. His efforts were ultimately frustrated by the near-impossibility of polishing small nonspherical surfaces to tolerances of about a thousandth the wavelength of visible light.

I had independently conceived of grazing-incidence paraboloids in 1959, when I first became concerned with the need to improve X-ray instrumentation. In 1960 Rossi and I published an article on the potential value of focusing optics for X-ray astronomy. In the following decade my group at American Science & Engineering carried out the long-range technological development that perfected X-ray telescopes. At each step in the development we were able to prove our instruments in a program of solar studies. We obtained the first true X-ray pictures of the sun in 1963 with a resolution of one arc minute. The program culminated in 1973 with the many thousands of X-ray pictures of the solar corona with five-arc-second resolution that were made by the astronauts of the Skylab missions. The solar X-ray rocket program was directed by Giuseppe S. Vaiana, who had joined our group in 1964. The high-resolution X-ray images of the sun enabled him and his colleagues to make a number of important new findings on the physical processes of the solar corona.

Observation of the sun with the new grazing optics was considerably simpler than the observation of stars because the sun's X-ray flux, measured at the distance of the earth, is enormously greater. The solar telescopes could be small and the images could be recorded directly on X-ray film. For stellar work we had to develop larger telescopes and a sensitive X-ray television camera capable of transmitting information to the ground over a period of years.

The new technology was sufficiently developed by 1970 for NASA to seriously consider including a stellar X-ray telescope in the satellite observatory *HEAO-2*. The proposal for such a mission was made by a consortium of four

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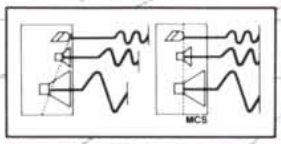

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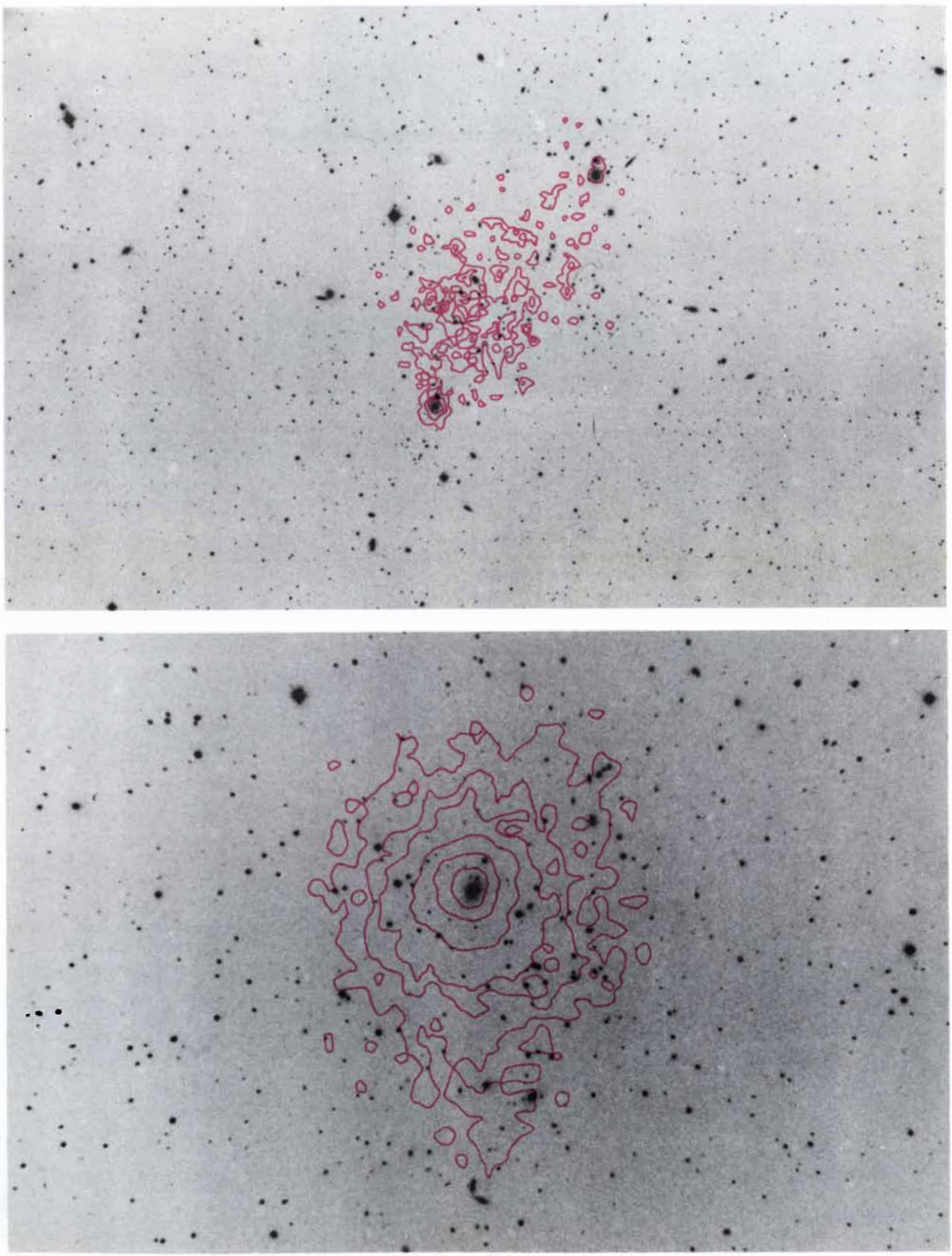


DISTRIBUTION OF GAS in clusters of galaxies has been revealed for the first time by the Einstein Observatory X-ray telescope. The first X-ray satellite, *Uhuru,* launched in 1970, discovered that the space between the galaxies in the clusters is pervaded by gas at a temperature of 10 million degrees K. High-resolution images now made by the Einstein Observatory telescope show that in some clusters, such as Abell 1367 (*top*), the gas (*color*) is clumped around individual galaxies or groups of galaxies. In other clusters, such as Abell 85 (*bottom*), a more evolved cluster, the gas has become more smoothly distributed, evidently in response to the gravitation of the entire cluster.

institutions: American Science & Engineering, the Astrophysical Laboratory of Columbia University, the Goddard Space Flight Center of NASA and M.I.T. With NASA's approval of the project, and after eight years of effort as principal investigator for such a mission, my 20-year dream was finally realized with the launching on November 13, 1978, of *HEAO-2:* the Einstein Observatory.

The Einstein Observatory

The Einstein Observatory is one of the most advanced scientific spacecraft ever flown by NASA. It is stabilized on three axes and can be pointed anywhere in the sky on command from the ground. The spacecraft, together with its solar-power system, attitude control, telemetry and housekeeping functions, were built by TRW Inc. under contract from the Marshall Space Flight Center of NASA. The entire HEAO program was managed from the Marshall Center by a group led by Fred Speer.

The Einstein Observatory X-ray telescope consists of four nested paraboloids and four nested hyperboloids that bring grazing photons to a focus 3.4 meters behind the entering aperture of 58 centimeters. Limitations imposed by the nested structure and the supporting face plate reduce the maximum collection area to 300 square centimeters. The effective collection area varies with photon energy, being highest for photons of 100 electron volts and falling essentially to zero for those of 4,000 electron volts. Each of the eight reflecting surfaces was fashioned from a single cylinder of low-expansion glass and polished to within a thousandth of a wavelength of light. All the optical elements were made by the Perkin-Elmer Corporation.

Inside the satellite an optical bench aligns the telescope with an assortment of X-ray detection and measuring instruments mounted on a turntable at the focal plane. The instruments are rotated into position on command. Target fields are selected with the aid of star sensors, which also provide a record for verifying the pointing direction after the field has been examined. The star sensors were built by Honeywell Inc. Much of the instrumentation and the mechanical structure were built by American Science & Engineering under the direction of my group, which in 1973 had moved to the Center for Astrophysics. Although the responsibility for overall scientific management was mine, as principal investigator, it was shared with my colleague Harvey Tananbaum, the scientific-program manager. Leon P. Van Speybroeck, also of the Center for Astrophysics, deserves much of the credit for the design and fabrication of the optical elements in the X-ray telescope, which is the largest ever built.

The group at the Center for Astrophysics was also responsible for the two X-ray imaging instruments at the focal plane. Tananbaum, Stephen Murray, J. Patrick Henry and Edwin M. Kellogg developed a photon-counting X-ray camera capable of detecting X-ray images at the full resolution of the telescope (four arc seconds) over a field of 20 arc minutes. The position and time of arrival of each detected photon is transmitted to the ground, where it is stored in a computer. The photon counts accumulated over an interval ranging from a few minutes to an hour or more can be translated into an X-ray image of the sky on a television screen, which is then photographed to produce pictures of the kind accompanying this article.

A second imaging camera with a larger field (60 arc minutes) and lower resolution (one arc minute) was designed by Paul Gorenstein and Rick F. Harnden of the Center for Astrophysics. The camera uses a proportional counter to measure not only position and arrival time but also the approximate energy of each detected photon. More accurate energy measurements are made by a cryogenically cooled silicon spectrometer of medium resolution that was developed by Elihu A. Boldt, Stephen S. Holt and Robert H. Becker of the Goddard Space Flight Center. The highest spectral resolution, although at unavoidably low sensitivity, is supplied by a Bragg crystal spectrometer developed by George W. Clark and Claude R. Canizares of M.I.T. A Columbia University group consisting of Robert Novick, Knox S. Long, William Hsin-Min Ku and David J. Helfand was responsible for most of the computer software and data analysis. The mission operation planning and implementation were carried out under the direction of Ethan Schreier of the Center for Astrophysics.

The data from the Einstein Observatory are transmitted to NASA ground stations around the world and from them to a control center at the Goddard Space Flight Center outside Washington, D.C., which is manned around the clock by a crew composed of Goddard, TRW and Center for Astrophysics engineers. After the removal of engineering readings the data are relayed to the Center for Astrophysics in Cambridge, Mass., where an efficient data-handling system has been developed, largely by Christine Jones, William Forman, Arnold Epstein and Jeffrey D. Morris. The data stream is further manipulated, the pointing direction of the observatory is found as a function of time and images are accumulated in the memory of the computer. From there they can be displayed on a television screen.

Since the Einstein Observatory was placed in orbit it has performed without significant difficulties, fulfilling all expectations with regard to angular resolution and sensitivity. It has detected X-ray sources 1,000 times fainter than any previously observed and 10 million times fainter than Sco X-1, the first source detected outside the solar system. The X-ray telescope's sensitivity is comparable to the optical sensitivity of the 200-inch telescope on Palomar Mountain, which in turn is about 10 million times more sensitive than the human eye.

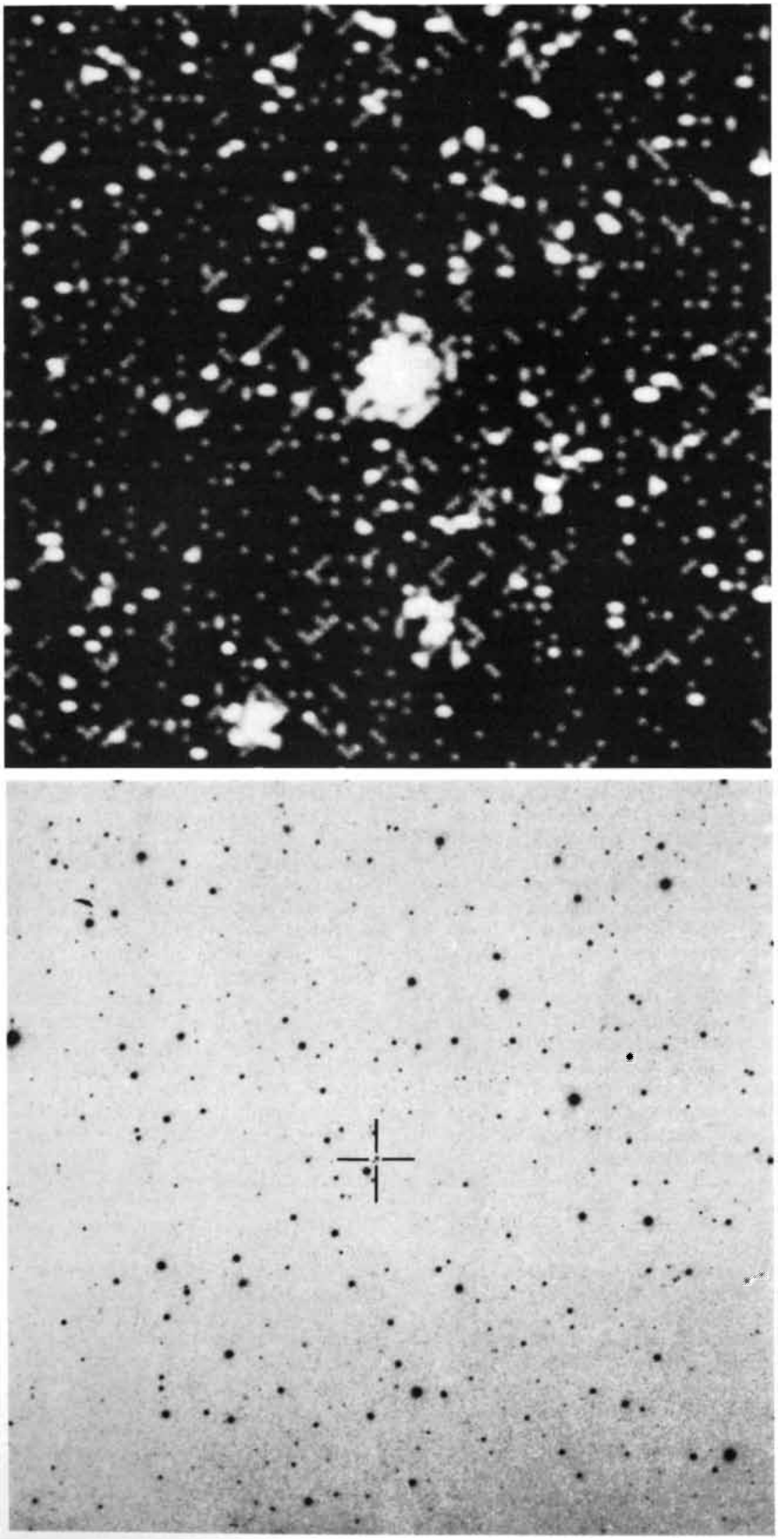
Under a NASA-sponsored program administered at the Center for Astrophysics by Frederick D. Seward astronomers from all over the world have been offered an opportunity to request observing time on the Einstein Observatory. More than 200 requests were accommodated in the first year of the telescope's operation. In what follows I shall describe some of the early results.

Stellar Coronas

The great sensitivity of the Einstein Observatory telescope has upset the previous understanding of the X-ray emission from stars within the galaxy whose optical luminosity is roughly equal to that of the sun. Before this mission X rays had been detected from only a small number of "special" stars, such as X-ray binaries, white dwarfs and cataclysmic variable dwarf novas. The observatory has measured X-ray emission from stars throughout the color-magnitude range, as conventionally plotted on the Hertzsprung-Russell diagram. X rays have now been detected from stars whose temperatures range from 3,000 to 40,000 degrees K. (the sun is 5,700 degrees) and whose visual magnitudes on an absolute scale range from a factor of 10,000 fainter than the sun to a factor of 10,000 brighter. The predictions of X-ray emission based on classical theories of energy transport and the heating of stellar coronas, where X rays are thought to originate, fail completely to account for the observations.

Traditionally the transport of energy outward from the core of a star had been considered in terms of only two processes: radiation and convection. Convection, the upward bubbling of hot material, is capable of transporting large amounts of energy. It is an acoustically noisy process, and it was thought that it was the leakage of acoustical energy that was chiefly responsible for heating the coronas of stars to temperatures of a million to 10 million degrees, with the consequent emission of X rays. Strong convection is found, however, only in stars in a rather limited range of compositions and in particular evolutionary stages of development. In short, traditional theories predicted that only stars in a rather narrow temperature range, roughly between 5,500 and 10,000 degrees (corresponding to the spectral types designated G, F and A) would emit X rays at levels comparable to, or higher than, those of the sun.

Some difficulties had already arisen in



QUASAR WITH RED SHIFT OF 3.1 is one of the most distant quasars imaged by the Einstein Observatory telescope. In the X-ray picture (*top*) the quasar, QSO 0420–388, is the brightest object. Image was made with wide-angle camera. In optical photograph (*bottom*), made with 1.2-meter Schmidt telescope on Palomar Mountain, quasar is marked by a reticle.

efforts to reconcile the convection theory with the X-ray emission of the sun. As a result some solar theorists had suggested as an alternative the possible role of magnetic fields in heating the solar corona. In addition optical and ultraviolet studies of stars with temperatures between 15,000 and 50,000 degrees (types O and B) and of certain dwarfs suggested that such stars were surrounded by a hot corona. Einstein Observatory studies undertaken by groups at the Center for Astrophysics and at Columbia and by guest investigators now disclose X-ray emission from the hot O, B and A stars and from the cool K and M dwarfs [*see illustration on page 85*]. For the dwarfs the observed emission is a million times greater than had been expected. Among the M stars the emission of energy in the X-ray region approaches one-tenth the emission of visible energy, compared with about a millionth for the sun. The important general finding by Vaiana, W. Rosner and their colleagues at the Center for Astrophysics that stellar X-ray emission is the norm rather than the exception will force a major reconsideration of theories of both stellar atmospheres and stellar evolution. It is clear that X-ray observations will provide important and perhaps unique tests for any new theories that emerge.

Supernova Remnants

A supernova explosion climaxes the evolution of a massive star. After the star's nuclear fuel is exhausted the outward radiation pressure is no longer able to balance the inward pull of gravity. The central region of the star collapses into a neutron star whose mass is equal to that of the sun but whose radius is only about 10 kilometers. The rebound shock from the collapse propagates outward, ejecting the star's outer shell at high velocity. The ejected material transfers its enormous kinetic energy to the surrounding interstellar gas, raising the temperature of the gas to millions of degrees. By studying the collapsed core and expanding shell of a supernova one hopes to discover details about the explosion itself. One also tries to learn how the interstellar gas is mixed with the stellar debris and heated by it. The entire complex process ultimately determines the temperature, composition and density of the raw material from which new stellar systems comparable to the solar system are created. Several supernova remnants had been observed at X-ray wavelengths before the launching of the Einstein Observatory. The instruments of the observatory add a new dimension to the earlier observations by virtue of their much higher image resolution and greatly increased spectroscopic sensitivity.

A dramatic X-ray picture of the supernova remnant in Cassiopeia, Cas A,

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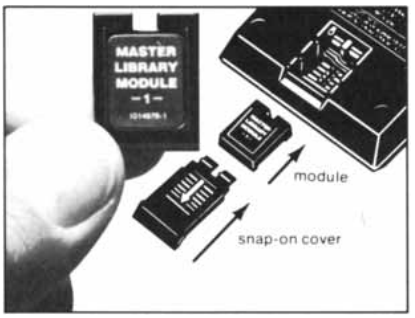

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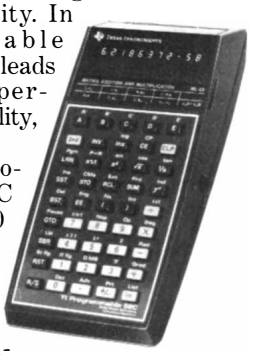

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obtained from the Einstein Observatory by Murray and his colleagues at the Center for Astrophysics, provides an example of the kind of detail never before visible [*see top illustration on page 81*]. The X-ray image is full of details that correspond to physical processes occurring simultaneously in different parts of the remnant. The brightest regions correspond to fast-moving knots of heated gas that can also be observed at the wavelengths of visible light.

The knots appear to contain material that had been enriched in oxygen and sulfur by nuclear processes in the interior of the star and were subsequently flung outward by the explosion. Some of the X rays seem to originate in stationary regions, possibly consisting of material shed from the star before the explosion and later heated by the passage of the shock front. One can also see a faint shell outside the brighter regions that seems to correspond to the shock front itself traveling just ahead of the expanding debris. The detailed spectra obtained by Holt and his colleagues at the Goddard Space Flight Center with the high-sensitivity spectrometer of the Einstein Observatory reveal the presence of sulfur, silicon and magnesium in the X-ray-emitting material.

Cas A is thought to be the most recent supernova, although the event is not reported in any known historical chronicle. Its age can be estimated, however, by measuring the speed at which the debris is moving and calculating when it would have been collected at a stellar point. Cas A must have exploded in the second half of the 17th century, considerably later than the famous supernova of 1572 seen by Tycho Brahe and the supernova of 1604 described by Johannes Kepler. Near the center of the remnant of each of these supernovas one would expect to see a pulsar, a rapidly spinning neutron star left behind by the star that had exploded. It is somewhat surprising that no pulsar can be detected in any of them, particularly Cas A. Since Cas A is young, if a pulsar had formed in it, the spinning neutron star would not have had time to move far from the center of the expanding nebula. The absence of a pulsar implies either that no neutron star was created in the explosion or that the neutron star cooled faster than current understanding of the structure of such objects would predict.

Extragalactic X-Ray Sources

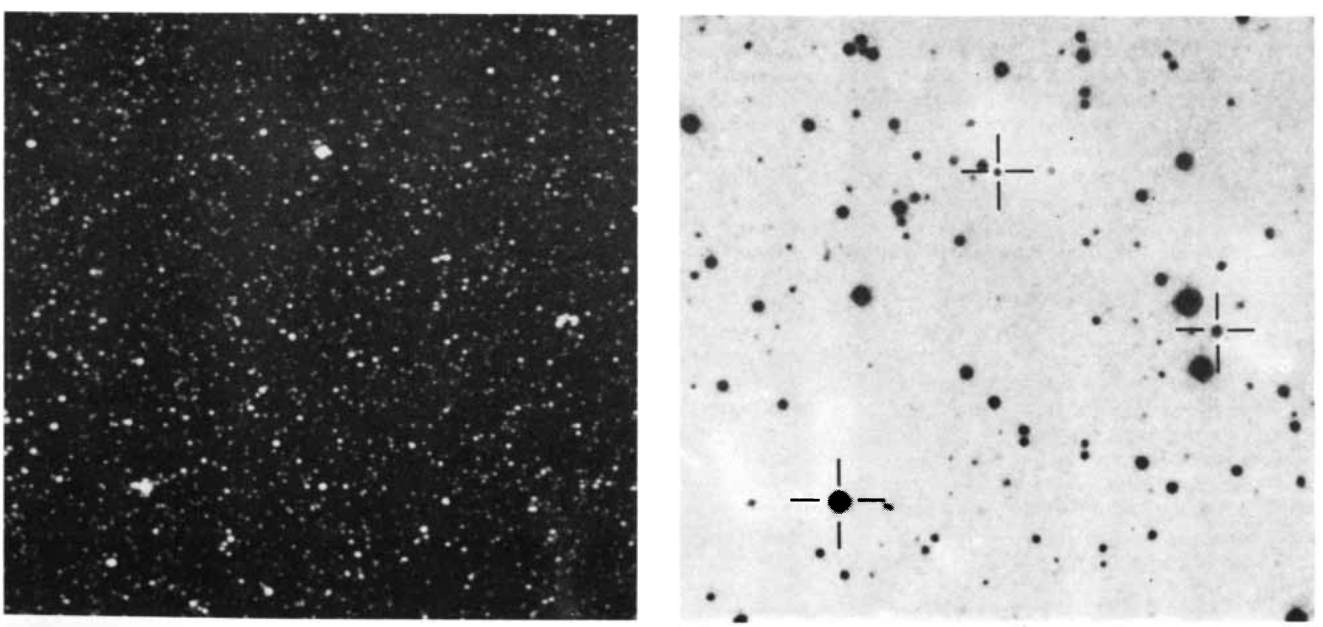
The sensitivity and resolution of the X-ray telescope on the Einstein Observatory have made it possible to observe for the first time individual X-ray sources in galaxies other than our own. Before the launching of the observatory the nearest spiral galaxy, M31 in Andromeda, some two million light-years away, showed up as only a faint blur of X rays representing the integrated emission from some 100 billion stars. With the X-ray telescope Van Speybroeck and his colleagues at the Center for Astrophysics have found in M31 at least 80 individual stellar systems each of which emits more than 10^{37} ergs per second of X-radiation. These sources are therefore comparable to the brighter X-ray sources in our own galaxy.

In the X-ray telescope image there is a clear distinction between sources associated with M31's spiral arms and sources in its central region. The spiral arms are rich in gas and dust, and so they have given rise to many young stars. They also seem to favor the creation of massive binary systems that eventually evolve into X-ray binaries of the mass-transfer type. In the central region of M31, on the other hand, the X-ray sources are of a different type, presumably low-mass binary systems created by capture processes whose probability is increased by the high density of stars in the region. It has been surprising, however, to find many more X-ray sources in the center of M31 than in the center of our own galaxy. The uncovering of such distinctions through X-ray observations should teach astronomers much about the evolutionary processes at work in different types of galaxies.

Clusters of Galaxies

There is a universal tendency, still unexplained, for groups of hundreds or thousands of galaxies to become gravitationally associated in a region of space whose diameter is in many instances no greater than the distance between our galaxy and M31. *Uhuru* discovered that the space within such clusters is pervaded by gas heated to some 10 million degrees. Other satellites found an iron emission line in the spectrum of the radiation from several clusters. Before the Einstein Observatory mission clusters of galaxies constituted the largest class of extragalactic X-ray emitters known.

The Einstein Observatory X-ray observations have opened an entirely new chapter in the investigation of clusters



TWO QUASARS AND A SUNLIKE STAR made the three brightest spots in the Einstein Observatory image at the left. The three objects are identified by reticles in the optical photograph at the right, which was made with the four-meter telescope at the Cerro Tololo Inter-American Observatory in Chile. The brightest of the three objects is the sunlike star. Upper quasar has a red shift of .5, lower one a red shift of 1.96. Many such sources appear in X-ray surveys and constitute a large fraction of extragalactic background X-radiation.

by revealing that a wide range of cluster forms can be classified directly from X-ray pictures of the distribution of gas in them. The observation extends to the most distant clusters known at any wavelength. Work by Jones and her colleagues at the Center for Astrophysics indicates that the gas distribution in clusters ranges from dispersed and clumpy to smooth and concentrated. The extremes are exemplified by the cluster Abell 1367, in which the gas is clumpy, and by Abell 85, in which the gas is concentrated near the center and falls off smoothly with distance [*see illustration on page 94*].

The difference in gas distribution presumably reflects the different evolutionary states of the two clusters. The gas evidently originates in individual galaxies and diffuses outward. In the case of Abell 1367 the gas is still near the galaxy of origin and is being held by that galaxy's gravitational field. In Abell 85, an older cluster, the gas and the galaxies have had time to interact with each other, giving rise to a smooth distribution in which the gas density conforms to the gravitational potential of the cluster as a whole. Intermediate gas distributions, and hence intermediate evolutionary states, are readily apparent in Einstein Observatory pictures of other clusters. One of the puzzling findings is that in unevolved clusters there are clumps of hot gas in places where no galaxy can be seen in optical photographs. One is left wondering how the underlying mass can have such a low luminosity that it escapes detection.

The X-ray observations provide a more direct and accurate way of determining the total mass in a cluster than can be achieved at any other wavelength. The data collected on a large sample of clusters may lead to a more quantitative classification scheme, so that the formation and evolution of clusters can be traced to early stages in the evolution of the universe. The most distant cluster known, which has a red shift of .8 (that is, a velocity of recession that increases the wavelength of the emitted radiation by 80 percent), can readily be detected by the X-ray telescope. No obvious evolutionary effects have been found by Henry and his colleagues at the Center for Astrophysics, however, in the X-ray images at red shifts of up to .5.

Quasars

When the Einstein Observatory instruments are trained on quasars, they extend the X-ray observations to objects with the largest red shifts known. The record is held by the quasar OQ 172, observed by Ku and his colleagues, which has a red shift of 3.5. If quasars are as far away as their red shifts indicate, they are the most distant objects

yet observed. Since light reaching the earth from such distant objects must have started on its way in the remote past, the study of quasars also provides a tool for probing the history of the universe. The X-ray instruments available before the Einstein Observatory was launched were able to detect X rays from only the three nearest quasars, with red shifts of less than .2.

The observatory has now recorded X-ray emission from every known quasar for which a careful position check has been made in the X-ray data. Moreover, we are confident that in the more than 3,000 fields observed so far by the observatory X-ray emission is recorded from many remote sources not identified optically as quasars. A selection of X-ray sources suspected of being quasars are now being examined optically to determine their red shifts and hence whether they are quasars or not. So far an extremely good correlation has been found by Tananbaum and his colleagues at the Center for Astrophysics between the visible-light emission of quasars and the X-ray emission. If this correlation is combined with the evidence from optical surveys that quasars were more numerous at early epochs than they are at present, one can conclude that the summed contribution of ancient quasars is sufficient to account for the integrated background flux of X-radiation from outside our galaxy. X-ray observations can thus provide crucial tests of theories of quasar luminosity and evolution.

X-ray observations should also yield clues to the nature of the "machine" hidden at the center of quasars that makes them the most powerful emitters of electromagnetic radiation in the universe. The most distant quasars, for example, emit in X rays alone as much energy as 10^{14} suns would emit at all wavelengths: 10^{47} ergs per second. Since quasars are known to vary significantly in optical and radio emission in less than a year, their vast output of energy must be generated within a volume no larger than a light-year in diameter. There is much current speculation that quasars may have at their center a giant black hole. The energy source would be the gravitational energy released as infalling stars are torn apart and swallowed by the black hole. Whatever the actual source, X rays should be formed much closer to the center of the object than infrared radiation or radio waves are. This has already been confirmed by the observation of large changes in the X-ray intensity of quasars in periods as short as three hours.

The X-Ray Background

The earliest rocket-borne X-ray detectors disclosed that there are in the sky not only discrete X-ray sources but also a diffuse background of X-radiation. The uniformity of the background, particularly at photon energies above 2,000 electron volts, strongly indicated that most of the radiation originated outside our own galaxy. It has been a matter of conjecture for years whether this radiation is truly diffuse, filling all space, or is the summed contribution of individual sources too faint to be resolved. If the source were a thin hot gas, some investigators had speculated, so much gas would be needed that its mass would exceed the combined mass of all the other constituents of the universe. If the universe had so much mass, the mutual gravitation of its constituents would ultimately bring its expansion to a halt and then cause it to collapse. Such a universe is called closed.

The Einstein Observatory may be capable of laying the question to rest. If the X-ray background is truly diffuse, no increase in the sensitivity and angular resolution of instruments could discern discrete sources; they would simply not be there. Preliminary data from the observatory, however, suggest that its thousandfold increase in sensitivity over previous instruments can reveal individual sources where none had been known to exist. For example, in one small region of the sky once thought to be "empty" the observatory has detected three X-ray sources. One has been identified on optical plates with a distant sunlike star in our galaxy and two have been identified with quasars having red shifts of .5 and 1.9.

By extrapolation from this one small region the number of faint but discrete X-ray sources must be very large, enough to account for at least a third of the background radiation. An X-ray telescope more sensitive than that of the Einstein Observatory is now being planned for a future mission and should be able to detect still fainter sources and perhaps account for all of the background. Then the X-ray emission from quasars alone could explain the integrated X-radiation from the entire sky. If it did explain it, then the all-pervasive diffuse gas does not exist, making it less likely that the universe is closed.

The Einstein Observatory will cease to operate in the spring of 1981, when atmospheric drag will take it out of orbit. It is clear that we have only begun to reap the rich harvest of new information reaching us through the X-ray window. Permanent X-ray observatories more powerful than the Einstein one are already on the drawing boards. If funding is provided, one of them could be in operation by 1987. The Einstein Observatory has clearly demonstrated the immense value of conducting astronomical investigations in the X-ray region of the spectrum.

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Yellowstone Park as a Window on the Earth's Interior

Yellowstone is a "hot spot" in the earth's crust. Its strong volcanic and tectonic activity makes it a unique location for the study of processes that originate deep in the earth

by Robert B. Smith and Robert L. Christiansen

Yellowstone National Park is part of the most seismically active region of the Rocky Mountains. Covering 8,950 square kilometers of Wyoming, Montana and Idaho, Yellowstone gets its name from the brightly colored products of the alteration of its volcanic rocks by steam and hot water. Most of the world's volcanic and tectonic activity is found near the boundaries of the rigid plates that make up the lithosphere: the solid surface of the earth. Some volcanism is nonetheless found at "hot spots" far from the plate boundaries. Yellowstone, which is 2,000 kilometers from the western boundary of the North American plate, is one of these hot spots. And unlike the hot spot represented by the volcanically active island of Hawaii in the Hawaiian Islands, Yellowstone is surrounded not by water but by land. The distinctive geophysical features of Yellowstone make the park a unique natural laboratory for studying the interior of the earth.

Yellowstone spans the continental divide at the juncture of the physiographically distinct northern and middle Rocky Mountains. Within the park is the Yellowstone Plateau, a forested area of 6,500 square kilometers with an average elevation of 2,000 meters. The plateau was formed out of the accumulation of rhyolite and basalt, common volcanic rocks that differ greatly in composition. Where more than 72 percent of the rhyolite consists of silicon dioxides only 50 percent of the basalt consists of them. The plateau is flanked on the north, east and south by mountains that rise to 4,000 meters. To the west and the southwest the terrain gradually decreases in elevation through a transitional area named Island Park to merge with an arid region of low relief: the Snake River Plain of southern Idaho. Like Yellowstone, the Snake River Plain is a region of active young volcanism. Unlike Yellowstone, however, the plain consists of much more basalt than rhyolite.

The framework for the volcanic and tectonic evolution of Yellowstone was established in the late Mesozoic era, a period of gross geological deformation in the western U.S. Sections of the earth's crust with a long history of stability were compressed and shortened to form large folds and overthrust faults. The deformation culminated 65 million years ago in the Laramide orogeny, which elevated huge blocks of crust to form the middle and southern Rockies. The crustal blocks were separated from basins that were later filled with thick sediment.

In the aftermath of the orogeny volcanism was common in the northern Rockies until about 40 million years ago. The volcanic outflows consisted chiefly of andesite: a volcanic rock with a silicon dioxide content intermediate between rhyolite and basalt. After a hiatus of almost 40 million years a new period of volcanism began in Yellowstone and Island Park.

MAP OF NORTHWESTERN U.S. shows the location of Yellowstone Park in Wyoming, Montana and Idaho. The park is part of the most seismically active region in the Rocky Mountains.

Several times in the past two million years magma, or fluid rock, has filled immense chambers under the plateau. The now partially crystallized and solidified magma is the source of heat of the numerous hydrothermal features in Yellowstone National Park: geysers, hot springs, mud pots and fumaroles (steam vents). Over the past two million years thousands of cubic kilometers of rhyolitic magma has erupted to the surface. The average rate of magma production has been comparable to the rate at the most active volcanic regions of the

earth, including Hawaii, Iceland and the mid-ocean ridges. The volcanism of Yellowstone is more episodic. Periods of voluminous eruption lasting for only a few hours, days or months are separated by quiescent intervals lasting for as much as hundreds of thousands of years. The predominantly basaltic volcanic activity of the oceanic regions is much more continuous.

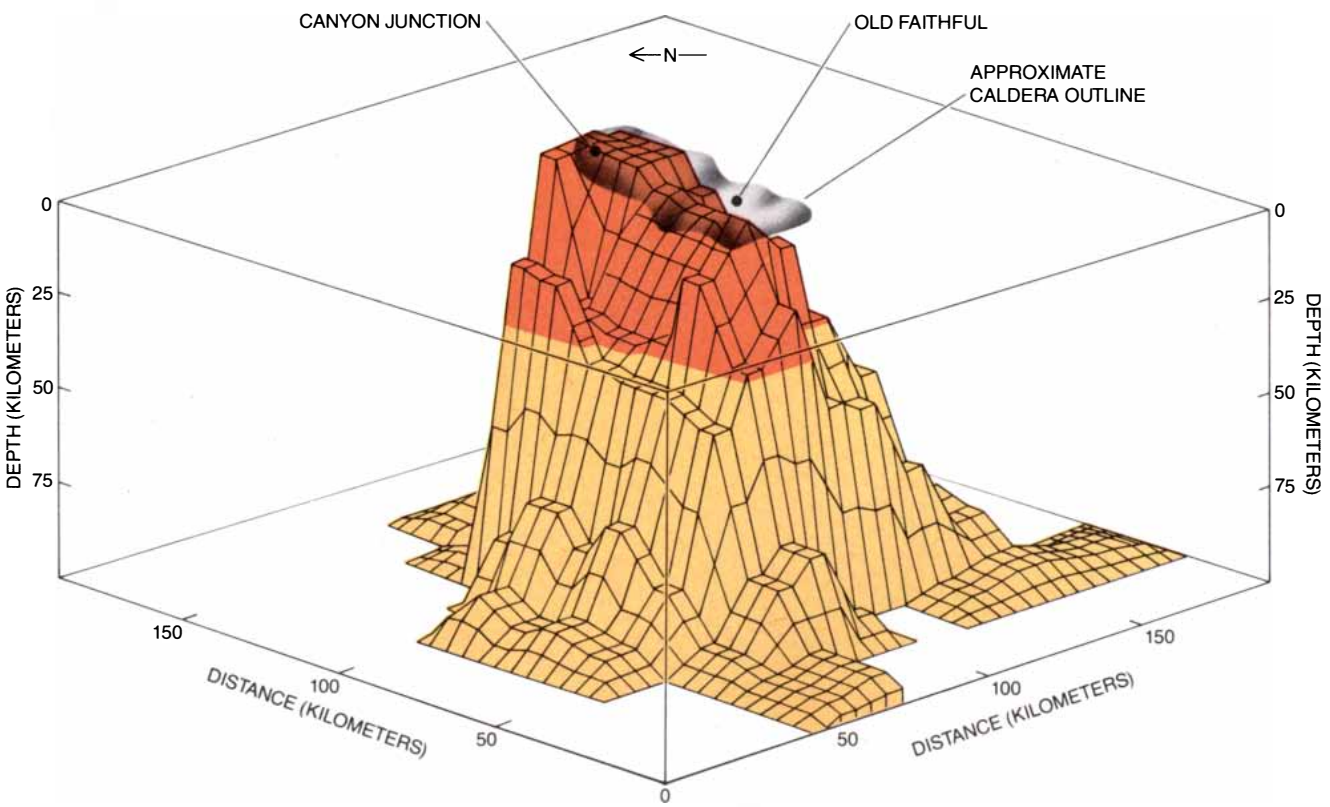
A major advance in the understanding of the volcanic evolution of Yellowstone came with the discovery that most of the rhyolite was erupted not as lava flows but as particulate flows of volcanic ash and hot gas. Work by one of us (Christiansen) and H. Richard Blank, Jr., of the U.S. Geological Survey has shown that most of the rhyolite erupted in three catastrophic cycles over the past two million years. In each cycle many ash flows erupted in such a short time that they cooled together as a unit, forming distinctive patterns of welding and crystallizing.

Each cycle began with intermittent lava flows, climaxed in a catastrophic ejection of fragmented material and ended with more lava flows. The voluminous hot-ash flows were on a scale known nowhere else in recorded geological history. The ash, which flowed for tens of kilometers, welded to form hard rhyolites covering thousands of square kilometers. The massive eruptions of each cycle considerably drained the subsurface magma chambers, causing the chamber roofs to collapse to form huge calderas: craterlike basins tens of kilometers across. In the course of these explosive eruptions fragments of glassy and crystalline volcanic material were thrown high into the atmosphere and carried for thousands of kilometers. Remnants of these materials have been found as far away as Saskatchewan, Texas and California. Subsequent eruptions of rhyolitic lava have partially filled the calderas.

The ages of the volcanic rocks created in the three cycles of volcanism were determined by John D. Obradovich of the Geological Survey. He dated the units by measuring the concentration of the radioactive isotope of potassium with respect to its decay product argon. This dating in conjunction with geological mapping and stratigraphy suggests that the first and most voluminous cycle of volcanism began about 2.2 million years ago with small eruptions of rhyolite and basalt and reached its climax two million years ago with the first catastrophic ash-flow eruption. The resulting cooling unit, named the Huckleberry Ridge Tuff, has a volume of more than 2,500 cubic kilometers. Such a large volume of igneous material erupting in such a short time establishes the existence of a large magma chamber in the upper crust. The roof collapsed as the chamber ejected magma, although the resulting caldera, which extended across Island Park and the Yellowstone Plateau, has been largely covered by younger volcanic rock.

The second cycle of volcanism was the least productive of the three. It began with eruptions of rhyolitic lava in an area inside the first caldera in the northern part of Island Park. The climactic ash-flow eruption, which formed the Mesa Falls Tuff, came 1.2 million years ago and gave rise to a cooling unit with a volume of more than 280 cubic kilometers. After the first two cycles of volcanism the center of volcanic activity shifted entirely away from Island Park to the Yellowstone Plateau. Over the past million years the chambers of rhyolitic magma under Island Park solidified. Over the past 200,000 years tectonic fractures have penetrated the old calderas and the underlying solidified magma bodies. As a result basalt has erupted through the fractured caldera floors.

The record of the third volcanic cycle, which began about 1.2 million years ago, is more complete than the record of the other two. For 600,000 years rhyolitic lava erupted on the Yellowstone Plateau intermittently. It poured out of a slowly forming set of ringlike fractures outlining an area that was to collapse subsequently to form the third-cycle caldera. These events suggest that a large magma chamber was forming in



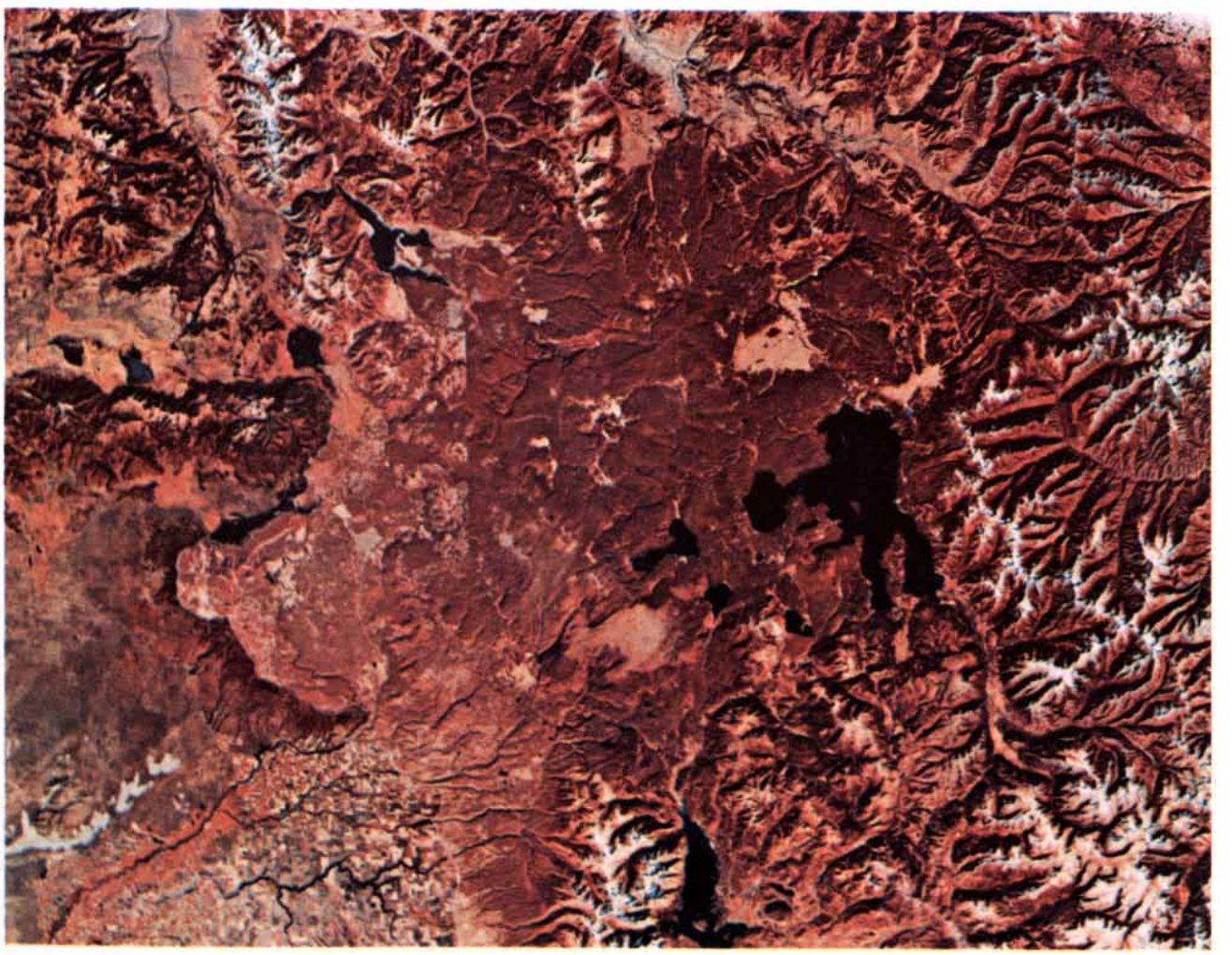
DENSITY MODEL of the crust and upper mantle under Yellowstone shows a 30-kilometer column of material whose peak density is .2 gram per cubic centimeter less than the density of the material that surrounds it laterally. Under the 30-kilometer column is a column of material whose maximum density is .1 gram per cubic centimeter less than the density of the material that surrounds it laterally.

the upper crust. The roof of the chamber domed, stretched and sagged periodically to form the ring fractures. By 600,000 years ago rhyolitic lava had broken through all parts of the ring-fracture system. The conditions were right for a climactic eruption that expelled a great volume of magma through the ring fractures.

What triggers such a large pyroclastic eruption is not completely clear. Magma is a silicate melt containing small amounts of water vapor, other dissolved gases and (if the temperatures are low enough) silicate crystals. In a tumescing system such as the Yellowstone one the ring fractures could propagate downward, eventually penetrating the main magma chamber and thereby reducing the pressure of the magma so that the dissolved gases would be exsolved. Another possibility is that deeply circulating ground water could enter the magma and saturate it. Either process could initiate a chain reaction of oversaturation, exsolution and degassing. The degassing would push frothing magma up through the ring fractures and reduce the pressure still further.

Whatever the triggering mechanism may actually be, it is clear that once degassing begins it will probably continue at a rate constrained only by the dimensions of the fissures carrying magma to the surface. Magma will cease to erupt only when the pressure in the chamber diminishes to an equilibrium value or when the limits of viscosity allowing the flow of magma are exceeded. In the course of the brief episode of explosive degassing a large amount of magma in the chamber is expanded by frothing and is then chilled and shattered by the explosive release of pressure. The quenched magma is expelled to the surface at high velocities in the form of glassy and crystalline fragments. Also expelled to the surface is rock torn out of the walls of the venting fissures.

The climactic eruption of the third cycle expelled 1,000 cubic kilometers of magma to form the Lava Creek Tuff. Detailed stratigraphic analysis reveals that the tuff consists of not one but two sheetlike deposits of ash that erupted so close in time that they welded and crystallized as a single cooling unit. Moreover, the caldera that formed out of the collapsed roof of the Lava Creek Tuff magma chamber has two adjacent and almost overlapping zones of ring fractures. The zones correspond to two accumulations at the top of the body of magma that fueled the Lava Creek Tuff eruptions. The rapid drainage of the main chamber caused the roof to collapse along the two overlapping ring-fracture zones, giving rise to a caldera



SATELLITE IMAGE OF YELLOWSTONE and the eastern Snake River Plain at the left is a composite false-color one made in the fall of 1978. The dark reddish brown areas are forests, the light brown areas open fields and the white areas either mountains or hydrothermal features. The map of the same area at the right gives the sites of volcanism, the major faults and the types of volcanic rock. The names of the major fault zones are in red. Yellowstone has had three cycles of volcanism in the past three million years. Each climactic eruption created a caldera, or large craterlike depression, whose boundary is in blue. The blue numbers correspond to the cycle of volcanism in

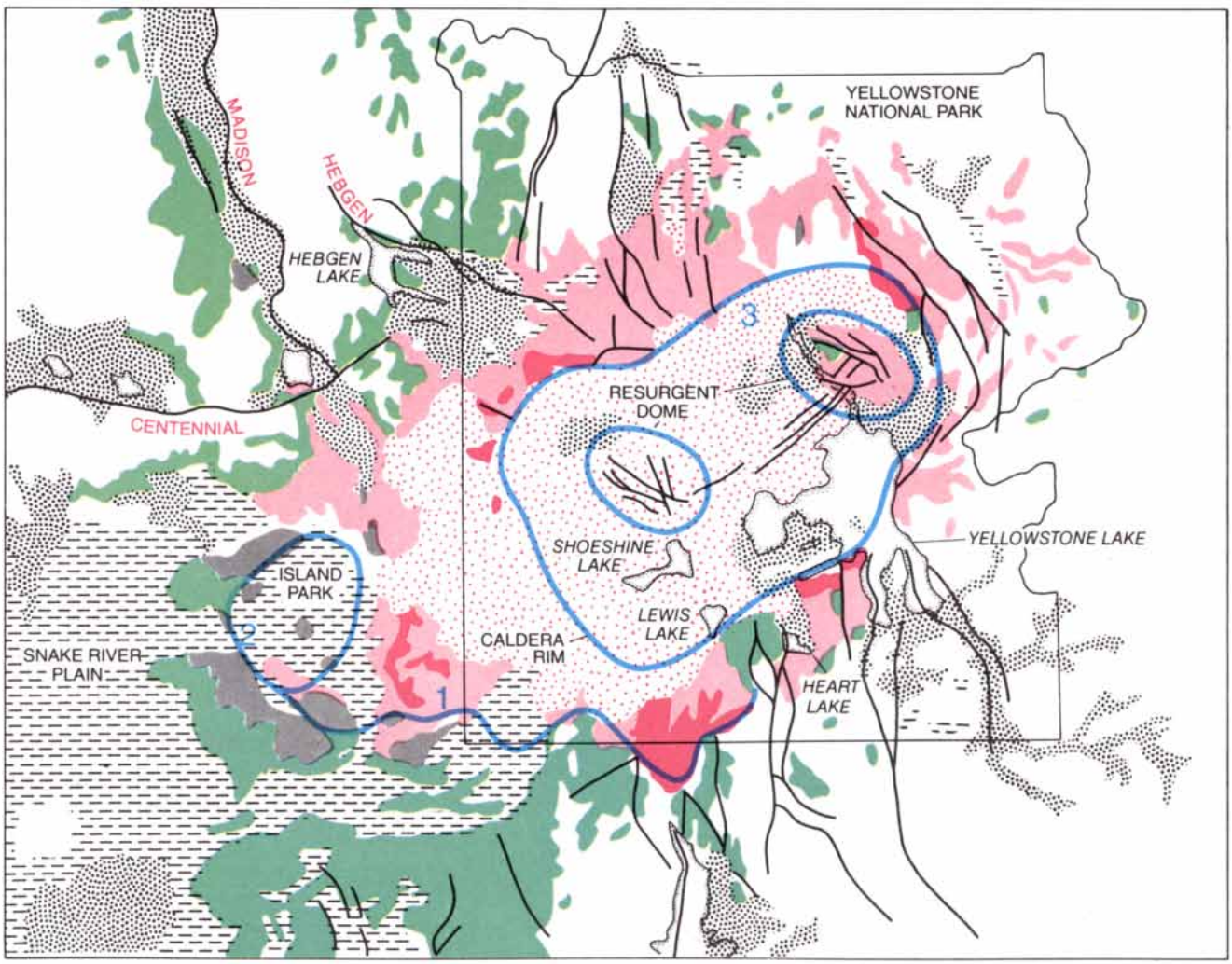
45 kilometers wide and 75 kilometers long.

If the Yellowstone caldera had remained a basin that later filled with sediment and fresh lava, little about the double-ring structure would be known today. The resurgence of magma in the chamber, however, uplifted the central unfractured part of each ring so that the parts form two domes. The floor of the caldera was uplifted immediately after its collapse. The ash-flow eruption, the collapse of the caldera, the resurgence of magma in the chamber and the doming of the caldera floor all took place within a few thousand years (a span too short to be resolved by the potassium-argon dating method).

Over the past 600,000 years both segments of the caldera filled with sediment and rhyolitic lava that has intermittently erupted. Much of the caldera basin is covered by rhyolitic lava that has erupted over the past 150,000 years. The source of the eruptions is along two systems of fissures that extend across the caldera from faults outside it. With few exceptions the fissures have vented rhyolitic magma only where they intersect the caldera's ring fractures. This fact suggests that magma at the top of the Yellowstone chamber has been crystallizing and solidifying over the past 150,000 years. As the solidified crust becomes rigid enough to fracture, faults break it, allowing deeper magma to rise to the surface and erupt.

The pattern in which heat flows out of the earth by conduction provides important clues to thermal processes in the earth's crust and the underlying mantle. The rate of the heat flow is measured in milliwatts per square meter. The value of the heat flow characterizes a region's stage of tectonic evolution. For example, tectonically stable parts of the Rockies near Yellowstone have an average heat flow of about 60 milliwatts per square meter, which is close to the global average. On the other hand, large areas of western North America that have been tectonically active over the past 17 million years have a heat flow of about 100 milliwatts per square meter. Parts of the Snake River Plain have a heat flow of 150 milliwatts per square meter.

Measurements of the conductive heat flow are complicated by the flow of water in the crust. For example, the circulation of ground water in subsurface aquifers can interfere with the measurements by decreasing the heat flow. By the same token the thermal energy transported by convective circulation in hot springs and geysers can disturb the measurements of conductive heat flow. The hot springs and geysers are found in basins that constitute the sur-



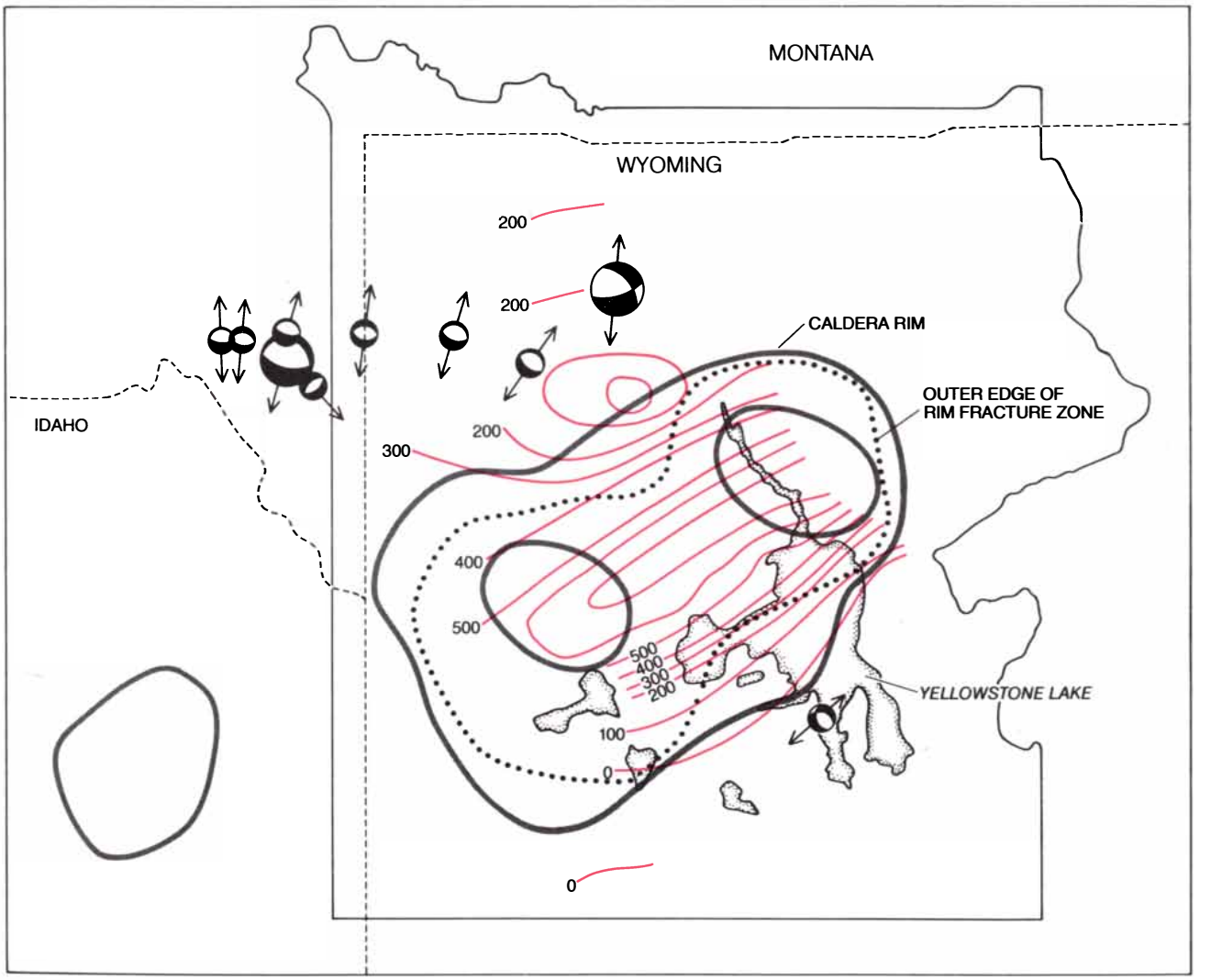
which the caldera formed. The dotted areas are alluvium (sediment deposited by flowing water); the dashed areas are basalt. The green, gray and red areas are accumulations of rhyolite (a glassy volcanic rock similar in composition to granite). The green areas are rhyolite that erupted in the first cycle of volcanic activity, the gray areas rhyolite that erupted in the second cycle and the dark red areas rhyolitic lava that erupted in the third cycle before the caldera formed. The light red areas are rhyolitic ash flows emplaced in the caldera-forming climax of the third cycle of volcanic activity; the red dots are rhyolitic lava erupted in the third cycle after the caldera formed.

face discharge of hot water circulating along systems of deep fractures, including the ring fractures of the caldera and the tectonic fractures that intersect the ring fractures radially.

Such hydrothermal activity transports heat from deep sources not by conduction but by convection. The convective heat flow has been estimated by Donald E. White, R. D. Fournier and Alfred H. Truesdell of the Geological Survey. They measured the amount of water flowing from the area and the concentration in the water of a stable constituent such as chloride. Chloride is abundant in the deep thermal reservoir but scarce in the normal ground water. From measurements and theoretical models of the temperature of liquid water in the underground reservoir a mass unit of chloride in water at depth can be equated with the enthalpy, or heat content, of the liquid. In this way the convective heat flow out of a hydrothermal basin can be estimated from the total mass discharge of the chloride in the surface drainage of the basin. The heat discharged from all chloride-enriched springs in Yellowstone is about 5.3×10^9 watts. The conclusion is that the average convective heat flow out of the caldera is at least 1,800 milliwatts per square meter, which is more than 20 times the continental average of conductive heat flow.

The southeastern sector of the caldera is flooded by Yellowstone Lake, below which lies an extensive reservoir of hot water. The conductive heat flow out of the lake floor was easy to determine because a 300-meter layer of sediment that is relatively impermeable to the flow of water inhibits convection. The lowest heat flow (120 milliwatts per square meter, or twice the regional average) is at the south end of the lake. Five kilometers inside the boundary of the caldera the heat flow rises to 700 milliwatts per square meter. This dramatic increase is compelling evidence for the lateral extent of the heat source in the shallow crust. Moreover, heat-flow values of some 1,500 milliwatts per square meter at West Thumb and Mary Bay probably reflect the flow of heat out of a shallow hydrothermal system under the lake. The measurement of temperatures of 104 degrees Celsius only four meters below the lake floor, together with the results of seismic profiling (in which the floor is bombarded with sound waves and the resulting echoes are recorded), reveals the possibility of steam-filled sediments at the top of a shallow hydrothermal system.

The total heat flow (conductive and convective together) through the Yellowstone caldera is due both to a high regional heat flow and to thermal energy



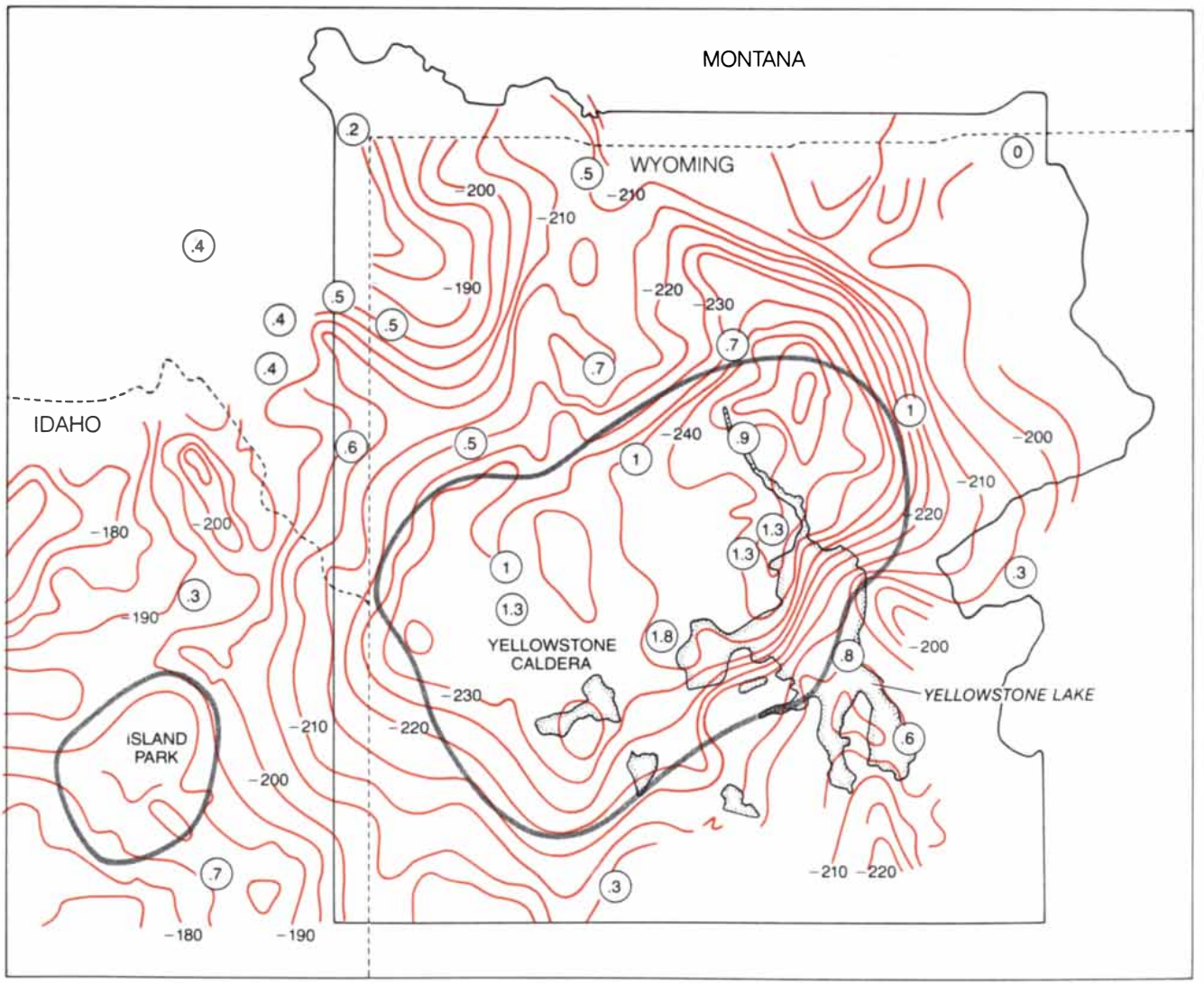
BALLOON DIAGRAMS are stereographic projections of ground motion that help geologists to determine the orientation of faults involved in earthquakes. The size of the balloon gives the strength of the earthquakes at that location. The black area of the balloon indicates where the ground was compressed or became denser; the white area indicates where the ground was extended or became less dense. The arrow marks the inferred direction of the horizontal component of the ground motion. The colored contour lines give the vertical displacement (in millimeters) of the surface of Yellowstone National Park with respect to a bench mark on the eastern side of the park.

from shallow localized sources in the crust. The heat transported to the surface by the convective hydrothermal system for at least the past 20,000 years (and probably for much longer) is a result of more than just the cooling of the volcanic rocks of the plateau. Liquid magma clearly existed quite recently in the chamber under Yellowstone and is possibly still there today. The large flow of heat through the caldera is due to the cooling and crystallization of a body of rhyolitic magma at a depth of a few kilometers and to the circulation of ground water deep enough in the caldera fractures to heat and drive the hydrothermal convection.

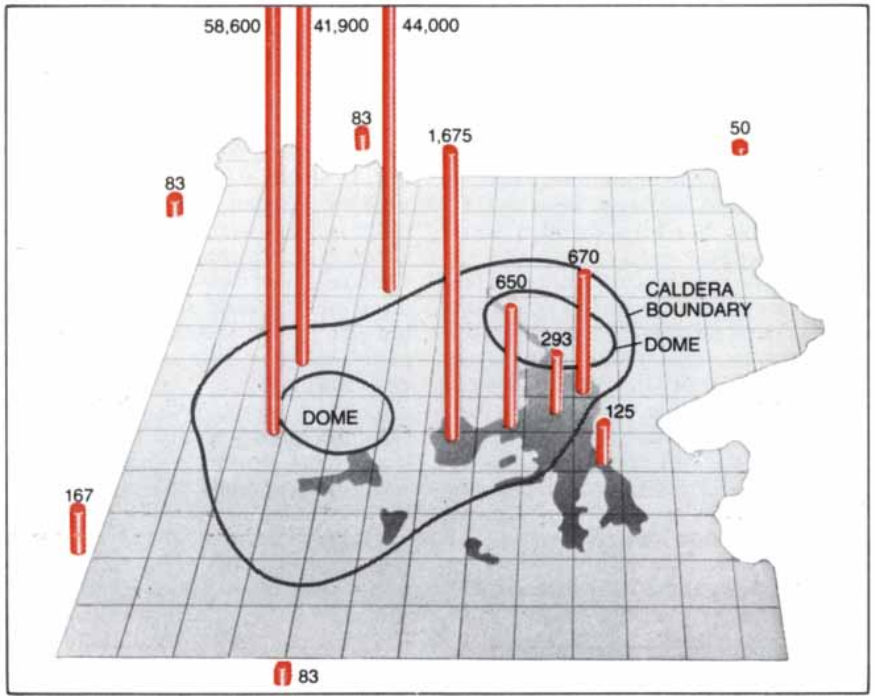
Earthquakes in Yellowstone are the result of brittle fracturing and faulting in the upper 10 to 20 kilometers of the crust. Investigations of the location, length, displacement and age of the faults in the Yellowstone area and the surrounding region reveal much about their tectonic history. The tectonic activity that began about 17 million years ago in much of the western U.S. has resulted both in the extension of the crust and in significant uplift. For example, since that time the Great Basin of Utah and Nevada has been elevated about 1.5 kilometers.

The uplift and the concomitant extension sustain the topography of parallel valleys and mountain ranges that are bounded by large faults such as the Wasatch Front of Utah and the Sierran Front of California and Nevada. Yellowstone, which lies in the northeastern part of the uplifted expanse, has undergone similar topographical changes. The spectacular escarpment on the east side of the Teton Range reflects a fault zone that extends to the north below the rhyolitic flows of the Yellowstone caldera. Over a period of at least 10 million years the rocks on one side of this fault have been vertically displaced by more than four kilometers with respect to the rocks on the other side. North and west of the caldera the trends of the faults shift to northwesterly ones. And farther west the Hebgen Lake and Centennial faults run westward at 90 degrees to the Teton fault. Internal structures of the Centennial and Teton ranges tilt toward the axis of the Snake River Plain and are buried by young volcanic rocks near the plain's margins. That suggests a crustal downwarping.

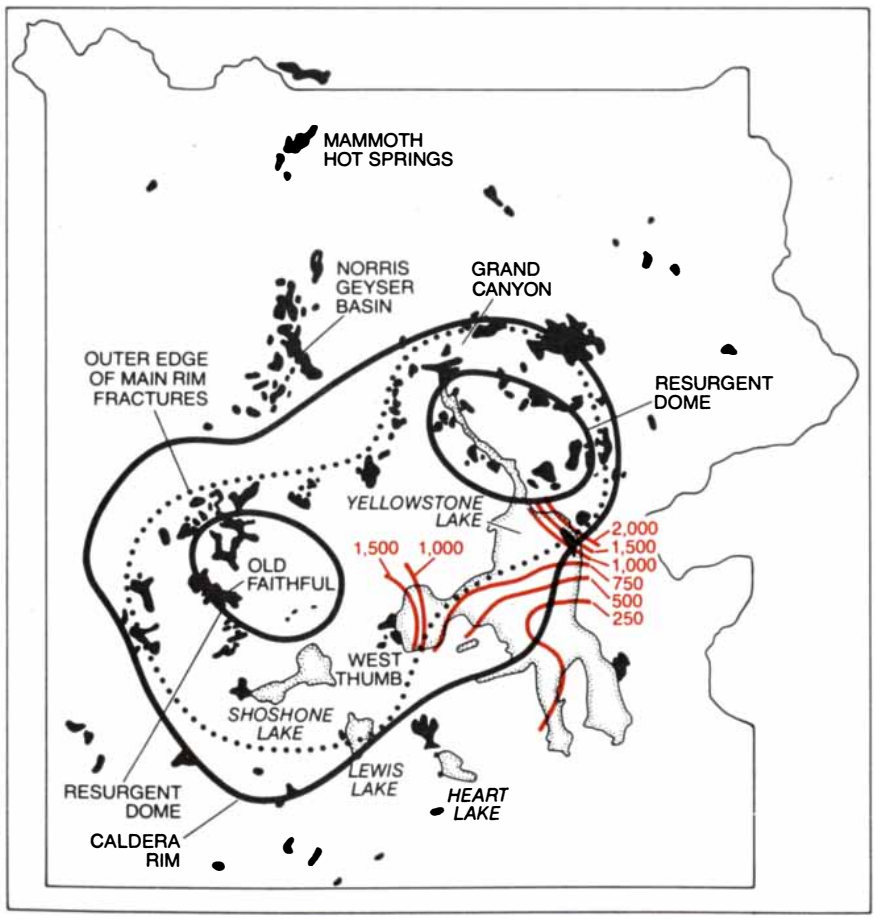
In other words, Yellowstone constitutes the intersection of three tectonic trends: the northeast-trending downwarp of the Snake River Plain, the north-trending faults south of the Yellowstone Plateau and the east-to-southeast-trending faults to the west and the north. The intersection of the trends



CONTOURS OF GRAVITATIONAL ACCELERATION measured in milligals (a milligal is equal to 10^{-3} centimeter per second squared) reveal that the material under the caldera is much less dense than the surrounding material. Each circled number gives the delay in the travel time of an earthquake compression wave (*P* wave) recorded on a seismograph at the circle. In general a delayed signal corresponds to a decrease in velocity of the material under the seismograph. The substantial delays of as much as 1.8 seconds (from earthquakes between 2,000 and 10,500 kilometers away) at seismographs on the caldera suggest the presence of low-velocity material under it.



FLOW OF HEAT out of the Yellowstone Plateau, resulting from conduction and convection, is given in milliwatts per square meter. The heat flow out of the bottom of Yellowstone Lake, which was measured by Paul Morgan and D. D. Blackwell of Southern Methodist University, is due only to conduction because impermeable sediments inhibit hydrothermal convection.



MAP OF HYDROTHERMAL FEATURES of Yellowstone (geysers, steam vents and hot springs) shows the heat-flow contours (*color*) in milliwatts per square meter for Yellowstone Lake. The caldera that formed in the third cycle of volcanism has two ringlike fracture zones.

suggests that Yellowstone lies at the focus of fracturing and stress that helped to localize much of the volcanism and crustal deformation. Extensive earthquake activity indicates that many of the faults are still active.

The exact locations of older earthquakes in Yellowstone National Park are not known because there were no seismographs in the park before the early 1960's, but the general distribution of the earthquake epicenters can be reconstructed from personal accounts of the intensity of the tremors. Such reports indicate that in the past century there have been many more earthquakes in and near Yellowstone than there have been in the surrounding areas of Montana, Wyoming and Idaho. The strongest recorded earthquake in the Rocky Mountains is the Hebgen Lake shock of 1959, the epicenter of which was a few kilometers west of Yellowstone. With a magnitude of 7.1 on the Richter scale, the earthquake was felt over an area of 1.5 million square kilometers. The surface was displaced by as much as six meters along one of two large faults associated with earthquake. The shock waves triggered a massive avalanche of rocks that dammed the Madison River; they also tilted the ground along the northern shore of Hebgen Lake downward by as much as six meters. Earthquakes as strong as this one have undoubtedly occurred in the area at least once every few hundred or few thousand years.

Some of the earthquakes recorded in the western part of the park over the past 20 years are aftershocks of the 1959 Hebgen Lake shock. Seismic studies, however, reveal a high incidence of earthquakes in a zone extending eastward 50 kilometers from the fault zone of Hebgen Lake to the northwest side of the Yellowstone caldera. The foci of these earthquakes are as deep as 16 kilometers. This zone of seismic activity extends eastward to the vicinity of the Norris Geyser Basin, where the strongest shock had reached a magnitude of 6.

In and near the caldera itself earthquake activity is episodic and clustered: a host of earthquakes occur in a short period of time in a limited area without a main shock. Laboratory models suggest that these "swarms" of earthquakes, which are common in areas of active volcanism, are related to concentrated stresses. In Yellowstone's hydrothermal areas such stresses could be the result of high fluid pressures and high temperatures. The Norris Geyser Basin probably has Yellowstone's shallowest thermal reservoir with the highest temperature (more than 275 degrees C.). The close association of seismic activity and intense hydrothermal activity in the basin suggests that fractures caused by earthquakes may serve as conduits for the flow of hot water above a shal-

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low heat source. Southeast of the Norris Geyser Basin the earthquake activity becomes more scattered, with the maximum depth of the earthquake foci seldom exceeding eight kilometers.

The uplift and subsidence of the crust in the Yellowstone area is the result of tectonic and seismic activity. Absolute values for the uplift and the subsidence cannot be determined because there are no stationary points of reference against which the changes in elevation could be measured. What is known is the change in elevation of areas of the park in relation to certain bench marks established in 1923 and resurveyed in the 1970's. John R. Pelton of the University of Utah and one of us (Smith) found that the contours of changes in elevation outlined an elongated area of 3,500 square kilometers coincident with the Yellowstone caldera. In relation to a bench mark east of the caldera the area has risen as much as 700 millimeters. The maximum measured uplift is between the two resurgent domes, where the peak rate of uplift has been more than 14 millimeters per year. Such a high rate of uplift is comparable to the rates measured for active volcanoes on Hawaii and Iceland.

The uplift could be the result of an increase in the pressure in a confined magma body, the increase in turn being the result of an exsolution of gas or an influx of magma from under the body. Alternatively, the uplift could be the result of tectonic stresses in the crust that are not specifically related to the movement of magma.

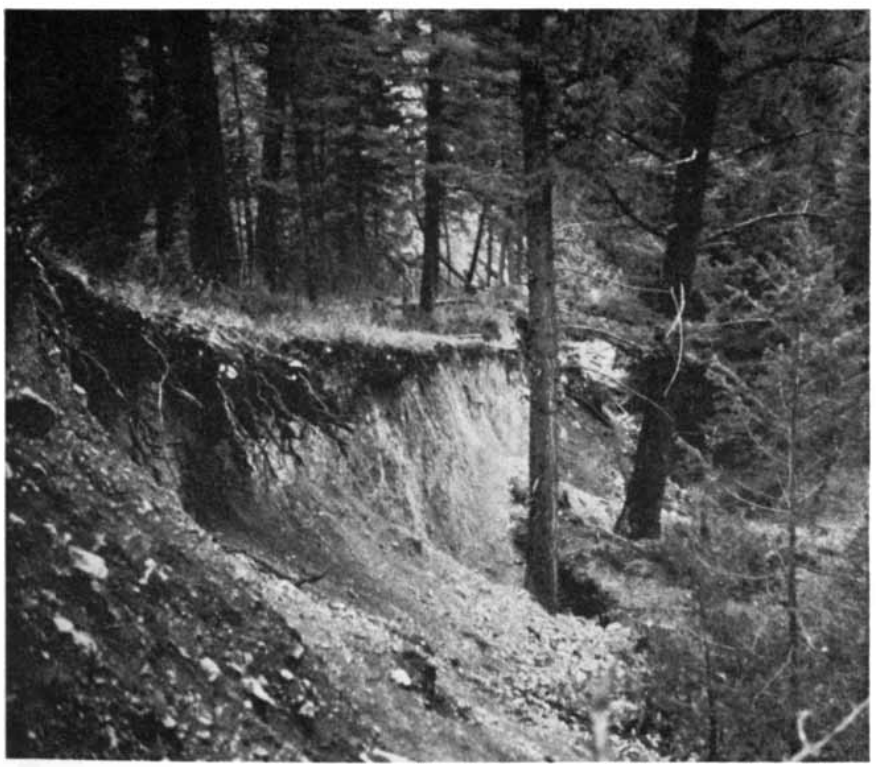
Surveys of the region surrounding Yellowstone reveal that the park itself is part of a larger area that is being uplifted about six millimeters per year, and that the Snake River Plain is subsiding relatively from two to six millimeters per year. In 1977 investigators at the University of Utah began monitoring uplift and subsidence in Yellowstone by measuring the acceleration of gravity at various points. If the density or the mass of the crust does not vary, changes in the acceleration of gravity at the surface can be attributed to changes in elevation. Measurements of gravitational acceleration can be made to a precision of about 3×10^{-3} milligal (a milligal being 10^{-3} centimeter per second squared), which corresponds to a change in elevation of about 10 millimeters. In five or 10 years the investigators will measure the gravitational acceleration at the same points so that the change in elevation can be calculated.

The subsurface geological structure of Yellowstone has been investigated by deep-sounding geophysical techniques that measure variations in density, in the velocity of seismic waves, in electrical conductivity and in magnetic susceptibility (the capacity of a material to become magnetized). Such measurements in conjunction with the record of volcanism provide a picture of the physical properties of the crust that influence phenomena at the surface. H. M. Iyer of the Geological Survey has measured the time it takes a distant earthquake compressional wave (a *P* wave) to travel from the epicenter to seismographs in Yellowstone. If the earth were homogeneous, the travel times would be identical for equivalent distances. Any delay or advance in the travel time indicates a change in the velocity below the surface. Seismographs in the vicinity of the Yellowstone caldera have recorded travel-time delays of as much as 1.8 seconds in *P* waves from earthquakes between 2,000 and 10,500 kilometers away. Delays of no more than .5 second were recorded in the area surrounding the caldera. Modeling of the *P*-wave delays under Yellowstone indicates a 15 percent reduction in velocity within the crust and a 5 percent reduction in velocity in a region that may extend as much as 250 kilometers into the upper mantle.

Measurements at 900 stations on the caldera and its immediate surroundings indicate that the gravitational acceleration is 60 milligals less than it would be if the earth below the caldera were homogeneous. Quantitative modeling has shown that the mass deficiency responsible for the 60-milligal anomaly could be due not only to low-density sediments in the caldera but also to low-density material in the subvolcanic basement. Such material could be magma or a solidified low-density igneous body.

Which of these possibilities is the most likely? A mathematical model incorporating both the gravity data and the *P*-wave time-delay data, employed by Jeffrey A. Evoy of the University of Utah, indicates that Yellowstone is underlain to a depth of at least 250 kilometers by a low-density, low-velocity body. Below this body is denser material. Such a structure is consistent with geological interpretations suggesting that a voluminous shallow chamber may consist at least partly of magma containing much silicon dioxide, whereas smaller pockets of magma with less silicon dioxide in the lower crust and the upper mantle are more dispersed.

Information about temperatures below the surface can be inferred from the magnetic properties of rocks. Below a depth called the Curie depth the rocks have reached a threshold temperature (the Curie temperature) where they are not magnetic. For pure magnetite the Curie temperature is 580 degrees C., and for other common crustal materials it is about 560 degrees. In the Yellowstone area the Curie depth is thought to be 10 kilometers below the surface, but in places under the caldera it may be as shallow as six kilometers. The Curie depth for some other areas of the continental U.S. is between 15 and 30 kilome-



ESCARPMENT OF THE RED CANYON FAULT, which is three kilometers north of Hebgen Lake in Montana and 10 kilometers west of the park, was vertically displaced by several meters by the Hebgen Lake earthquake of August, 1959. The quake had a magnitude of 7.1.

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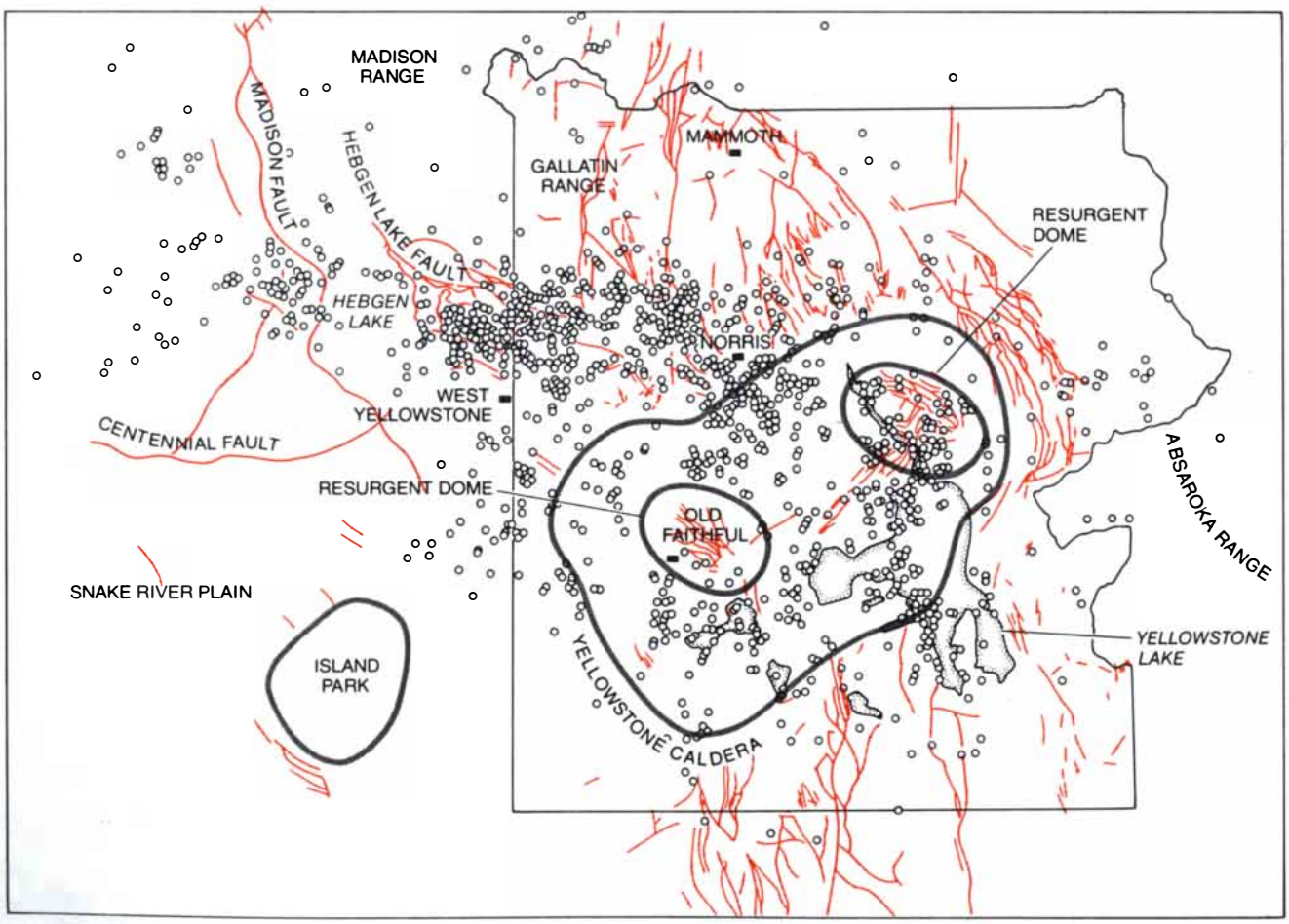
ters. This of course means that the rock under Yellowstone reaches a temperature of 560 degrees at a shallower depth than the rock under these other areas does. Measurements of the electric conductivity of the material under Yellowstone indicate that the material at this depth is a good conductor. Materials at high temperatures often are good conductors, and so the magnetic and electrical investigations are in agreement.

All the geophysical data point to an anomalous crustal and upper-mantle structure under Yellowstone. Low seismic-wave velocities, low densities, high electric conductivity and a shallow Curie depth all favor a crustal body at high temperatures. At between five and 10 kilometers below the surface the crustal material apparently becomes so hot and weak that it cannot fracture, although it can deform by flow and creep. Although it is not known with certainty whether some of this material is currently a liquid, much evidence points to that conclusion.

It is time to relate the geophysical picture of Yellowstone to the tectonic and volcanic history of the surrounding areas, particularly the eastern part of the Snake River Plain. We mentioned above that the Laramide mountain building took place in an environment of crustal shortening with the convergence of two lithospheric plates. The plates were the one forming the floor of the Pacific and the one carrying the continent of North America. At the time of the plates' convergence andesitic volcanism was prevalent on the continent. Over the past 30 million years the large-scale tectonics of the western U.S. has changed substantially because of a gradual transition from the comparatively simple convergence of two plates to the complex interaction of three plates: the North American plate, the Pacific plate and the Juan de Fuca plate. Displacement along the San Andreas fault in California indicates that currently the relative motion between the North American and the Pacific plate is chiefly horizontal. Much of the western U.S. is now undergoing tectonic extension and has experienced both rhyolitic and basaltic volcanism of the kind that has occurred in Yellowstone.

During this period of regional tectonic extension the eastern Snake River Plain has evolved in a remarkable way. Some 15 million years ago the eastern Snake River Plain and the Yellowstone Plateau did not exist. Since that time basalt and rhyolite have erupted in a systematic sequence propagating northeastward from near the borders of Idaho, Nevada and Oregon along a line that is now the axis of the eastern Snake River Plain. If an observer could go back to any given time in this period, he would see a "Yellowstone": a topographically high area of voluminous rhyolitic volcanism and extensive thermal and seismic activity. Yet on a subsequent visit he would find "Yellowstone" farther northeast than it had been. As the zone of voluminous rhyolitic volcanism propagates northeastward at the rate of between two and four centimeters per year basaltic volcanism continues to occur periodically in its wake. The regions of past active rhyolitic volcanism, which have subsided, have been flooded by basalts to form the eastern Snake River Plain.

A close association of rhyolitic and basaltic magma has characterized the development of Yellowstone and the Snake River Plain. Many explanations have been put forward to explain the origin of the two kinds of magma, the most promising hypothesis being that two different source materials melted partially to form two distinct liquids, one rhyolitic and the other basaltic.



MAP OF EPICENTERS (*black circles*) of more than 1,500 earthquakes with magnitudes on the Richter scale of between 1 and 6 comes from measurements made on seismographs of the U.S. Geological Survey and the University of Utah. The peak focal depth was 16 kilometers.

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It will jump shift if that's its logical response and, of course, it recognizes doubling and re-doubling. It respects preemptive bids and will make them itself, if it so chooses. Via its display, the game moves along. It shows illegal bids and displays reneges or revokes. It indicates vulnerability and identifies dealer. At the end of each game, the above and below line scores are displayed.

SET UP PROBLEMS

Most of the keys on the keypad are self-explanatory. Many are only used when you are setting up specific problems through the problem mode (PB) key. As an example, when teams are vulnerable, the unit automatically lights to indicate vulnerability. It is only during the problem mode that you would have to press the "V" key to tell the computer who is vulnerable.

FASCINATING PLAY

The Challenger comes complete with 3 felt playing fields onto which you place the dealt cards. There are two ways to "deal." To play out specific problems, where you know what cards each hand should contain, you would enter them directly from the keyboard. To set up an actual game, you must advance the (PL) player key. This lets the computer know which hands it is playing and which are real people hands. The Challenger comes with its own deck of cards. Each card is marked, quite like the new price codes appearing on grocery packages.

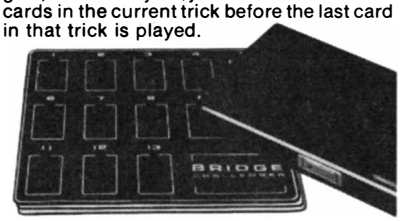
When dealing a game, the computer will ask for the cards that belong to it. It assumes that you will deal to all human players in the traditional fashion. For the computer's hands, you merely run the marked cards across the unit's optical scanner and place them face down on the respective north, south, east, or west fields. The Challenger will tell you which of its hands you are dealing.

IT WON'T CHEAT

One of our concerns was, could the Challenger cheat? If, for example, while playing as an opposing team, could it "peek" at both of its hands? The answer is a resounding "no." It keeps each hand it plays entirely separate from the others it is playing, as though it truly were several different people.

Play is easy. To communicate with the computer, you must press the (EN) enter key for everything *you* do. Everything *it* does must be acknowledged by you by pressing the "A" key.

There is even a Bid Review (BR) key that will permit players to review the bidding before the first card is dropped. Once play begins, the BR key may be used to review all cards in the current trick before the last card in that trick is played.



SOME SPECIFICATIONS

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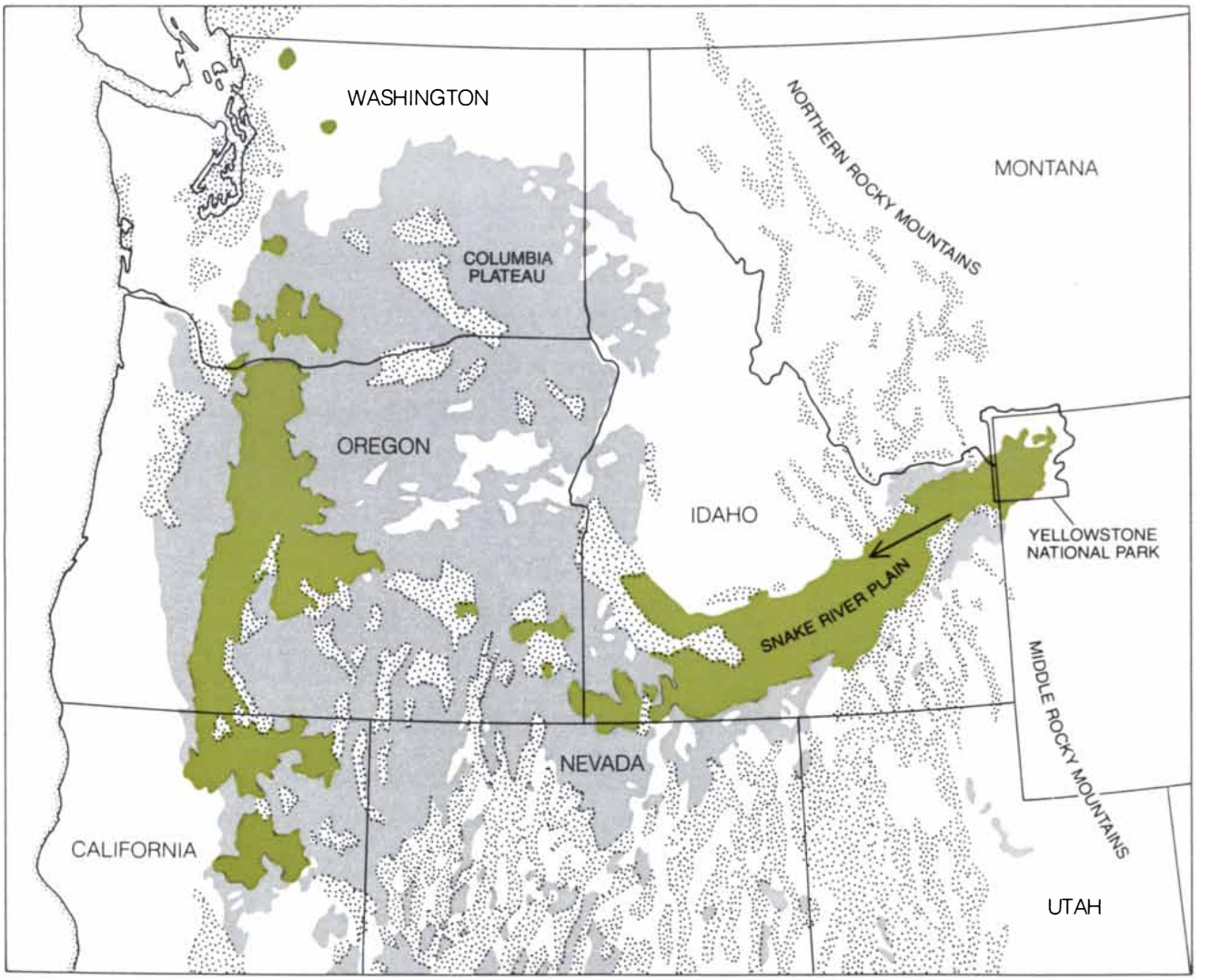
(This explanation may seem trivial, but it is not. The two kinds of magma could conceivably have formed not out of two materials but out of a single material with two immiscible ingredients.) The basaltic magma is quite similar to the basaltic magma that forms under oceanic islands; in both settings the basaltic magmas are partial melts of the earth's upper mantle. The origin of the rhyolitic magma is probably the partial melting of metamorphic rocks of the earth's lower crust.

The generation of basaltic magma by the partial melting of the upper mantle is the fundamental process that drives the Yellowstone magmatic system. The continuing uplift and tectonic extension of broad areas of the Yellowstone region requires the upward displacement of the mantle. As the crust is stretched and the underlying mantle moves upward the reduction of pressure may cause materials with low melting points to begin melting. Basalt is the result of this partial melting, as it is in the floor of the deep ocean, where the mantle lies only a few kilometers below the solid surface. The flowing of the basaltic magma from the mantle to the crust transports heat upward. The material of the lower crust is under less pressure and has a higher concentration of silicon dioxides than the underlying mantle. As a result when this material melts, it yields magma with a higher concentration of silicon dioxides. Such magma has a lower temperature, a lower density and a greater viscosity than basaltic magma, and so its buoyancy causes it to rise and accumulate as a large mass in the upper crust.

It seems that rhyolitic magma chambers, such as those that have underlain Yellowstone and Island Park for the past two million years, must have evolved in each successive area of rhyolitic volcanism along the propagating axis of the eastern Snake River Plain. This kind of volcanic propagation has also occurred on Hawaii. The volcanism of Yellowstone and that of Hawaii are remarkably similar, with the difference that the Yellowstone system has evolved not under oceanic crust but under continental crust.

In both Yellowstone and Hawaii an area of concentrated melting seems to be fixed and localized within the earth under a moving lithospheric plate. The movement of a plate over each of these hot spots has left a trail of extinct volcanoes, which are milestones marking the passage of the plate. All the islands of the Hawaiian chain were created by a single source of magma over which the Pacific plate passed as it proceeded on a course roughly toward the northeast. The relative motion of the tectonic plates has been reconstructed in detail, but the motion of one plate with respect to another cannot readily be translated into motion with respect to the earth's interior, except in relation to the hot spots anchored in the mantle.



MAP OF THE YELLOWSTONE AREA relates the young tectonic and volcanic features of the park to the tectonic and volcanic features of the rest of the northwestern U.S. The valleys filled with young alluvium (*dots*) reveal mountain ranges and basins bounded by linear faults. The youngest volcanic rocks (younger than two million years) are in color; the older Cenozoic volcanic rocks are in gray. The vector with a magnitude of 4.5 centimeters per year marks the motion of the North American plate with respect to a point deep in the mantle.

The calculated motion of the North American plate with respect to the Hawaiian hot spot is 4.5 centimeters per year to the southwest. The rhyolitic volcanism along the axis of the Snake River Plain and Yellowstone has propagated at about the same rate in the opposite direction.

What is the mechanism that generates hot spots? Several mechanisms have been proposed, but it is difficult to choose among them because the circulation of the material in the mantle is still poorly understood. According to one hypothesis, the hot spots are surface manifestations of "plumes": rising columnar currents of hot material. Another hypothesis considers the hot spots to be the result of a localized overabundance of heat-generating radioactive material in the mantle. According to another explanation, the frictional heating of the base of the lithosphere as it moves over the underlying asthenosphere could generate a hot spot if the conditions were right to sustain the heat. Still another explanation locates the hot spots at the tips of linearly propagating fractures of the lithosphere that are driven by extensional forces. The hot spot anchored under Yellowstone is more accessible to investigation than most of the other continental hot spots, and so the continuing studies of the park should help in identifying the generative mechanism.

Does the picture of Yellowstone that has emerged out of investigations of its volcanic and tectonic history suggest anything about the future evolution of the park? We think it does, although not enough information has yet been gathered to make detailed predictions. The extent of past volcanism and uplift, the length of time between volcanic eruptions, the probable existence of a strong heat source just below the surface, the swarms of earthquakes, the rhyolitic volcanism in the caldera and the current rapid rate of uplift all point to future volcanic activity in the Yellowstone Plateau. The high heat flow, the delays in earthquake *P* waves and other geophysical data are consistent with the probable existence of magma in the crustal chamber under the plateau. The evidence does not indicate what form the future volcanism might take; it could consist of relatively small eruptions of rhyolite and basalt at the margins of the plateau, medium-sized eruptions of rhyolitic lava within the caldera or a major ash flow. Any renewal of volcanism in the park would probably be preceded by phenomena such as localized earthquake activity and increased gas emissions. Future earthquake activity is a certainty, presumably including shocks at least as strong as the Hebgen Lake earthquake. It is also known that the surface of the Yellowstone caldera will continue to undergo deformation.

Hydrogen Storage in Metal Hydrides

The exploitation of hydrogen as a fuel for motor vehicles requires a method for storing it safely and compactly at ambient temperature. Forcing it into the gaps among metal atoms may be the best approach

by J. J. Reilly and Gary D. Sandrock

What fuel will power the motor vehicles of the world when petroleum is no longer an economic source? Hydrogen is high on the list of candidates, but the problem of storing it safely and compactly has seemed to stand in the way. Now a solution to that problem is at hand in the form of metal hydrides: chemical compounds of hydrogen and metals. Already hydrogen stored in this way has served as a fuel for buses operated experimentally in the U.S. and West Germany and for an experimental automobile. Metal hydrides have also served on an experimental basis as energy-storage compounds for leveling peak demands on an electric-power system. In addition they hold promise for such applications as refrigeration, heat pumps and heat engines.

Hydrogen is by far the most abundant element in the universe. It is the raw material from which all the other elements have been made in the interior of stars. Moreover, it is chemically unique in that it can behave either as an alkali metal or as a halogen, that is, in forming a chemical bond it can either donate an electron (as an alkali metal does) or accept one (as a halogen does). This property is useful in processes that make chemical compounds by combining hydrogen with one or more elements.

Since hydrogen on the earth is almost always combined with another element or elements in a compound such as water, it must be separated in order to serve human purposes. The annual worldwide production of pure hydrogen is about 10 trillion cubic feet. The main consumer is the chemical industry, which utilizes hydrogen as a raw material in the manufacture of a large number of products ranging from plastics to fertilizers.

Hydrogen is attractive as a fuel because it has the highest density of energy per unit of weight of any chemical fuel, is essentially nonpolluting (the main byproduct of burning it is water) and can serve in a variety of energy converters ranging from internal-combustion engines to fuel cells. In the near future hydrogen could be extracted relatively cheaply from coal. In the more distant future, when fossil fuels are no longer economic, hydrogen could be separated from water by the process of electrolysis, driven by nuclear, solar or other forms of energy.

The present methods of storing hydrogen are suitable and safe for the present industrial uses of hydrogen, but they would never do for moving vehicles or for special applications where compactness is required. For example, hydrogen stored as a compressed gas calls for large and heavy vessels. At a typical pressure of 136 atmospheres hydrogen gas in a steel container weighs about 30 times more than an equivalent amount of gasoline, and 99 percent of the weight is in the container. The same container takes up about 24 times more space than a container holding the equivalent amount of gasoline. Hydrogen as a liquid is useful in certain circumstances, but the energy consumed in the liquefaction process is a major fraction of what could be generated by burning the hydrogen. Moreover, liquid hydrogen would present a serious and probably insoluble safety problem if it were to be considered as a common fuel for use in motor vehicles. Liquid hydrogen is extremely cold (it boils at 20 degrees Kelvin, or -253 degrees Celsius), and it is highly volatile if it is spilled. Metal hydrides, in contrast, store hydrogen compactly and safely at ambient temperatures.

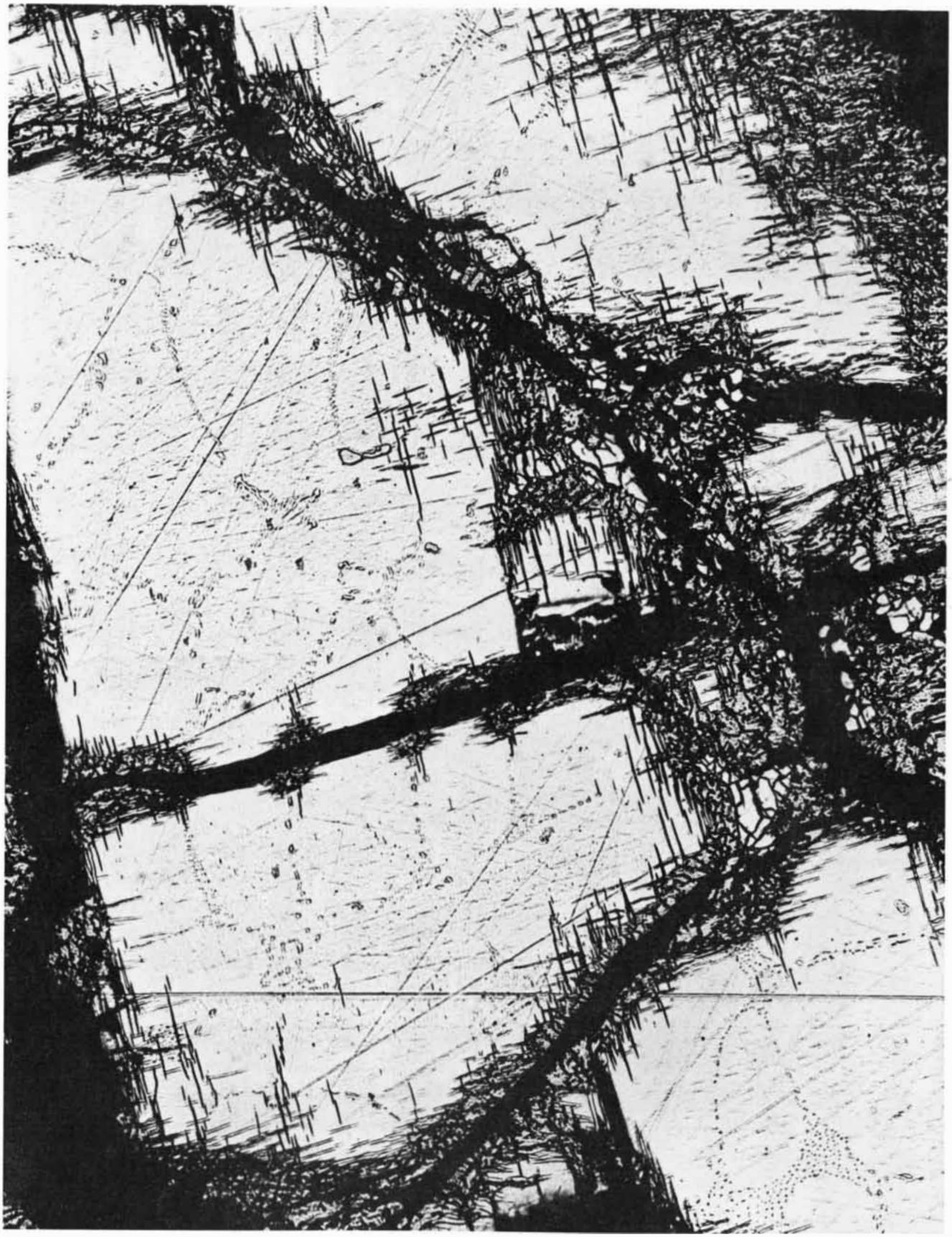
Most elemental metals will form metal hydrides. In many cases the reaction is simple and direct, consisting merely of bringing gaseous hydrogen (H_2) in contact with the metal (M). In chemical shorthand a typical reaction can be written $M + H_2 \rightleftarrows MH_2$. The arrows point in two directions, which means that the reaction is reversible. Its direction is determined by the pressure of the hydrogen gas. If the pressure is above a certain level (termed the equilibrium pressure), the reaction proceeds to the right to form the metal hydride; if it is below that level, the metal hydride decomposes into the metal and gaseous hydrogen. The metal is in the form of particles in order to provide a large surface area for reaction with the gas.

The primary reason metal hydrides have been proposed for the storage of hydrogen as an energy carrier is that they accommodate an extremely high density of hydrogen. Indeed, it is possible to pack more hydrogen into a metal hydride than into the same volume of liquid hydrogen. A consideration of the mechanism by which a metal hydride is formed reveals why such a high packing density is possible.

When gaseous hydrogen is brought in contact with a metal that forms a hydride, hydrogen molecules (H_2) are adsorbed onto the surface of the metal. Some of the molecules dissociate into hydrogen atoms (H), which then enter the crystal lattice of the metal and occupy specific sites among the metal atoms. Such locations are called interstitial sites. They must have a certain minimum volume in order to easily accommodate the hydrogen atom.

As the pressure of the gas is increased, a limited number of hydrogen atoms are forced into the crystal. Usually at some critical concentration and pressure the metal becomes saturated with hydrogen and goes into a new phase: the metal-hydride phase. If the hydrogen pressure is now slightly increased further, much greater amounts of hydrogen are absorbed. Ultimately all the original hydrogen-saturated metal phase will be converted into the metal-hydride phase. Since metal crystals have many interstitial sites, it is possible for them to accommodate large amounts of hydrogen in a highly compact manner. In many hydrides the number of hydrogen atoms in the crystal will be two or three times the number of metal atoms.

Although the density of hydrogen by volume in a hydride is high, the density by weight is less satisfactory (compared with pure hydrogen) because of the weight of the associated metal. It is only the high density of energy by



PARTIALLY HYDRIDED PARTICLES of an alloy of iron and titanium are seen magnified some 400 diameters in this metallographic cross section prepared by one of the authors (Sandrock) at the Inco Research and Development Center. The heavily cracked areas near the surfaces of the particles are already hydrided. Since the hydride is less dense than the metal, stresses induced in the crystal structure by the increase in volume as the reaction proceeds cause the particles to crack and new surfaces to be exposed. After the initial hydriding step the particles have a much higher ratio of surface area to volume than before, and they then react readily with a charge of hydrogen.

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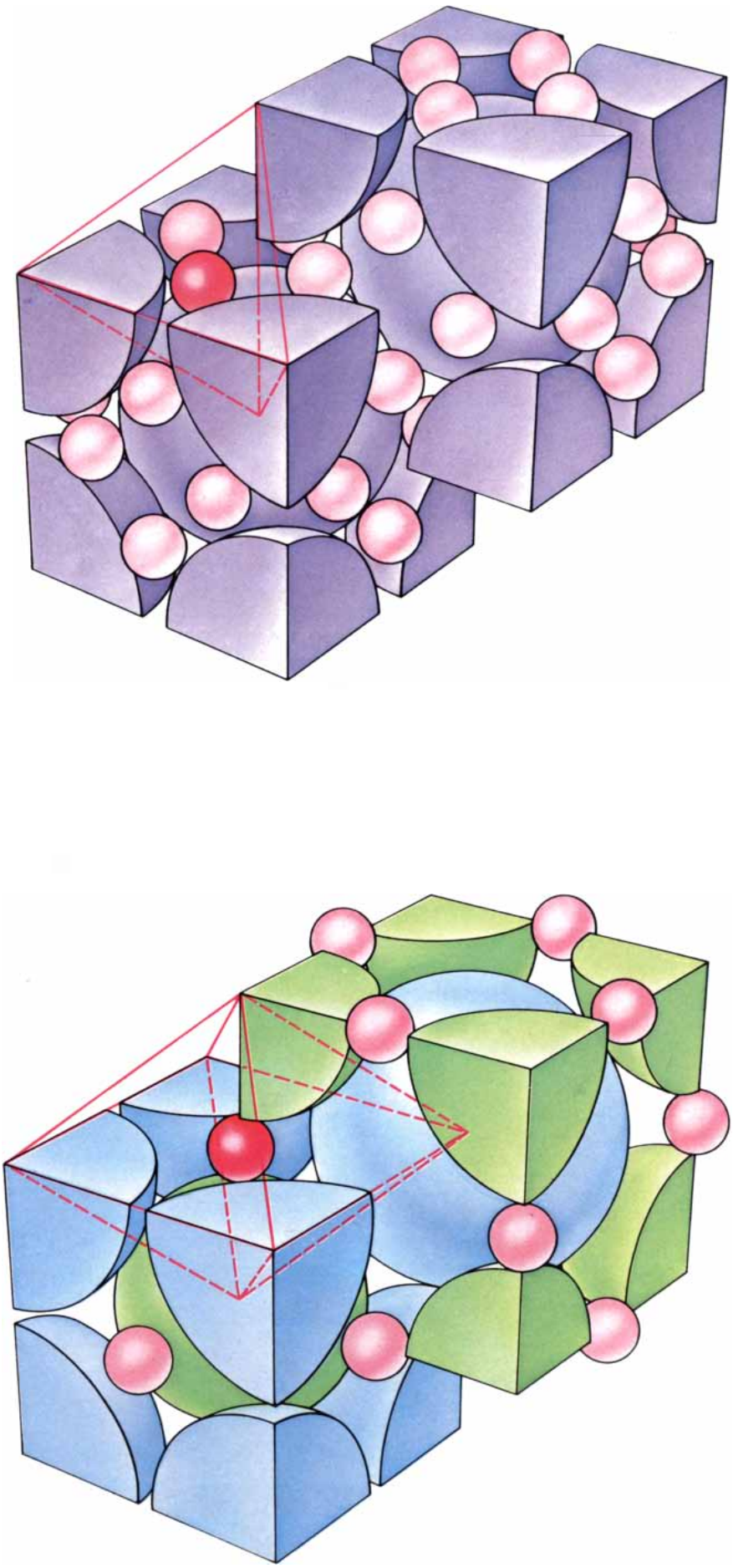
weight of hydrogen as a fuel (approximately three times the density of gasoline) that makes metal hydrides feasible for the storage of energy.

Another fundamental property of metal hydrides is their heat of formation, the heat given off when the hydride is formed by the reaction of hydrogen with the metal. In order to decompose the hydride back into its original constituents, metal and hydrogen gas, the same amount of heat must be added to the system; it is termed the heat of decomposition. The heat effect can be quite large. It is roughly proportional to the stability of the hydride, that is, to the ease or difficulty of taking hydrogen out of the system. The stabler the hydride is, the higher the temperature and heat of decomposition will be. The fact that heat is evolved when hydrogen is stored in a metal hydride and is required when hydrogen is released is of great practical consequence. It is a primary consideration in the design of systems for storing hydrogen in metal hydrides.

If a material is to serve as a medium



INTERSTITIAL SITES where hydrogen atoms can fit into the crystal structure of a metal or an alloy are characterized as being either tetrahedral (*top*) or octahedral (*bottom*). In these space-filling atomic models of two body-centered-cubic-type structures the potentially occupied interstitial sites are identified by the small pink balls. Two interpenetrating unit cells of the host structure are depicted in each case. In niobium, shown at the top, both unit cells of the metal have a niobium atom (*purple ball*) at the center. In the iron-titanium alloy shown at the bottom one unit cell has an iron atom (*green ball*) at its center and the other unit cell has a titanium atom (*blue ball*) at its center. In both drawings the surrounding metal atoms are truncated at the outer faces of the unit cells. In principle every simple body-centered-cubic metal or alloy has 12 tetrahedral sites and six octahedral sites per unit cell. In niobium, however, only the tetrahedral sites, which are formed by perpendicularly opposed pairs of niobium atoms, can be occupied; one such site is shown here occupied by a hydrogen atom (*red ball in top drawing*). Recent structural studies done at the Brookhaven National Laboratory have shown that in the iron-titanium intermetallic compound only those octahedral sites that are formed by an array of two iron atoms and four titanium atoms can be occupied initially; again one such site is shown occupied by a hydrogen atom (*red ball in bottom drawing*). Although there are corresponding octahedral sites surrounded by two titanium atoms and four iron atoms, they are not occupied in this compound, since there is less room available at such sites for the hydrogen atom. Tetrahedral sites also exist in the iron-titanium alloy, but they are never occupied, probably because of unfavorable energy conditions. When the iron-titanium alloy is fully charged with hydrogen, there is nearly one hydrogen atom for every metal atom, causing a distortion of the crystal lattice and resulting in a more complicated, expanded structure in which virtually all octahedral sites are occupied by hydrogen.

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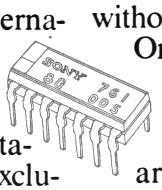

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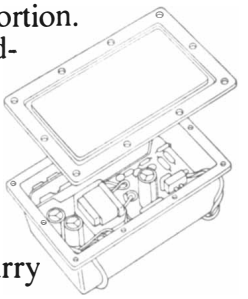

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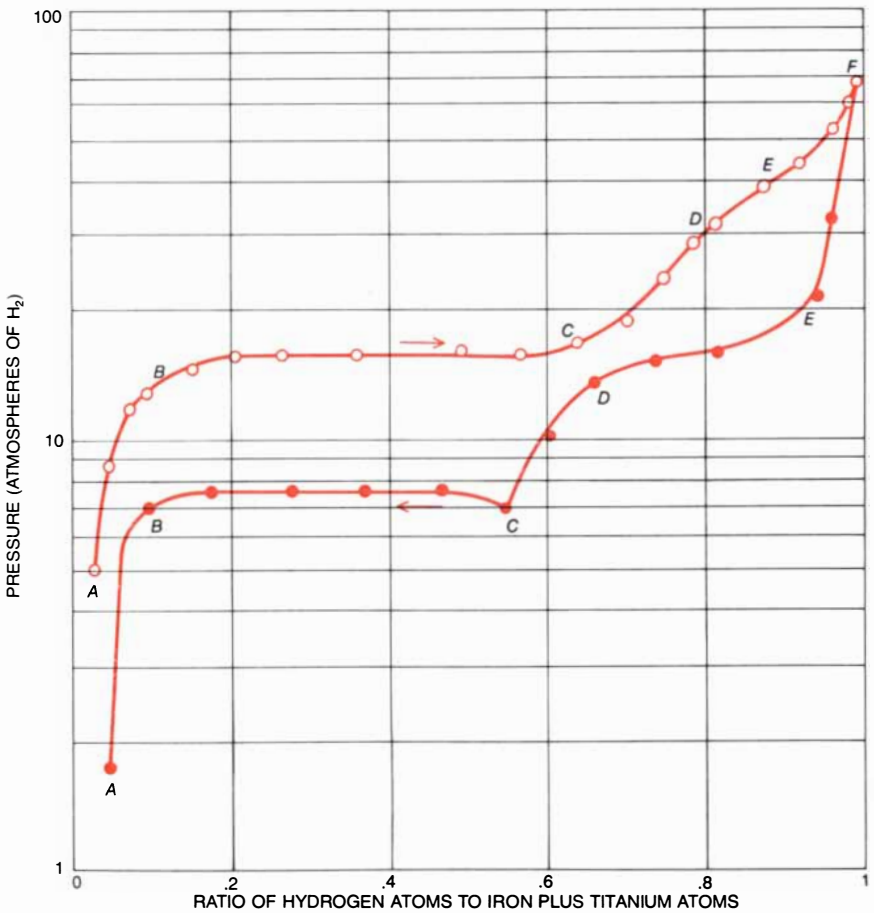
STORAGE MEDIUM	HYDROGEN STORAGE CAPACITY		ENERGY DENSITY	
	BY WEIGHT (PERCENT)	BY VOLUME (GRAMS PER MILLILITER)	BY WEIGHT (CALORIES PER GRAM)	BY VOLUME (CALORIES PER MILLILITER)
MAGNESIUM HYDRIDE (MgH_2)	7	.101	2,373	3,423
MAGNESIUM-NICKEL HYDRIDE (Mg_2NiH_4)	3.16	.081	1,071	2,745
VANADIUM HYDRIDE (VH_2)	2.07	.095	701	3,227
IRON-TITANIUM HYDRIDE ($FeTiH_{1.95}$)	1.75	.096	593	3,254
LANTHANUM-PENTANICKEL HYDRIDE ($LaNi_5H_7$)	1.37	.089	464	3,017
LIQUID HYDROGEN (H_2)	100	.07	33,900	2,373
GASEOUS HYDROGEN (H_2)	100	.008	33,900	271

PROPERTIES of some representative hydrogen-storage mediums can be compared with the aid of this table. Magnesium hydride, the more promising of the two binary hydrides shown, is thought to be only a borderline possibility as a hydrogen-storage medium at present. Of the three ternary hydrides listed the leading contender is iron-titanium hydride. Its main advantage over lanthanum-pentanickel hydride is one of cost. Note that all the metal hydrides listed in the table have a higher hydrogen-storage capacity than an equal volume of liquid or gaseous hydrogen has. (The gaseous hydrogen is assumed to be at a pressure of 100 atmospheres.) The figures given for the energy density of the hydrides refer to their hydrogen component only.



HYSTERESIS EFFECT is observed when isotherms, or equal-temperature curves, are plotted on a graph relating the equilibrium pressure of the hydrogen gas in a metal-hydride system to the hydrogen content of the system. The upper curve represents the equilibrium pressure measured as hydrogen was added to an alloy of iron and titanium; the lower curve represents the equilibrium pressure measured as hydrogen was being removed from the same system. Hydrogen can exist in such a system in several ways: as a solid solution of hydrogen atoms in the metal lattice (*A—B*), as a solution of hydrogen atoms coexisting with the monohydride phase of the compound (*B—C*), as the monohydride phase alone (*C—D*), as both monohydride and dihydride phases (*D—E*) and as dihydride phase alone (*E—F*). Causes of the hysteresis loop are not known, and its magnitude differs between systems. These isotherms were obtained at a constant temperature of 40 degrees Celsius; increasing the temperature increases the pressure.

for storing hydrogen as an energy carrier, which at present is the largest potential application for metal hydrides, it must satisfy a number of criteria. The most important criterion is that it be readily formed and decomposed. In effect the metal-hydrogen system should act as the chemical analogue of a battery, with hydrogen taking the place of electricity. Hence hydrides that do not decompose and evolve hydrogen at fairly low temperatures (say below 300 degrees C.) can be eliminated from consideration. On the other hand, the hydride must not be too unstable in the sense that an impractically high hydrogen pressure is needed to form it. Another important criterion is that the metal forming the hydride should be abundant and inexpensive. It should also hold up under many cycles of charging and discharging. Finally, the material in both the hydrided and the dehydrided state should be at least as safe in ordinary service as common fuels such as gasoline are.

These criteria eliminate all known binary hydrides, consisting of hydrogen and one metal, from consideration except perhaps magnesium hydride (MgH_2). It is a borderline possibility because it will evolve hydrogen (at a pressure of one atmosphere) at a temperature of 289 degrees C. One need not be limited, however, to binary hydrides. Hydrogen reacts as readily with alloys of metals as it does with single metals, and the resulting hydride can have properties quite different from those of the binary hydrides made from each of the constituents of the alloy.

A particularly fruitful area has been the formation of ternary hydrides from intermetallic compounds. A ternary hydride is a compound of two metals and hydrogen. An intermetallic compound is an alloy with a definite range of compositions and an ordered crystal structure different from the structures of the parent metals. Almost all the hydrides that are of interest for storing hydrogen as a fuel are of this type.

The compounds exhibiting the most promise for storing energy are based on iron-titanium hydride ($FeTiH_x$, where x represents a variable number of hydrogen atoms, in this case up to about two). Its properties on an overall basis come closest to satisfying the criteria we have listed. For example, its advantage over another intermetallic hydride, lanthanum-pentanickel hydride ($LaNi_5H_x$, where x is up to about six), is primarily one of cost. Again, although the binary magnesium hydride contains much more hydrogen per unit of weight and would also be cheaper, its high temperature of formation and decomposition makes it much less attractive than iron-titanium hydride, which can be charged and discharged easily at ambient temperature. For these reasons iron-titani-

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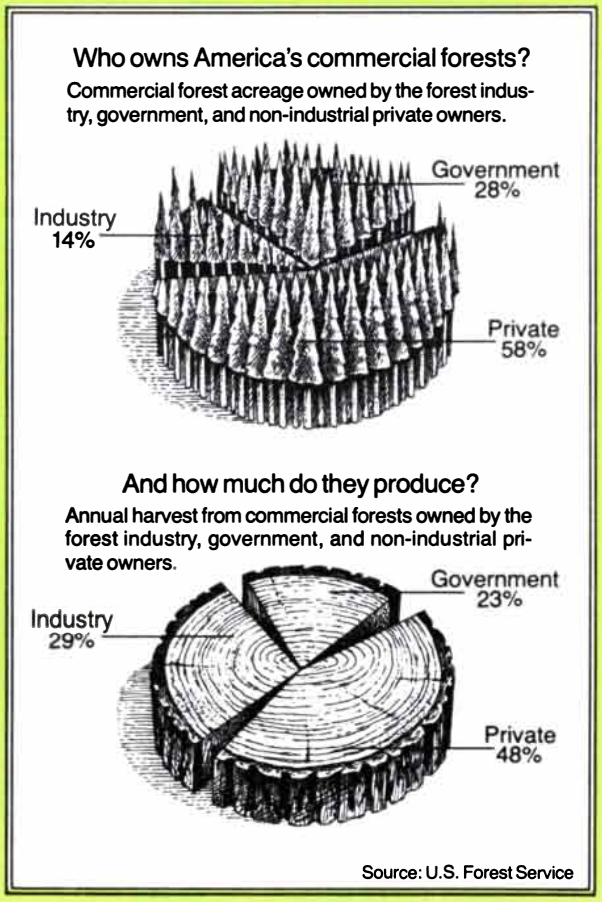

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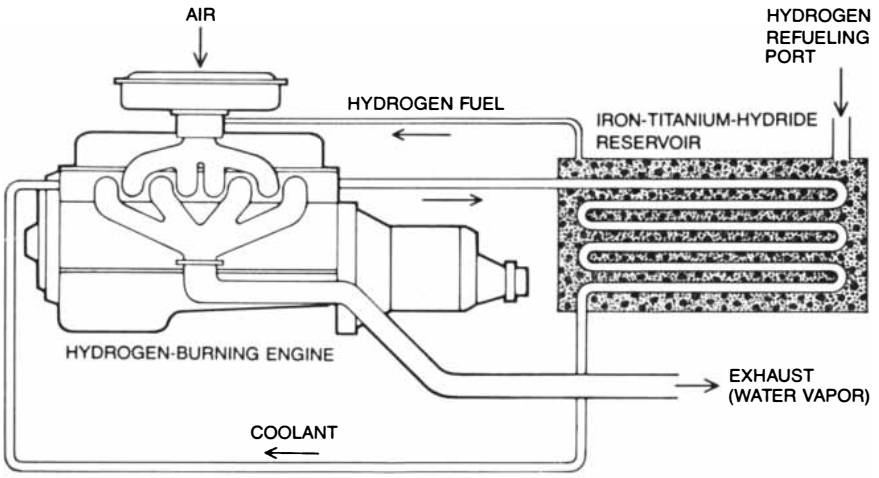

HYDROGEN-STORAGE SYSTEM based on the use of a metal hydride is shown in this schematic diagram coupled with a standard internal-combustion engine that has been adapted to burn hydrogen gas. The heat of decomposition required to release the hydrogen from the metal hydride is supplied in this case by circulating a coolant (water) bearing the waste heat of the engine through a heat exchanger inside the reservoir containing the metal hydride. The heat must be supplied at a rate consistent with the fuel demand of the engine. If the storage medium is iron-titanium hydride, for example, a temperature of at least 10 degrees C. must be maintained by the waste heat from the engine in order to deliver a continuous high flow of hydrogen to the engine at pressures in excess of one atmosphere. If the supply of heat is insufficient, the hydrogen-storage bed will gradually cool, and the flow of hydrogen will decrease until a balance is struck between the rate of hydrogen release and the available heat. When the hydride bed is exhausted, it can be recharged by following the opposite procedure: the bed is brought in contact with hydrogen at a pressure substantially above the equilibrium pressure, and cold water is circulated through the heat exchanger to remove the heat of formation of the metal hydride.

um hydride has so far been the material of choice for most energy-storage applications.

If a virgin alloy is to be made into a hydride for storing hydrogen as a fuel, it must first be "activated." The process is essentially hydriding the alloy for the first time. Certain alloys such as lanthanum-pentanickel ($LaNi_5$) and calcium-pentanickel ($CaNi_5$) can be activated quite easily even at ambient temperature; they react with hydrogen almost immediately in the absence of air. The same is true of an iron-titanium alloy containing about 5 percent manganese.

Pure iron-titanium is difficult to activate, apparently because of a surface barrier that must first be eliminated. The barrier can be broken down by heating the alloy in the presence of low-pressure hydrogen (and in the absence of other gases) to about 400 degrees C. and then cooling it to room temperature; thereafter it will react readily with hydrogen. At that time the hydrogen pressure should be considerably above the equilibrium absorption pressure in order to provide a strong driving force that will make the reaction proceed rapidly.

The hydriding reaction proceeds inward from the surface of the alloy. Eventually the alloy is entirely converted into the hydride, developing many cracks and fissures in the process. This effect greatly increases the ratio of surface area to volume, thereby increasing the rates of reaction when the material is later put through repeated cycles of hydriding and dehydriding.

A problem to be guarded against once such a material has been activated is that it can be poisoned, or deactivated, by the presence of contaminants in the hydrogen gas such as air, carbon monoxide and sulfur dioxide. Different compounds have different degrees of tolerance for such contaminants. For example, iron-titanium is quite sensitive, whereas lanthanum-pentanickel and an iron-titanium alloy modified by manganese are considerably less so. Usually the poisoning is not permanent and can be reversed by repeating the activation procedure that was followed with the virgin material.

POWER SOURCE	ENERGY DENSITY (WATT-HOURS PER KILOGRAM)	CONVERSION EFFICIENCY (PERCENT)	NET ENERGY DENSITY (WATT-HOURS PER KILOGRAM)
LEAD-ACID BATTERY	30–50	70	21–35
LITHIUM-METAL-SULFIDE BATTERY	150	70	105
IRON-TITANIUM HYDRIDE ($FeTiH_{1.7}$)	510	30	153
MAGNESIUM-NICKEL HYDRIDE (Mg_2NiH_4)	1,110	30	333
MAGNESIUM HYDRIDE (MgH_2)	2,332	30	700
GASOLINE	12,880	23	2,962

ENERGY DENSITIES characteristic of various automotive power sources either already in existence or proposed are indicated in this table. As the figures in the column at the right show, metal hydrides lag far behind gasoline in terms of energy density, but they are competitive with electric batteries in this respect. (No allowance has been made in these calculations for the weight of the container holding either the metal hydrides or the gasoline.) The figures for the metal hydrides are based only on the available hydrogen in each case. The particular magnesium hydride tested contained an additive of nickel amounting to about 10 percent by weight.

In considering the potential applications of metal hydrides one should bear in mind that every device for converting energy produces waste heat, which is normally rejected to the surroundings. If a metal hydride is to be feasible for storing hydrogen as a fuel, the heat of decomposition must be supplied from the stream of waste heat. Fortunately with iron-titanium hydride and similar unstable hydrides it is fairly easy to couple a hydride-storage reservoir to an energy converter.

At present the most important use for a rechargeable hydride is as a fuel carrier for hydrogen-powered vehicles. A modern internal-combustion engine can be readily modified to run on hydrogen fuel. Such an engine would be virtually nonpolluting, since the exhaust would consist only of water and traces of nitrogen oxides. There is also good evidence that such an engine has significantly better thermal efficiency than a corresponding gasoline engine.

Metal hydrides do suffer a considerable weight penalty compared with gasoline. Nevertheless, they should not be discounted for automotive applications, since they are quite competitive with another alternative carrier of automotive energy: the electric battery. The virtues of metal hydrides in this respect have not gone unnoticed. Several hydrogen-powered vehicles have been built and demonstrated. In most of them the fuel is a metal hydride based on iron-titanium, because such hydrides operate in a favorable range of pressure and tem-

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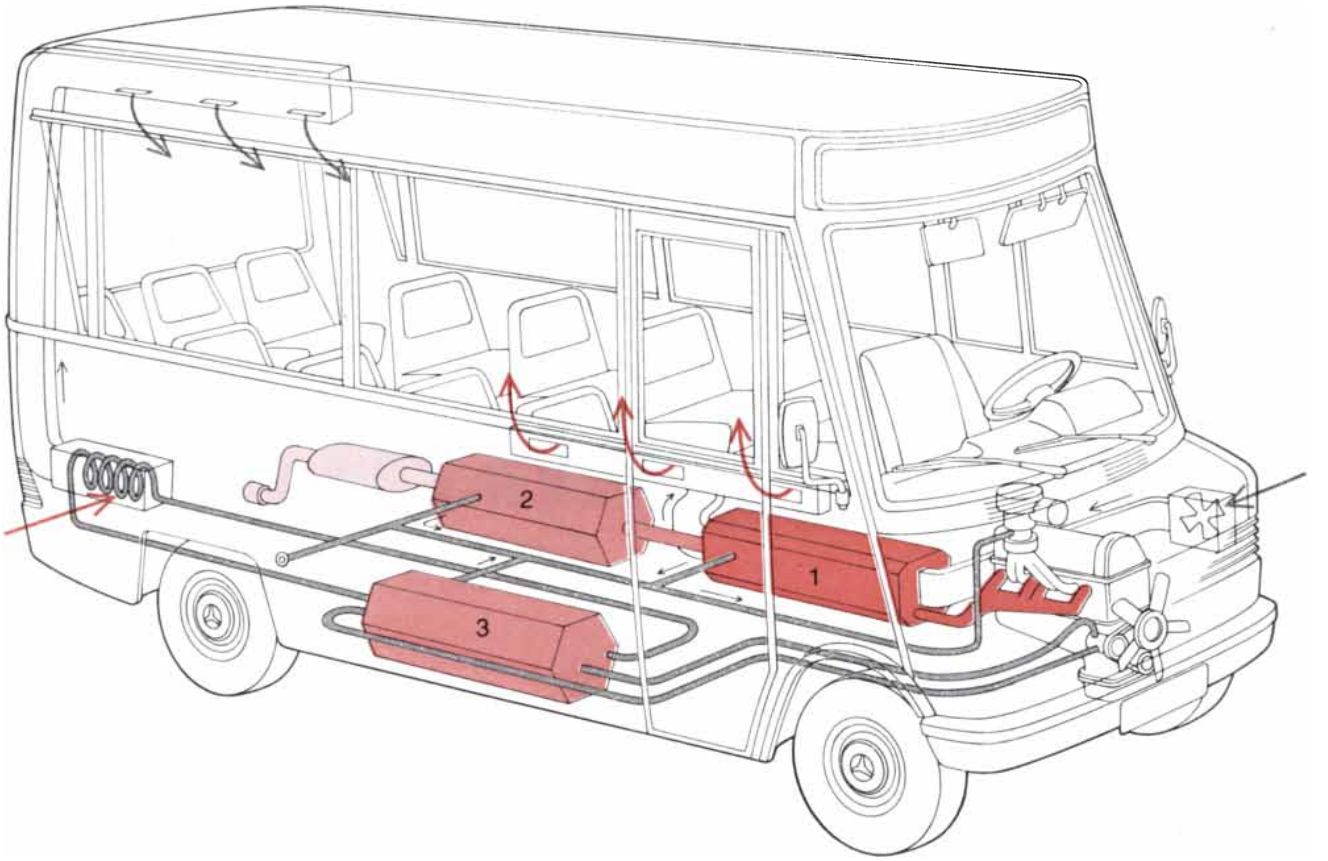


HYDROGEN-POWERED BUS built by Daimler-Benz, A.G., in West Germany relies on three separate beds for hydrogen storage, one bed containing magnesium-nickel hydride and the other two containing iron-titanium hydride. The high-temperature bed holding the magnesium-nickel hydride (*1*) is heated by exhaust gas (mainly steam) directly from the engine; it can also serve as an auxiliary heater for the interior of the bus. The low-temperature iron-titanium-hydride bed just behind it (*2*) is also heated by engine-exhaust steam as it condenses after being partially cooled by the first (magnesium-nickel) bed. The other low-temperature iron-titanium-hydride bed (*3*) encloses a liquid heat exchanger to provide air conditioning for the bus. Alloys for hydrogen-storage beds were supplied by Ergenics Division of the MPD Technology Corporation of the International Nickel Co. Colored arrows denote warm air, gray arrows cold air.

perature and are relatively inexpensive.

In automotive applications weight is a critical factor. Perhaps the most recent advance in this area is the development of a dual-bed storage system, with one bed containing an iron-titanium hydride and the other a lighter hydride based on an alloy of magnesium and nickel. A dual-bed Daimler-Benz bus has been demonstrated in West Germany.

The complete substitution of hydrogen for gasoline can be considered only as a long-term option because of the massive investment that would be required (for power plants, coal-gasification plants, electrolyzers, pipelines and other installations) to produce and distribute the hydrogen. There are, however, certain short-term applications where such constraints would not hold. One particularly attractive possibility is the operation of fleets of hydrogen-powered vehicles serviced by central garages. Such a fleet, involving 20 vehicles, is being planned in West Germany as a demonstration project. The low polluting effect of hydrogen fuel makes vehicles of this kind particularly desirable in congested urban and industrialized settings.

Opportunities also exist for industrial and mine vehicles in situations where pollution must be held to a minimum. Here the weight disadvantage of the hydride compared with liquid fuel is not significant because most such vehicles need to carry a heavy ballast. Moreover, many of them already run on batteries in order to minimize pollution. This area is being studied by the Denver Research Institute and the MPD Technology Corporation of the International Nickel Company.

One should also recognize that it may not be necessary to burn hydrogen alone in order to achieve significant fuel economies and environmental benefits. An experimental vehicle that can run on either hydrogen or gasoline has been demonstrated. Another design would incorporate the capability of burning hydrogen and gasoline simultaneously. The addition of hydrogen to a gasoline fuel stream increases the thermal efficiency of the fuel mixture substantially over the efficiency of gasoline alone.

A number of stationary applications are feasible, since the weight of the hydride would not be a critical factor. One is peak leveling by electric utilities, which entails generating and storing energy at times when power consumption is low and drawing on the reserve at times when it is high. A pilot plant embodying this concept was operated by the Public Service Electric and Gas Co. of New Jersey between 1974 and 1976. Hydrogen was separated from water by electrolysis and then compressed and stored as iron-titanium hydride. The heat of reaction was removed by circulating cold water (17 degrees C.) through a heat exchanger inside the reservoir. In the other part of the cycle the hydride was decomposed by means of hot water (45 degrees). The hydrogen thereby made available powered a 12.5-kilowatt fuel cell. During the two years of operation the storage system went through about 60 cycles of charging and discharging. No operating difficulties were encountered, but the state of development of hydrogen-powered systems for this particular purpose

was not far enough advanced to overcome problems of cost and efficiency, and so the experiment was not continued.

The reactions involved in the formation and decomposition of several unstable hydrides are rapid enough to warrant considering the use of these materials in compressors and pumps. The driving force for such devices is obtained by alternately decomposing and regenerating a metal hydride by heating and cooling it, thus creating a cyclic variation in pressure. For example, calcium-pentanickel will absorb hydrogen at a pressure below one atmosphere at 25 degrees C. and can discharge it at four atmospheres and 80 degrees. The Philips Company in the Netherlands has demonstrated a lanthanum-pentanickel compressor that operates at a somewhat higher pressure but in the same temperature range. One can conceive of a multistage unit with two or more different hydrides that would compress hydrogen from one atmosphere to more than 100 atmospheres with low-grade heat as the energy source.

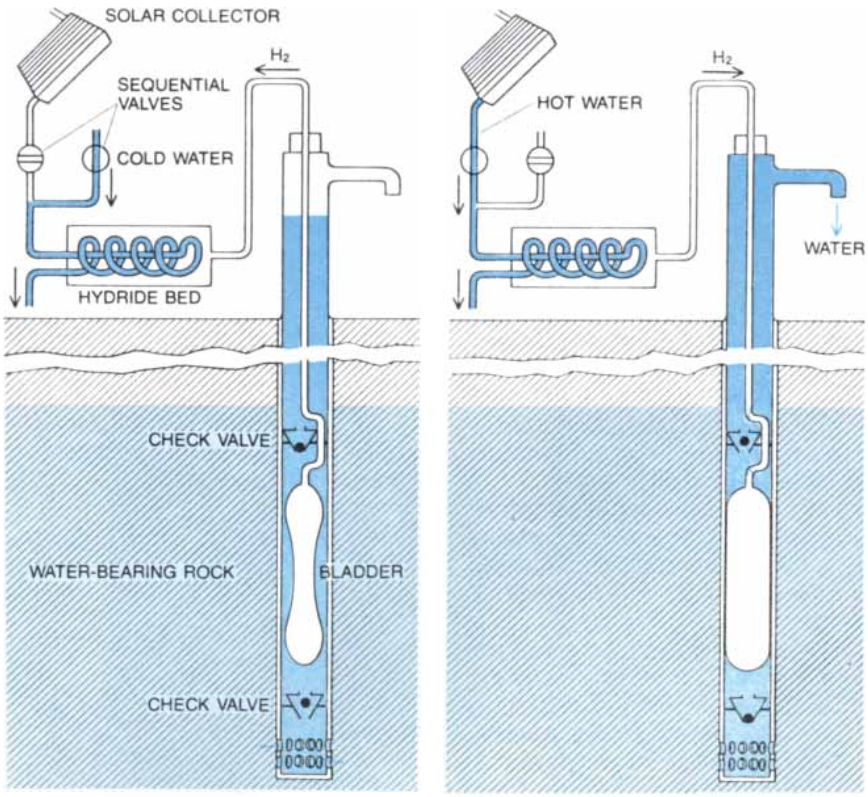
A heat engine in the form of a solar-powered water pump has been designed and demonstrated at Sandia Laboratories. It couples a simple metal-hydride hydrogen compressor to a rubber bladder in a well. The pumping action is achieved by alternately heating and cooling the hydride bed with hot and cold water. The hot water is obtained from solar heat and the cold water from the well. The pump is an example of several heat-engine concepts that utilize metal hydrides to convert low-grade heat into mechanical energy.

The heat effects of the reactions between hydrogen and hydride-forming metals offer the possibility of putting hydrides to work in heat-pump and refrigeration cycles. These applications, like the water pump, are closed systems that use the same supply of hydrogen repeatedly in a cyclic operation. The heat-pump effect is achieved by decomposing a metal-hydride bed at a given temperature, transferring the evolved hydrogen to a second bed and reacting it there at a higher temperature with a metal that forms a stabler hydride (a higher-temperature one). The decomposition requires heat, which can be of low grade; it can be got from the surroundings, from a solar collector or from a waste source. The reaction of hydrogen with the metal in the second bed gives off heat of a higher grade. Depending on the selection of hydrides, the difference between the low-grade and the high-grade heat can be from 50 to 100 degrees C.

A refrigeration cycle is essentially the same process in reverse. Such a cycle, which could serve for air-conditioning a home, has been demonstrated in a two-bed system at the Argonne National Laboratory. The first bed contained calcium-pentanickel and the second lanthanum-pentanickel, which forms a less stable hydride. In the first (compression) part of the cycle solar heat is employed to decompose the calcium-pentanickel hydride. The evolved hydrogen is reacted with the previously dehydrided metal in the second bed, with the resulting heat of formation being given off to the outside surroundings. In the second (refrigeration) part of the cycle the first bed is cooled to the ambient temperature and the hydrogen flow is reversed, thereby dehydriding the second bed and causing it to cool below the ambient temperature. For the cycle to work the two hydrides must have different pressure-temperature properties. If the properties are suitably matched, the cooling effect can be about 25 degrees C. (from, say, an ambient temperature of 25 degrees to zero degrees).

The main hazard associated with metal-hydride storage materials is the possibility of fire, involving the hydrogen or the metal or both, if the tank is ruptured. Safety studies of iron-titanium hydride and lanthanum-pentanickel hydride were carried out by the Billings Energy Corporation and the Denver Research Institute. It was concluded from the tests that the hydrogen stored in these compounds is inherently less hazardous than the same amount of hydrogen stored in liquid or gaseous form. Further tests comparing iron-titanium hydride with gasoline indicated that the hydride is safer than gasoline on an equivalent-energy basis.

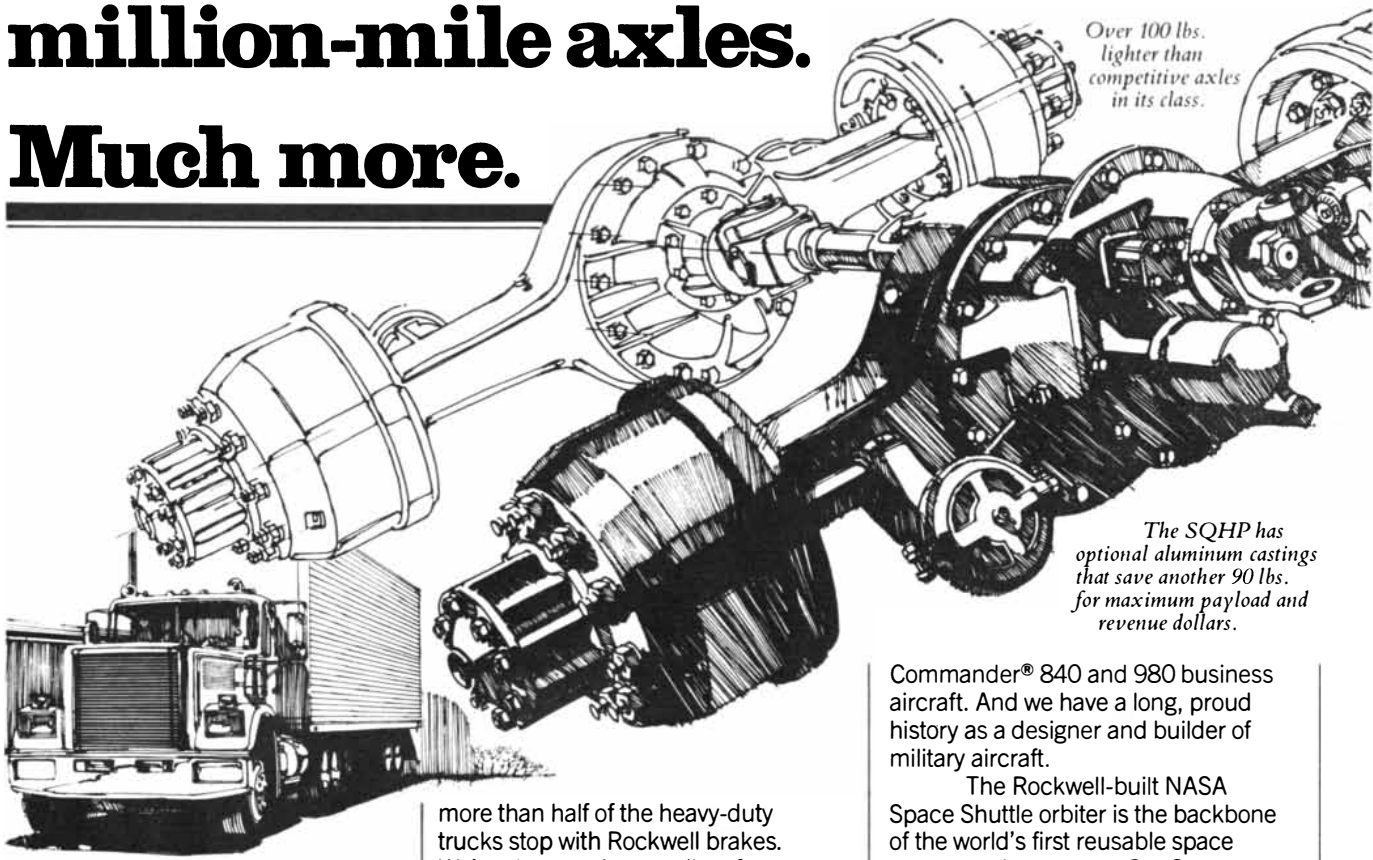
It seems certain that over the next few decades the energy picture will change significantly in the U.S. as petroleum becomes scarcer and costlier. We believe hydrogen will play a key role in this change, both as a carrier of energy and as a raw material for a variety of synthetic fuels. We also believe metal hydrides of the kind we have described will accelerate and facilitate the assumption of that role by hydrogen. In only a few years these novel materials have advanced from a laboratory curiosity to practical demonstrations on an engineering scale. It is highly probable that the most dramatic innovations are still to come. The spectrum of possible applications for rechargeable metal hydrides is limited only by the imagination of the inventor.



STATIONARY APPLICATION of the metal-hydride approach to hydrogen storage is represented by this solar-powered water pump, designed and demonstrated by workers at Sandia Laboratories. Hot water produced by solar heat and cold water obtained from the well are supplied alternately to a heat exchanger in a metal-hydride bed by means of two sequentially operated valves. Hydrogen gas released from the bed during the heating phase of the cycle inflates a rubber bladder in the well, lifting water through the upper check valve. Ground water then flows into the well through the lower check valve, deflating the bladder and forcing hydrogen back into the hydride bed during the cooling phase, returning the system to its starting position.

Rockwell International is more than the builder of million-mile axles.

Much more.



Over 100 lbs. lighter than competitive axles in its class.

The SQHP has optional aluminum castings that save another 90 lbs. for maximum payload and revenue dollars.

You may have heard Rockwell International referred to as "the company that makes heavy-duty truck components." Our SQHP tandem truck axle is a prime example of our automotive capabilities; it's designed to go up to a million miles in line-haul service, and a half-million miles without a major overhaul. We can produce products like this because we operate the country's largest independent automotive components research facility. Providing components for the land transportation industry, however, is only one of Rockwell's businesses.

Rockwell International is a major multi-industry company, applying advanced technology to a wide range of products — in automotive, aerospace, electronics and general industries. Following are some examples of our balanced diversification.

Automotive.

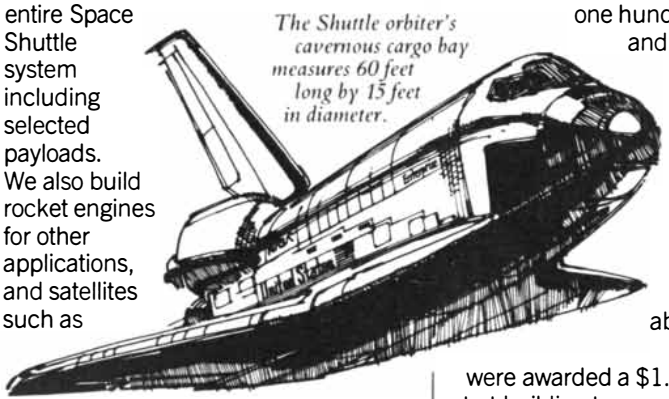
(Sales, fiscal 1979: $1.8 billion.)

One-half of the highway tandem tractors in North America are equipped with Rockwell axles — and more than half of the heavy-duty trucks stop with Rockwell brakes. We're also a major supplier of drivelines, steel and styled aluminum wheels, mechanical devices, castings, stainless steel wheel covers and other components for trucks, trailers, buses, vans and passenger cars.

Aerospace.

(Sales, fiscal 1979: $1.6 billion.)

We're prime contractor to NASA for its Space Shuttle orbiters and their main engines, and for integrating the entire Space Shuttle system including selected payloads. We also build rocket engines for other applications, and satellites such as Navstar. We manufacture Sabreliner® business jets and Jetprop Commander® 840 and 980 business aircraft. And we have a long, proud history as a designer and builder of military aircraft.

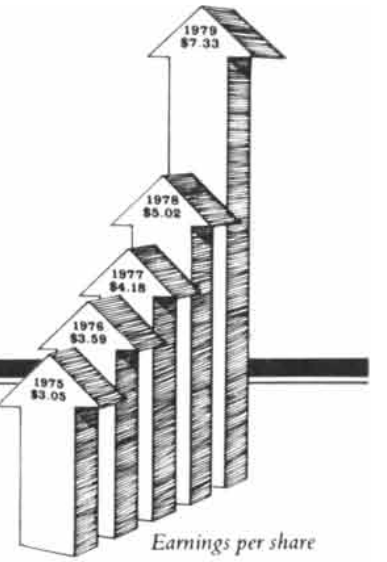


The Shuttle orbiter's cavernous cargo bay measures 60 feet long by 15 feet in diameter.

The Rockwell-built NASA Space Shuttle orbiter is the backbone of the world's first reusable space transportation system. Our Space Systems Group and Rocketdyne Division began work on it over nine years ago. Rockwell brings to this program the technology and systems management experience gained as a prime contractor to NASA for its Apollo program.

The Space Shuttle will launch like a rocket, haul like a truck, work like a space station, then return to Earth, landing like a glider. Each Shuttle is designed to make at least one hundred trips to space and back, carrying as much as 32½ tons of payload into orbit each time — twice the payload today's largest expendable rocket can handle — at about half the cost.

In early 1979, we were awarded a $1.9 billion contract to start building two more Shuttle orbiters and to modify the present two to meet operational mission requirements.

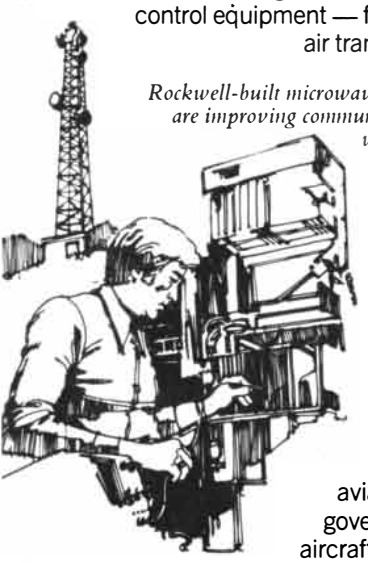


Earnings per share

Electronics.

(Sales, fiscal 1979: $1.5 billion.)

We're one of the world's leading suppliers of avionics — communications, navigation and flight control equipment — for air transport, general aviation, and government aircraft. We also make microelectronic systems and devices and missile guidance and control systems.


Rockwell-built microwave systems are improving communications worldwide.

And we manufacture and install telecommunications systems for businesses and governments worldwide.

As a matter of fact, we're one of the nation's largest independent suppliers of microwave systems for transmission of telephone calls, television pictures and computerized data.

We've been making and installing microwave systems for over 26 years, and our many customers include telephone companies, broadcasters, pipeline companies, railroads and U.S. and foreign government agencies.

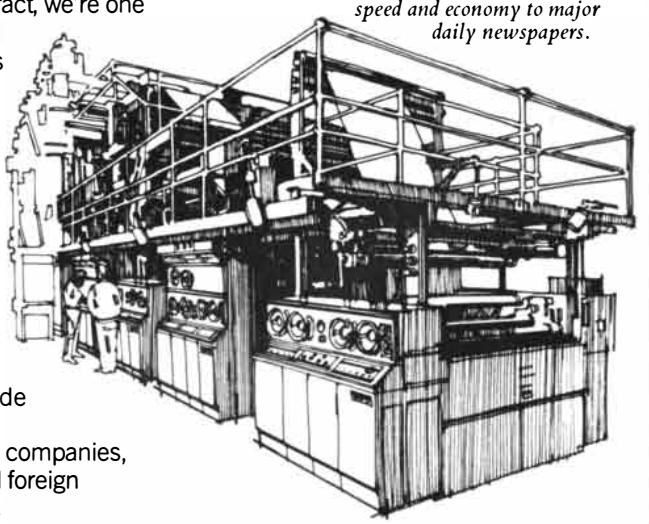
General Industries.

(Sales, fiscal 1979: $1.2 billion.)

Rockwell is one of the world's largest suppliers of high-technology valves for the energy market and for general industry. Our extensive technology is also being applied to the world's growing need for alternate sources of energy. We're involved in projects for nuclear energy, coal gasification, flue gas desulfurization, and solar, wind and geothermal power. We also make printing presses, textile equipment, industrial sewing machines, power tools and products for utilities.

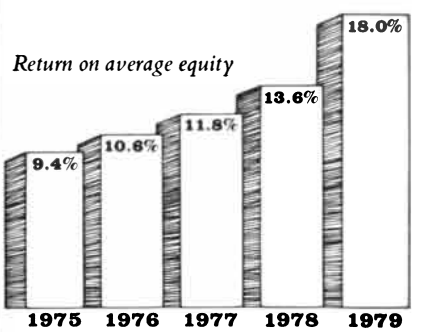
Speaking of our printing presses, most of America's big newspapers are printed on them. The list of major American dailies that are printed on just one of our presses — the Goss Metroliner — reads like a *Who's Who* of newspapers. Another Goss press, the Signature HV, is designed to give smaller newspapers and commercial printers unprecedented speed and flexibility. Almost 16,000 Goss offset press units are installed worldwide.

Today our Goss Metroliner offers improved reproduction, speed and economy to major daily newspapers.



Earnings up in '79 4th consecutive year.

Rockwell International's total sales for fiscal 1979 were $6.2 billion, up 16 percent over $5.3 billion in the prior year. Net income totaled $261.1 million, or $7.33 per share, an increase of 48 percent over 1978 net income of $176.6 million, or $5.02 per share. Return on average equity has increased to 18 percent, which



places the company among the top one-third in the *Fortune 100* listing of U.S. industrial corporations. This is a substantial improvement over the previous year and nearly twice that of 1975.

For more of the Rockwell story, please write us for a copy of our annual report: Rockwell International, Dept. 815S-26, 600 Grant Street, Pittsburgh, PA 15219.

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The Perception of Human Growth

How does the human head change shape from infancy to adulthood? Tests of the way most people perceive the process show that growth can be represented by a particular type of geometric transformation

by James T. Todd, Leonard S. Mark, Robert E. Shaw and John B. Pittenger

The human body, like any other growing organism, changes dramatically in form as it develops from infancy to adulthood. Everyone has an intuitive understanding of the morphological changes involved in human growth. It is easy to distinguish between normal maturation and other types of biological change such as a gain in weight or a disfiguring disease, yet the ability to perceive these changes as distinct events has never been explained adequately.

In order to comprehend better how people perceive the phenomenon of growth it is first necessary to describe the phenomenon in rigorous terms. One approach is to consider a growing object as a set of points. If the analysis is limited to two dimensions, the position of any point can be specified by the values of two coordinates, which are often designated by the variable names x and y. The concept of a geometric transformation serves to describe how the coordinates of a set of points can be systematically altered by growth or some other process. A transformation is designated by introducing two new variables, x' and y', as functional relations of x and y.

It is important to recognize that any system of equations relating x and y to x' and y' can be interpreted in two ways. In one sense such equations represent a change in the original coordinate system, as is commonly observed when data are transformed from rectangular coordinates to polar ones [*see top illustration on page 134*]. In another sense, however, the equations represent a change in an object within a fixed coordinate system. The latter interpretation is easily demonstrated by considering the different ways a square object can be transformed [*see bottom illustration on page 134*]. For example, one of the simplest ways of transforming a square is to rotate it. A rotational transformation changes the coordinates of every point on the object being rotated; although every point is displaced, however, there are more abstract properties of the object, such as its overall shape or the distance between each pair of vertexes, that are not affected by the rotation. In the language of mathematics these properties are said to remain invariant.

A geometric transformation can often be perceived as a distinct style of change independent of the particular objects to which it is applied. The abstract event of rotation can easily be recognized when it is applied to a triangle, a square or even an object one has never seen before. One possible basis for distinguishing different transformations is to compare the different properties they leave invariant. For example, it is easy to see that a rigid transformation such as rotation preserves the angles and the distances between the points of an object. By the same token, a conformal transformation preserves the angular coordinate of every point in a polar coordinate system, an affine transformation preserves parallel lines and a reflective transformation preserves bilateral symmetry about a specific axis.

One of the first people to recognize that the concept of a geometric transformation might be useful for describing morphological change was the Scottish naturalist D'Arcy Wentworth Thompson. In his classic work *On Growth and Form*, first published in 1917, he argued that the phylogenetic progression from one species to another and the ontogenetic progression from infant to adult are both processes involving the entire organism rather than a succession of minor alterations of individual body parts. His primary evidence for this assertion was his ability to represent apparently complex changes in morphology as the geometric distortion of a grid placed over an evolving or growing organism. Thompson also contended that these geometric distortions generally result from physical forces in an animal's environment, the effects of which can often be described by a single mathematical transformation.

Thompson's drawings are particularly instructive because they illustrate the fundamentally abstract nature of biological change and the ability of different observers to perceive change. His special insight was that the presumably complex processes of growth and evolution could be adequately represented with a simple object such as a square grid just as easily as with a complex object such as a human head. Thompson gave no physical or biological explanations for the phenomena he was modeling. In most cases he did not even attempt to describe the phenomena with mathematical equations. The power of his approach lay primarily in the domain of visual perception. Thompson's drawings made it possible to "see" how different transformations operate, even though he did not formally analyze their effects with any degree of precision.

Although Thompson's methods could be criticized for their inherent subjectivity, it is worth noting that a reliance on perception seems to be present in almost every attempt that has ever been made to study the morphology of either living or inert forms. In biology, for example, the taxonomic system of classification depends on the fact that human observers are able to agree on the various similarities and dissimilarities between the morphological characteristics of different biological organisms. Our own research on the growth of the human head is consistent with this tradition. The basic methodology is to select geometric transformations that could potentially describe the phenomenon of growth, and to evaluate each prospective transformation by how it is perceived.

Our interest in the problem dates back to 1972 when two of us (Shaw and Pittenger), who were then working at the University of Minnesota, began to investigate the changes in craniofacial morphology that provide information for the perception of age level. Other investigators had previously noted that the head of a newborn infant has an exaggerated cranium and a diminutive face, but that during development the face grows more rapidly than the cranium, resulting in a change in facial angle. We wanted to show that similar effects

could be produced by a single geometric transformation, and that such a transformation would be perceived as growth when it was applied to human craniofacial profiles in the absence of all other changes.

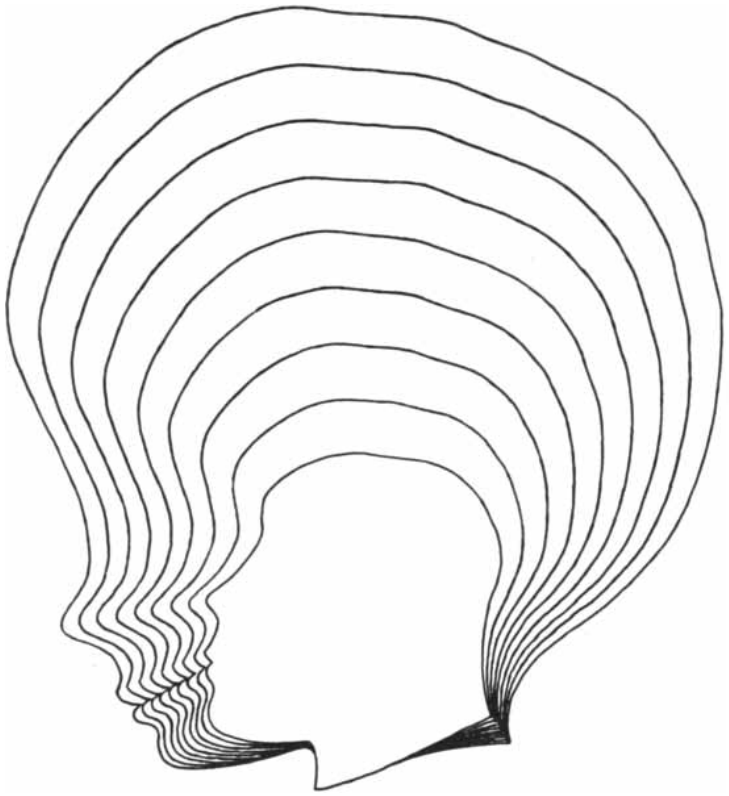
The initial series of experiments examined two transformations, cardioidal strain and affine shear, both of which are capable of producing the changes in facial angle that are normally characteristic of craniofacial growth. The cardioidal-strain transformation is so named because it transforms a circle into the heart-shaped form called a cardioid. The affine-shear transformation, in contrast, transforms a circle into a diagonally oriented ellipse; it is part of a more general class of affine transformations whose common invariant is that they preserve parallel lines.

A "relative-age judgment" task was arranged to evaluate the effectiveness of these prospective growth transformations. Observers were presented with the profile of a human head and were asked to assign the profile an arbitrary number, say 100. They were then shown some additional profiles that had been systematically altered in various degrees by the cardioidal-strain and affine-shear transformations [*see illustration on page 140*]. The observers were told to rate the age of each profile with respect to the first. Thus if an observer assigned 100 to the first profile and a subsequent profile was perceived to be twice as old as the first one, the latter profile would be assigned the number 200.

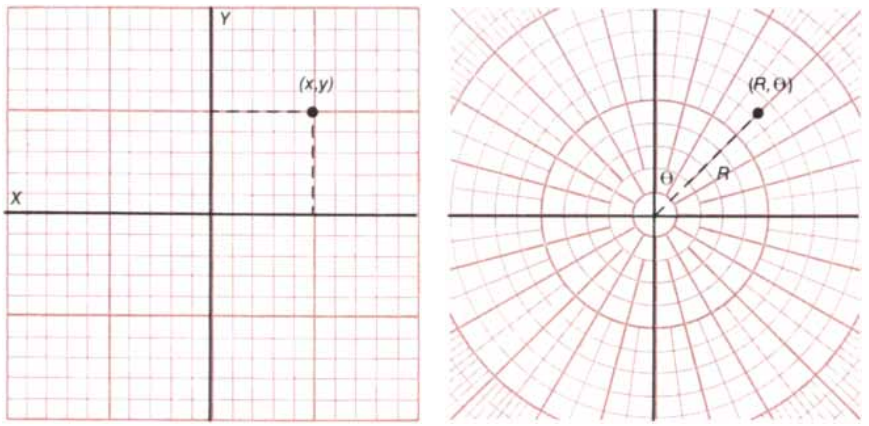
The results showed that the cardioidal-strain transformation produced large changes in the perceived age of the facial profiles and that the affine-shear transformation produced little change. The contrasting perceptual effects of these transformations suggest strongly that the necessary information for specifying growth is inherently abstract. Indeed, on examining the profiles it is difficult to isolate a specific dimension along which the two transformations differ. They both affect the facial angle and the overall shape of the head, but the changes produced by cardioidal strain resemble growth or evolution, whereas affine shear produces nothing more than an unidentifiable distortion. It should also be noted that the cardioidal-strain transformation is perceived as growth even though the stimulus profiles lacked all the internal detail normally associated with human faces. This observation provides some evidence that the perception of growth need not depend on any particular set of object properties.

We have since performed a follow-up series of experiments that demonstrate this last point even more dramatically. We relied on the same procedure for making relative-age judgments as before, but this time we did not use hu-

GROWTH OF A HUMAN HEAD is simulated in this sequence of computer-generated profiles obtained by the use of a geometric procedure called a revised cardioidal-strain transformation. Sequence proceeds from infancy (*innermost profile*) to adulthood (*outermost profile*).



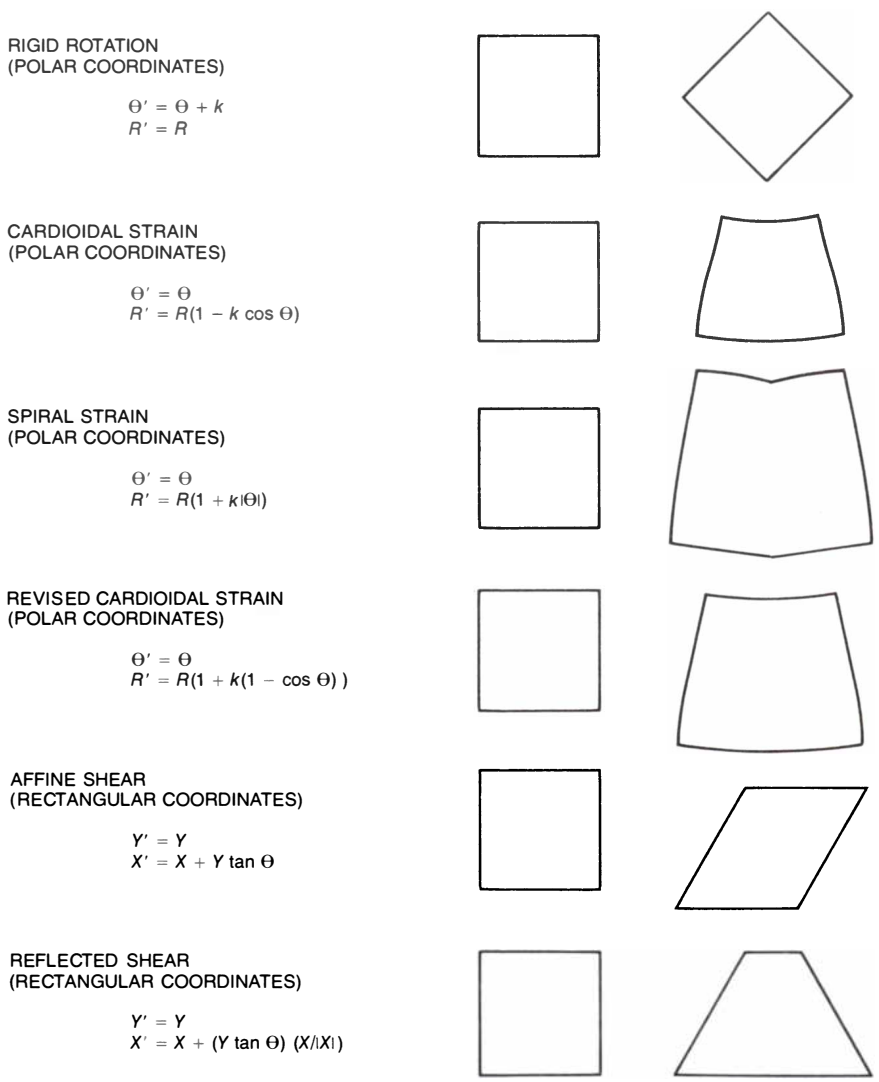
EVOLUTION OF THE HUMAN HEAD is suggested by this somewhat different sequence of profiles generated by a variant of the revised cardioidal-strain transformation. Sequence proceeds from a "Neanderthal" man (*innermost profile*) to a futuristic being (*outermost profile*). Both sequences were drawn with the aid of a computer at the University of Connecticut.



$x = R \sin \Theta$
$y = R \cos \Theta$

$R = (x^2 + y^2)^{1/2}$
$\Theta = \tan^{-1} y/x$

GEOMETRIC TRANSFORMATIONS for converting data back and forth between a rectangular coordinate system (*left*) and a polar one (*right*) are given by pairs of equations at bottom.



SHAPE OF AN OBJECT can be altered within a fixed coordinate system by applying a variety of geometric transformations, six of which are listed by name and also represented in the form of equations at the left. (The fixed coordinate system in each case is given in parentheses.) The effects of the different transformations on a square object are shown at right. A conformal transformation such as spiral strain or the two kinds of cardioidal strain depicted has the special property of preserving the angular coordinate of every point in a polar coordinate system.

man facial profiles as stimuli. In one experiment observers were presented with profile drawings of birds, dogs and monkeys that had been systematically transformed with various amounts of cardioidal strain and affine shear. As in the earlier experiment with human facial profiles, the results showed clearly that the cardioidal-strain transformation was perceived as growth, whereas the affine-shear transformation again had little effect on perceived age.

The results of a second experiment were even more revealing. Observers were presented with transformed drawings of front and side views of Volkswagen "beetles," both with and without facial features drawn in to make them look more facelike. The cardioidal-strain transformation produced large changes in the perceived age of all these stimuli in spite of the fact that Volkswagens do not grow. The affine-shear transformation produced almost no changes. These results suggest that observers were responding to growth as an abstract type of change, much like rotation, which is easily recognized regardless of the objects to which it is applied.

In a more recent series of experiments done at the University of Connecticut we have attempted to determine whether the effects of cardioidal strain are perceptually equivalent to the morphological changes normally produced by the actual growth of a human head, and whether other transformations not previously examined might be perceived similarly. Our stimuli consisted of many different sequences of five facial profiles, each arranged from left to right on a single page [*see illustration on page 140B*]. Observers were instructed to rate each sequence from 0 to 4 on the basis of its resemblance to actual growth and to indicate the direction in which growth appeared to be occurring. The sequences were designed so that the perceived age of the different profiles would increase sequentially from left to right. For those sequences that generally produced low ratings, however, there were a few instances where subjects reported that the direction of growth seemed to be in the opposite direction. Whenever this occurred, the rating was interpreted as a negative number.

The stimulus sequences were prepared from a selection of long-term growth records originally collected by the Child Research Council of Denver, Colo., as part of a study lasting from 1925 to 1970. One group of stimuli, the actual growth sequences, provided a convenient base-line measure for evaluating different transformations. Each actual growth sequence consisted of facial profiles of a single individual at five different ages. These profiles were traced directly from X-ray plates made with small amounts of radiation so that the outline of the skin was clearly visi-

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Consumer Orientation

No. 4 in a Series
of Technical Papers

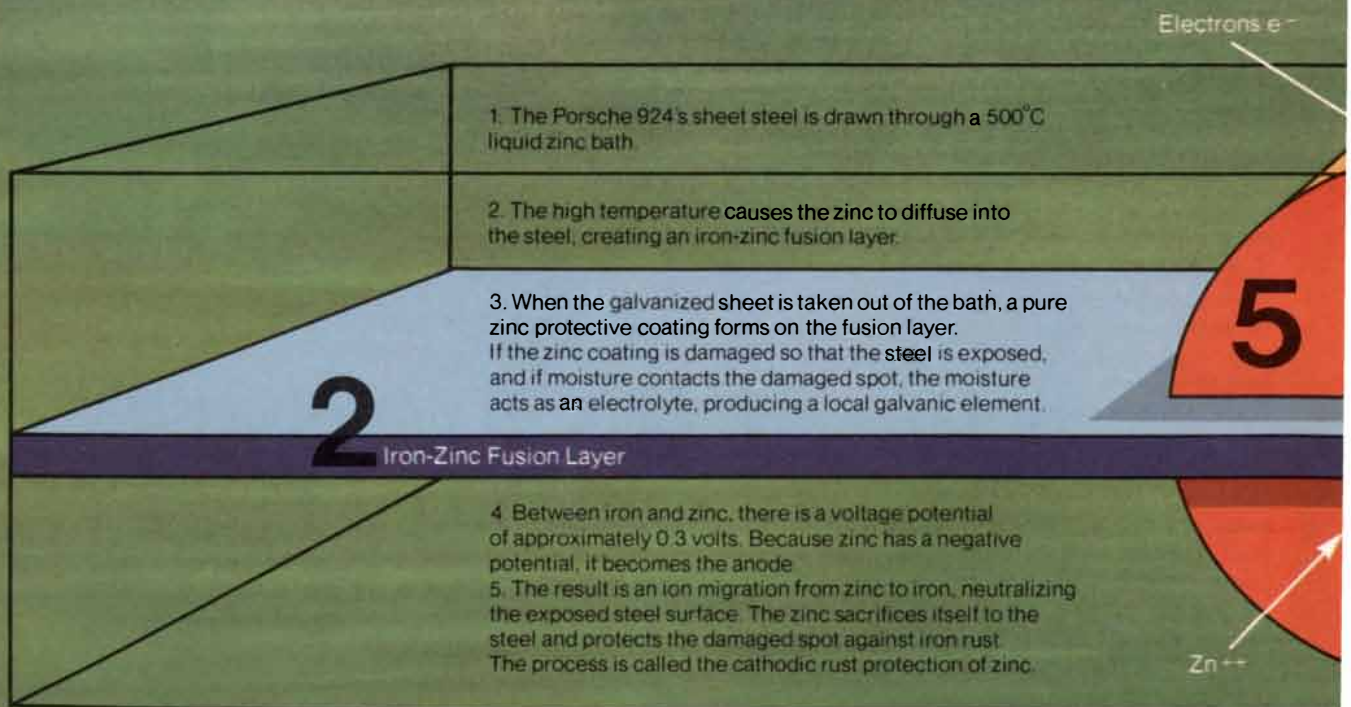
4

Subject:
Body Longevity.
The Cathodic Rust Protection
of Zinc.

Paint alone is no protection against rust. Moisture—and other corrosive elements—can attack metal through pinholes on a painted surface. Unchecked, rust can expand, mar the finish, and weaken an ordinary steel body. Andso, inadditionto a 4-steppaintprocess, the Porsche 924, like all Porsches, is protected by a hot dip galvanizing process.

All of the sheet steel used in the Porsche 924 is hot dip galvanized—on both sides—in a zinc bath. This produces a zinc oxide that actually *grows* into any damaged portion of the paint skin—plugging pinholes and preventing further corrosion.

The manufacturing process itself is extremely expensive. It was selected by Porsche to help fulfill an important objective: to make the 924 a sports car that not only is fun to drive today, but also will be a pleasure to own in years to come. So with the introduction of the 1980 model year, Porsche warrants the entire lower body shell against rust perforation for 6 years.*



Porsche 924

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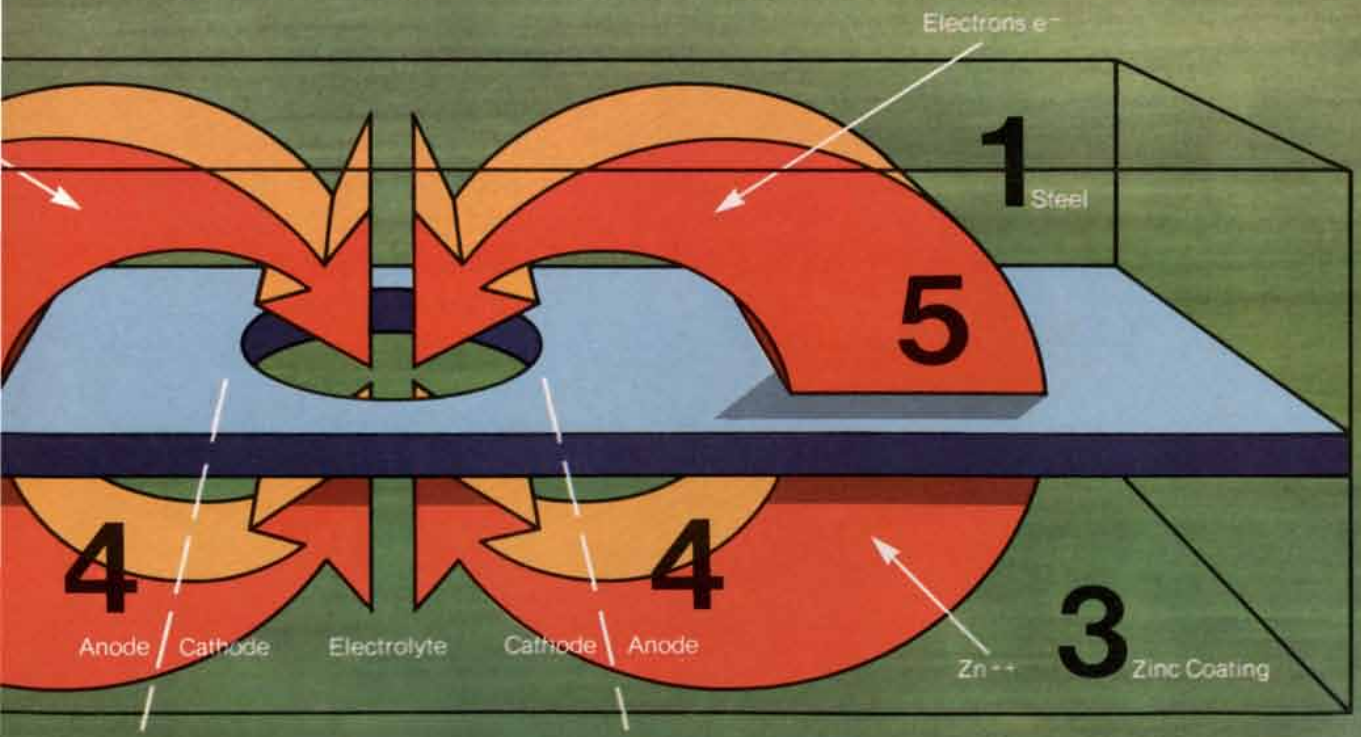

A FUNNY THING HAPPENED ON THE WAY TO THE OCEAN.

Not so long ago most of the water that fell on our continent ran downhill and back to the ocean, from which it came.

No more. Modern man called that "wasting to the sea." He had other ideas. He would control all that free-running water.

He built dams, dikes, and diversions; levees, locks and canals. Where water inconveniently ran in crooked courses, he channeled it. Where it ran too shallow, he dredged. Where it ran the wrong way, he turned it around. And often, where he did let it return to the sea, he filled it with wastes.

Up to a point it worked. Some of America's waters could now be used for irrigation, cities, industry, power generation, sewage disposal and transportation. And still many of our waters were left to their own devices, providing their natural, less tangible benefits to man.

But then the balance swung.

In many places there was an overkill of manipulation and use. Lakes died. Rivers became conduits of sewage and toxic wastes; others were turned into a series of still ponds. Magnificent streams and awesome canyons were drowned. Fresh waters turned salty.

Fish are among the casualties. Many of them chemically contaminated. Much of their habitat changed—fouled and stilled. Those special conditions necessary for the health and propagation of our worthiest sport and commercial species, gone. As our waters go, so go our fisheries.

The American League of Anglers believes that natural and free-flowing waterways are more than pleasant amenities for fishermen. Their ecological health is essential to man as well as to all forms of wildlife.

We are committed to preserving a proper balance between the need for water manipulation now and the desire for pure, free-flowing waters forever.

We act and speak for this goal on a national level. We urge all anglers, who receive extra benefits from good water, to participate. We invite all those who revere our dwindling stock of natural waters to support our efforts.

THE AMERICAN LEAGUE OF ANGLERS, 810 18TH STREET NORTHWEST, WASHINGTON, D.C. 20006

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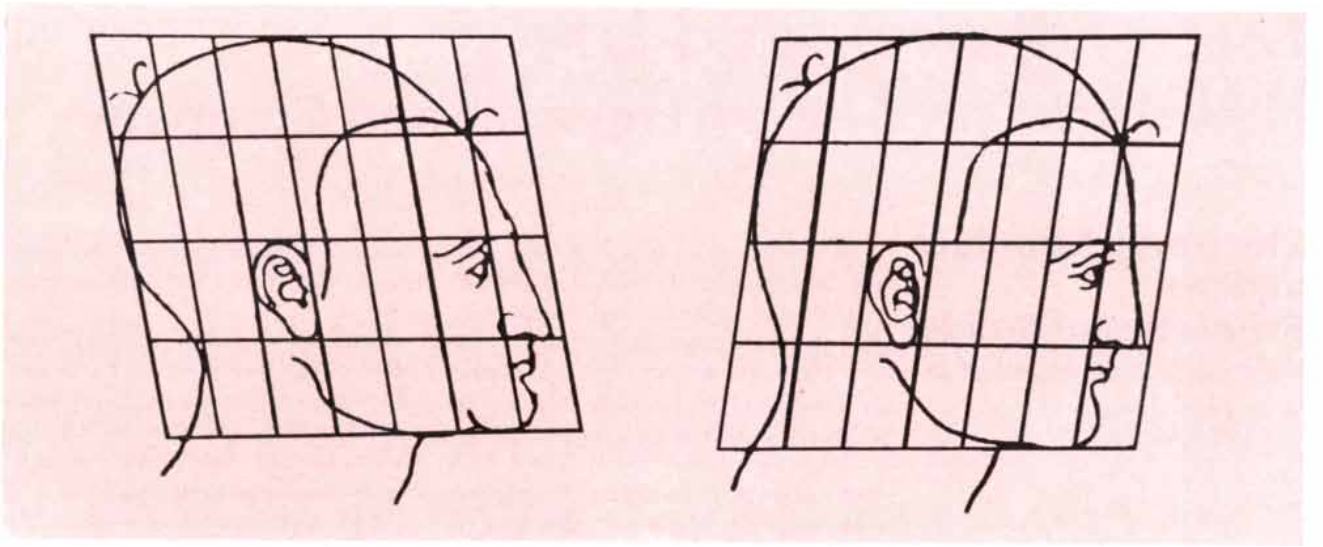
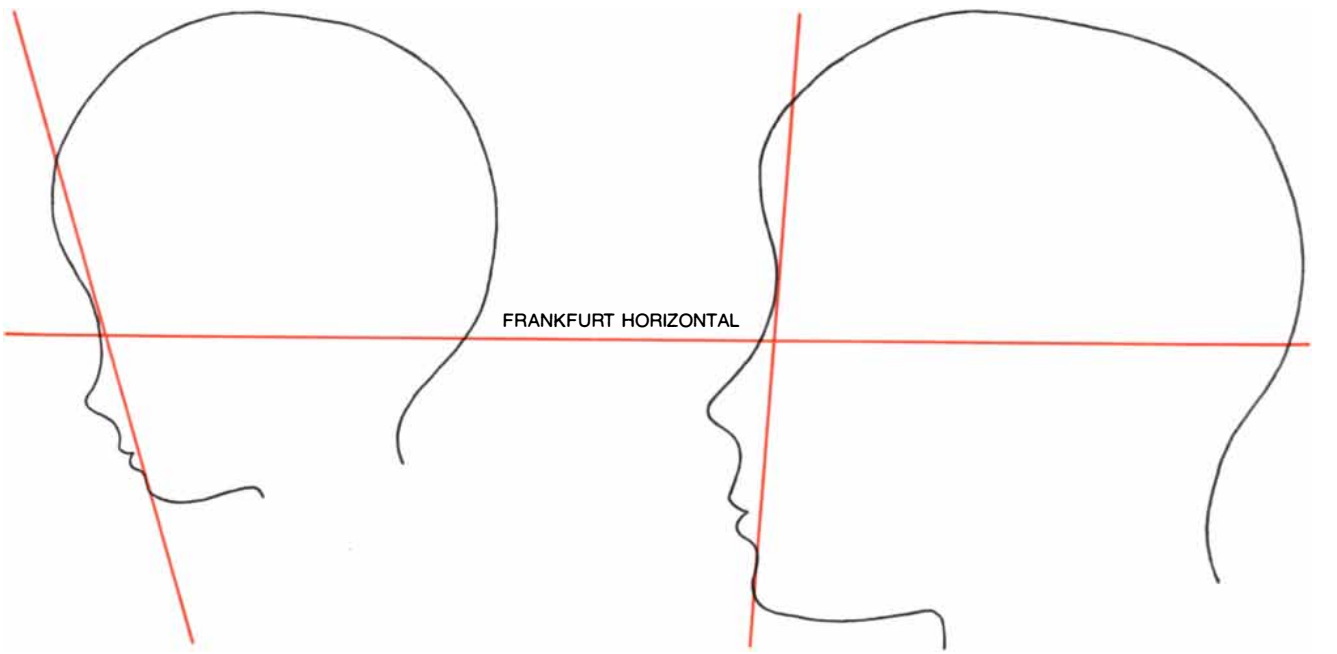


PIONEERING ATTEMPT to apply the concept of a geometric transformation to the description of morphological change was made by the Scottish naturalist D'Arcy Wentworth Thompson, who succeeded in representing all kinds of apparently complex changes in morphology in terms of the geometric distortion of a grid placed over an evolving or growing organism. In this illustration of the basic technique, taken from his 1917 book *On Growth and Form*, Thompson superposed a pair of square grids, distorted by different degrees of affine shear, over two line drawings of human heads that he copied from the 1613 edition of Albrecht Dürer's *Treatise on Proportion*.

ble. The overall change in facial angle between the youngest profile and the oldest one was used as an index of the amount of deformation that had resulted from actual growth. A second group of stimuli, called transformation sequences, were mathematically computed on a digital computer by systematically transforming the youngest profile of each actual growth sequence. Specific values of cardioidal strain, spiral strain, affine shear, reflected shear and rotation were selected for each individual so that the overall change in facial angle would be identical with the change that had occurred in the individual as a result of normal growth processes. There was also a group of control sequences in which all five profiles were identical. These provided an additional base-line measure for evaluating transformations that did not resemble growth.

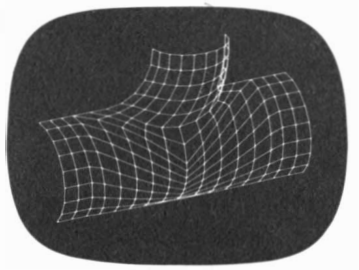
The experiment was carried out with 40 subjects. As might be expected, the highest mean ratings were produced by the actual growth sequences. The ratings were slightly lower for cardioidal strain and lower still for spiral strain. None of the other transformations produced significantly greater ratings than the control sequences did.

This basic pattern of results has since been replicated with a variety of other procedures. For example, a free-response task was administered in which subjects were not told of our specific interest in growth. They viewed the same profile sequences the subjects in the earlier experiment had and were asked to describe, if possible, how each pattern of change might have come about in a natural environment. As we expected,



FACIAL ANGLE changes during growth. In the authors' work the facial angle is defined by the intersection of two lines. One line, the Frankfurt horizontal, passes through the top of the earhole and the bottom of the eye socket. The other connects the most prominent part of the chin with the deepest part of the depression just above the nose. The profile at the left is of an infant; the one at the right is of an adult.

Picture this:



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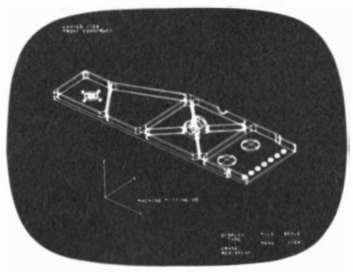

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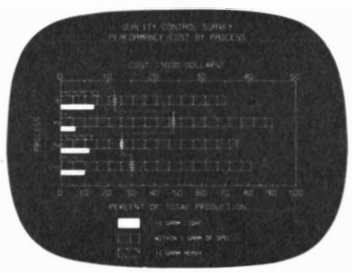

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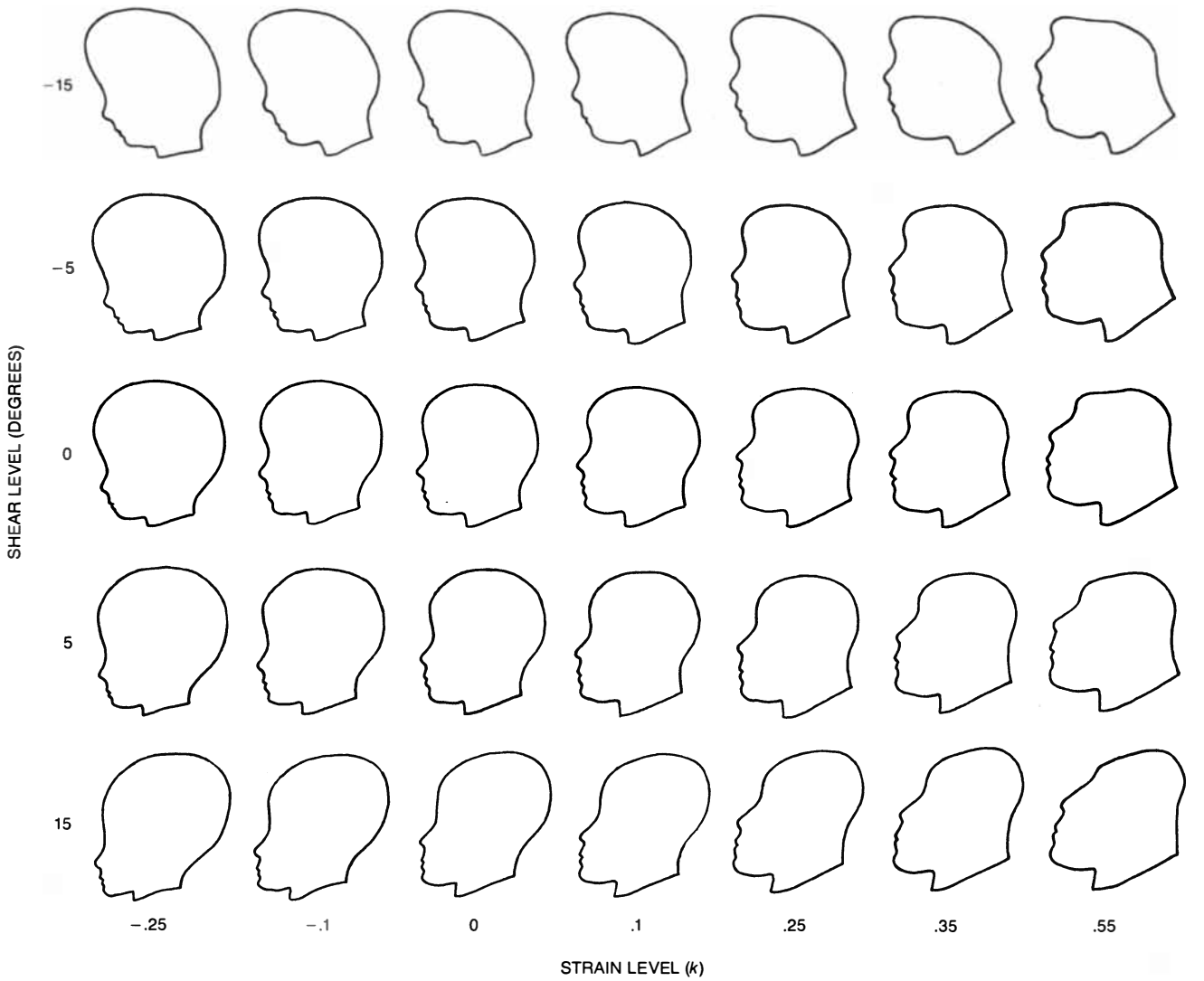
there was a high incidence of growth-related responses for the cardioidal-strain, spiral-strain and actual-growth sequences, and there were almost no growth-related responses for the affine-shear, reflected-shear, rotation and no-change sequences. These findings appear to be general. The same basic pattern of results has been observed for more than 85 percent of the subjects who have participated in these experiments or related ones.

It is possible to conclude from these results that the perception of growth is surprisingly selective. Of the five transformations examined, only cardioidal strain and spiral strain are consistently responded to as growth. These transformations have much in common mathematically. They both preserve the angular coordinate of every point in a polar coordinate system, and they both produce a cusp, or indentation, at the top of the object being transformed. The consistency of subjects' responses in these experiments and the fact that cardioidal strain is perceived as growth almost as readily as growth itself provide strong evidence that this particular type of change is a close approximation to the overall effects of maturation in a variety of naturally occurring situations. After all, it would be difficult to imagine that observers would selectively respond to a particular transformation as growth if that transformation had no relation to the actual event seen in their everyday experience. Our results suggest, therefore, that human heads are somehow constrained to grow cardioidally.

Why do heads grow in such a regular manner? Thompson addressed the issue by suggesting that the biological processes of growth and evolution are somehow integrated with the physical forces in an animal's environment. He noted that the application of pressure or stress on living tissue seems to have a direct influence on the control of growth. There are many examples of this phenomenon. The soles of one's feet grow thicker the more one walks on them. Bone becomes thick where stress is high and thin where stress is low. Even the internal structure of a bone reflects the environmental forces to which it has been subjected. When one examines the interior of any weight-carrying bone, there is a clearly defined lattice structure that bears a striking resemblance to the lines of stress produced by the bone's natural load. The biological mechanism by which growing cells are aligned is not entirely understood. One promising hypothesis is that stress generates an electric field within the growing material and that electrically charged molecules and ions align themselves in exactly the same way that iron filings become aligned in a magnetic field. This is an important area of research, but it is nec-



ASSORTED PROFILES of a human head were produced by applying various combinations of affine shear and cardioidal strain to the profile of a 10-year-old boy. In an early experiment conducted by two of the authors (Shaw and Pittenger) at the University of Minnesota observers were asked to judge the relative age of each of the transformed profiles with respect to the untransformed original (which appears here at the position where both the shear and the strain are equal to zero). The results demonstrated that the cardioidal-strain transformation accounted for much greater changes in the perceived age of the craniofacial profiles than the affine-shear transformation.

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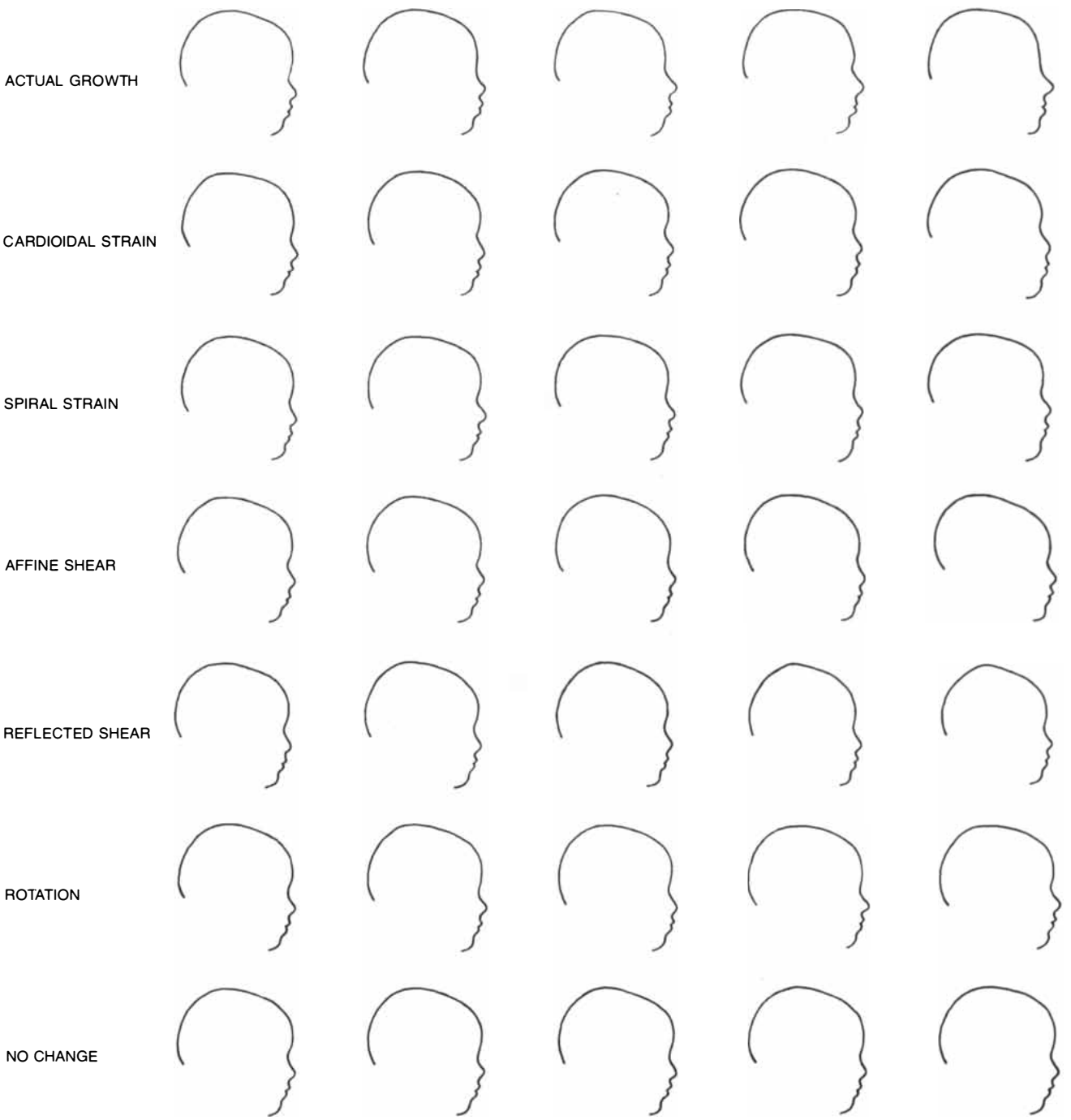
essary to recognize that such research can never explain why growth is cardioidal. Even if one understood in complete detail how cells respond to stress, one could not predict changes in morphology unless one also understood the patterns of stress to which the growing material is subjected.

Following this line of argument, it seems reasonable to speculate that if heads grow cardioidally, then the patterns of stress to which heads are subjected must also be cardioidal. In order to test this hypothesis we considered the craniofacial complex as a spherical tank filled with fluid. From elementary hydrostatics we knew that the amount of pressure at any point on the surface of the tank is directly determined by the amount of fluid above it. This pressure can easily be expressed as a function of position by an equation that relates the pressure to the radius of a sphere multiplied by a constant representing the product of the force of gravity and the density of the fluid. If the structure of the head is remodeled in accordance with this pressure gradient, a new transformation is obtained.

As it happens, the new transformation



RECENT SERIES OF TESTS was designed to compare various prospective growth-simulating transformations, including cardioidal strain, with actual growth. For this purpose the authors used as stimuli a number of different sequences of facial profiles, each sequence arranged from left to right on a single page. Forty observers were asked to rate each sequence from 0 to 4 on the basis of its resemblance to actual growth and to indicate the direction in which growth seemed to be occurring. The sequences were prepared from long-term growth records collected by Child Research Council of Denver, Colo., from 1925 to 1970. Unchanging sequence (*bottom*) served as a control.

is strikingly similar to the cardioidal-strain transformation originally devised by two of us (Shaw and Pittenger). For this reason it is referred to as a revised cardioidal strain. Both styles of change preserve the angular coordinate of every point in a polar coordinate system, and both will transform a circle into a cardioid. The primary difference between them is that the revised cardioidal-strain transformation affects the size of an object in a way that is more in keeping with the effects of actual growth.

The analysis suggested above is of course oversimplified. Heads are not perfectly spherical and there are other sources of stress operating on the craniofacial complex besides the force of gravity. The resulting model can be thought of as a kind of ideal case, similar to analyzing a falling body without considering air resistance. Such a model can be quite useful if it helps one to appreciate the overall influences on craniofacial growth or provides one with a means of approximating the course of growth in any given individual.

This brings us back to the question of what the relation is between growth and the perception of growth. We have already demonstrated that the cardioidal-strain transformation is a perceptually accurate model of growth, but is it accurate enough to satisfy the needs of a clinician, for example, in planning corrective treatment for patients with facial anomalies? We have begun experiments designed to answer this question.

Our procedure is quite simple. Working with the same series of longitudinal X rays of the skull that we used in our earlier perceptual experiments, we trace the outline of a young child's skull and try to predict how the skull will be shaped on reaching maturity. We then compare our prediction with an X-ray image of the same individual made during adulthood.

A fundamental issue that had to be addressed before we could make reliable predictions is that our model does not suggest precisely how to orient a head before applying a transformation. Although our earlier research has indicated that the cardioidal-strain transformation is perceived as growth over a considerable range of facial orientations, there is a noticeably large effect of orientation when the faces are compared on a point-to-point basis. It is therefore necessary to have a specific procedure for orienting a head so that different investigators can make the same predictions on different occasions. Our solution to this problem, arrived at through trial and error, is to orient each X-ray image over a sheet of polar graph paper. We are able to get satisfactory predictions by placing the tip of the chin at 160 degrees and placing the point where the bone at the base of the nostrils

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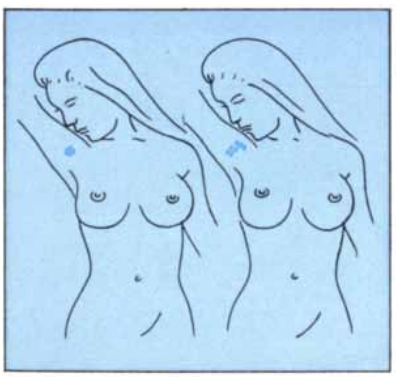

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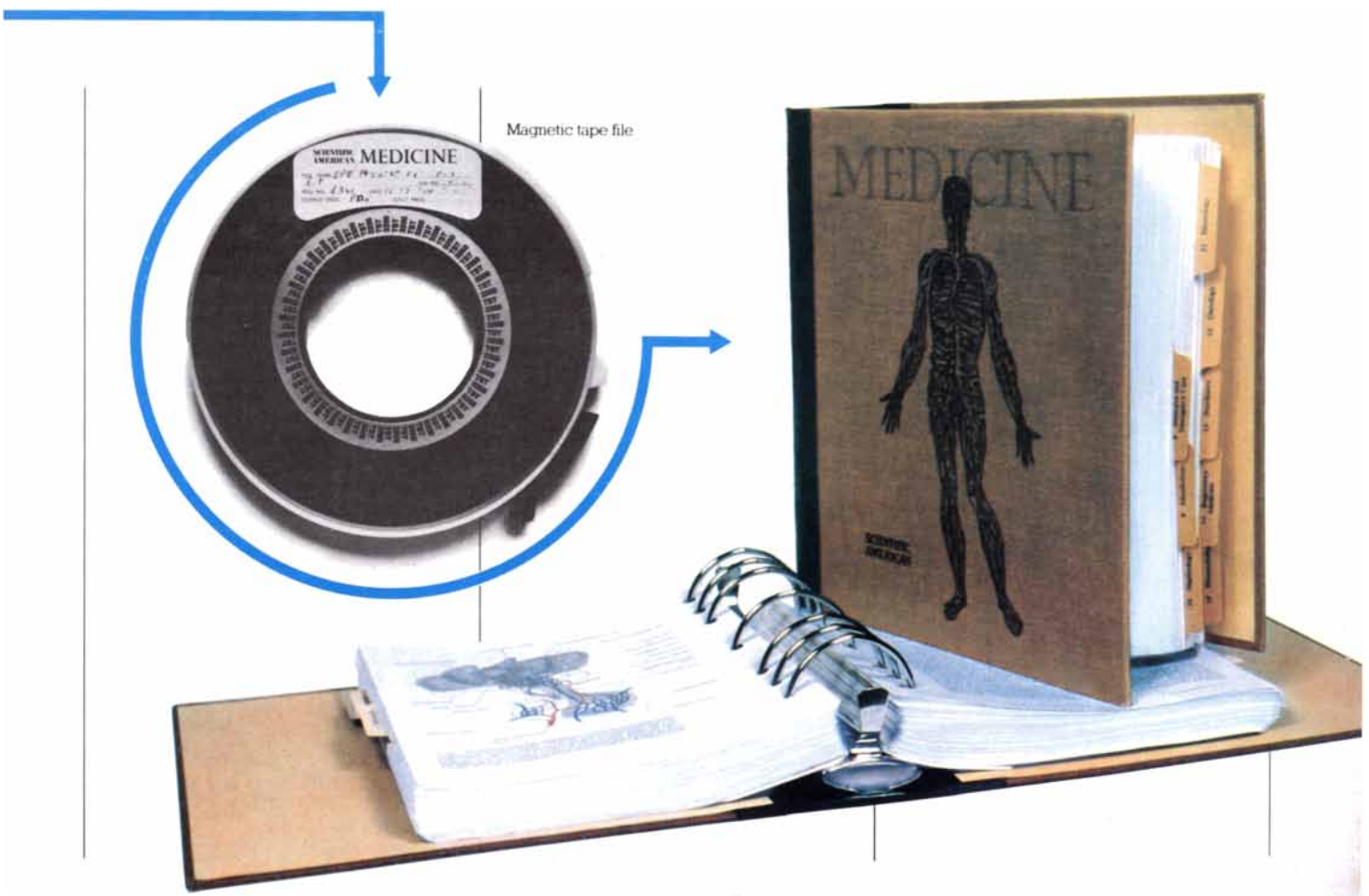
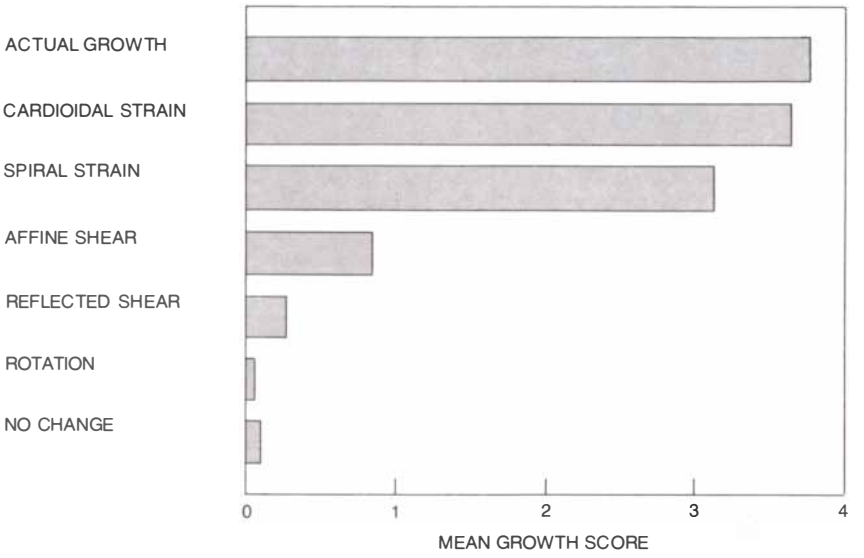




RESULTS OF THE EXPERIMENT illustrated on page 140B are presented in this bar chart. The mean growth score for the cardioidal-strain transformation was closest to that of the actual growth sequence, with the spiral-strain transformation coming in not very far behind. None of the other prospective geometric transformations yielded a significantly greater score than that of the control sequence (*"No change"*). This basic pattern of results, suggesting that heads grow cardioidally, has since been replicated by the authors in a variety of other experiments.

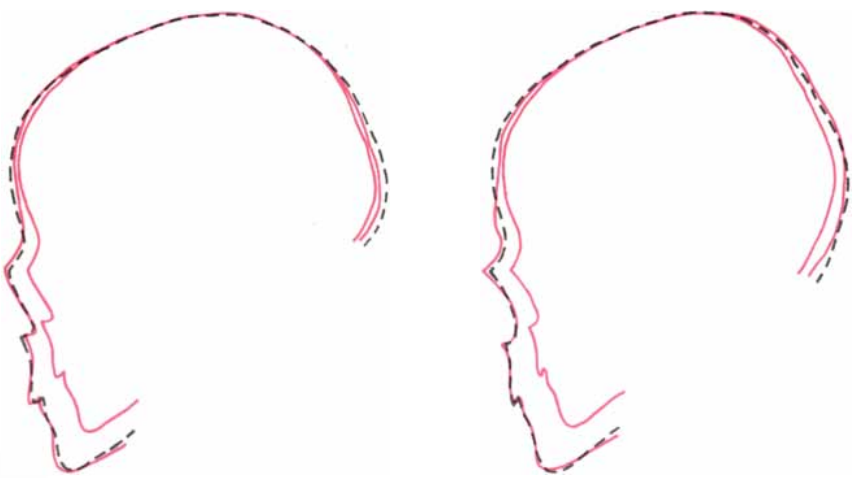
meets the rest of the skull at 125 degrees, so that the origin of the graph paper is midway between the two points where the skull intersects the horizontal axis.

After an X ray is properly oriented a continuum of transformed skull outlines is generated with successively larger values of the revised cardioidal-strain transformation. The resulting family of forms constitutes a predicted path of craniofacial growth. According to our model, an individual might grow at varying rates at different times, but barring some unexpected trauma, the direction of growth should always follow the predicted path. This hypothesis can be tested by comparing the predicted skull outlines for any given individual with an actual X-ray image made at maturity. The results of this procedure for two typical subjects are presented in the illustration below. It should be clear from the figure that our cardioidal model of craniofacial growth is able to generate surprisingly accurate predictions.

There are several important clinical applications that could eventually result from this research. A major problem confronting cosmetologists, orthodontists and oral surgeons is their present inability to predict how a given medical treatment will interact with normal growth processes. For this reason individuals who suffer from craniofacial abnormalities must often wait until they reach maturity before corrective treatment can be started. The ability to predict growth may also provide clinicians with a useful tool for the diagnosis of craniofacial abnormalities. If a human head is normally constrained to grow along a cardioidal path, then significant deviations from the path are likely to indicate that normal growth processes have somehow gone awry. By comparing a patient's actual craniofacial development with the predicted cardioidal path, a clinician could gain important insights about the underlying causes of abnormal growth and could reasonably assess what the patient would have looked like under more normal conditions. The latter information would be particularly useful for establishing the goals of corrective treatment.

There are many other issues that must be resolved before we fully understand the overall regularities of craniofacial growth and the ability to perceive growth as a distinct type of change. One such issue that we are currently investigating is the pattern of growth in other parts of the body in relation to the head. The first biologist to study this problem with a transformational approach was P. B. Medawar. In 1944 he reported a geometric transformation that adequately describes the changes in human body proportions observed from infancy to adulthood. Our own research in this area has been primarily concerned with demonstrating the perceptual salience of Medawar's transformation as an abstract type of change. Our results so far indicate that Medawar's transformation is similar to cardioidal strain in that it is perceived as growth even when it is applied to unfamiliar objects.

Another related issue that we are currently investigating is the apparent similarity between growth and evolution. In the course of our perceptual research we were surprised to discover that by reversing a sign in the revised cardioidal-strain transformation it is possible to produce a pattern of change closely resembling evolution [*see bottom illustration on page 133*]. Observers have frequently noted that the innermost profile looks something like a Neanderthal man, whereas the outermost profile looks like a futuristic being such as one might see in a science-fiction motion picture. Since both growth and evolution can apparently be described by a single geometric transformation, it seems reasonable to speculate that both processes are affected by the same influences. Such speculations may eventually help in gaining an understanding of why evolutionary change is perceived to be a continuous process that, like growth, moves inexorably along a specific path of morphological change.



REVISED CARDIOIDAL-STRAIN TRANSFORMATION was tested by fitting it to tracings of actual X-ray pictures made of the same person at different ages. The colored outlines at the left were traced from the X-ray pictures of a female at the ages of seven and 22; the colored outlines at the right were traced from the X-ray pictures of a male at the ages of eight and 19. The broken black outlines are the transformed versions of the younger profile of each person. The values of the revised cardioidal-strain transformation were chosen so that the transformed younger profile in each case would be as similar as possible to the actual older profile.

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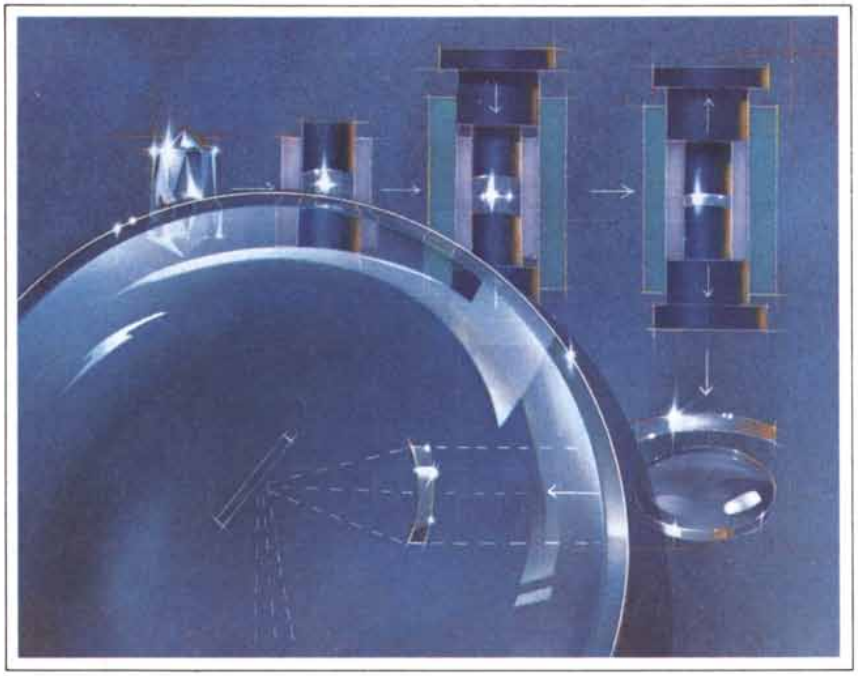

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Decorator Crabs

Many species of spider crabs can camouflage themselves by patterns of behavior in which they select materials from their environment and festoon them on their shell

by Mary K. Wicksten

Animals that camouflage themselves are seen—or not seen!—throughout the natural world. Certain insects resemble a twig; certain lizards are able to change their coloring to match different backgrounds; certain mammals are spotted so that they blend into a pattern of light and shade. In the marine environment some of the best-hidden animals are crabs. Many of the thousands of species of crabs have lines, spots or patterns that serve to break up the outline of their carapace, or upper shell. A few species have a pair of modified back legs with which they pick up objects such as shells or sponges and hold them on or over their carapace. The crabs most adept at camouflage, however, are those that deliberately select bits of material from their environment and attach them to various parts of their shell. Called masking crabs or decorator crabs, these animals can become so heavily encrusted with strands of red or brown algae, pieces of fluffy branched bryozoans, segments of feathery brownish yellow hydroids and brightly colored sponges that an experienced underwater naturalist can sit on a decorator crab before realizing that it is there.

Crabs belong to the crustacean order Decapoda, and decorator crabs belong to the decapod family Majidae, commonly known as spider crabs. Spider crabs have a rounded or elongated body, four pairs of long, slender "walking" legs and a pair of front legs that are modified as chelae, or pincers. It is the chelae that gather fragments of decorating material and attach them to the minutehook-shaped setae, or bristles, found on various parts of the crab's shell.

Naturalists have known of spider crabs' habit of decorating their shell at least since the middle of the 19th century. In 1889 the Swedish naturalist Karl Aurivillius gave a detailed account of the decorating activities of many European species. Before the introduction of scuba diving equipment, however, all such studies were based on observations in aquariums of crabs that had been captured by dredging, a nonselective procedure that tended to injure the animals. In recent years it has been possible not only to stock aquariums with healthy crabs in a wide variety of species, sizes and stages of maturity but also to observe the animals in their natural habitat. With the application of modern techniques for underwater and slow-motion photography and scanning electron microscopy workers in this field have gained new perspectives on decorating behavior. I shall discuss here some of the most recent findings about the form, function and development of decorating in spider crabs.

Decorating is actually a complex chain of activities that begins with the acquisition of a piece of decorating material. For this task a spider crab relies on its nimble chelae, which are slender and forcepslike in females and immature males and heavier in mature males. The chelae can work separately to pick pieces of algae or other detritus directly off the bottom or together to twist off branches of bryozoans or hydroids and break them into pieces of suitable length. The fingers of the chelae can also snip off pieces of sponges or compound ascidians. (Orange or white compound ascidians, which are found on the shell of many decorator crabs, are fleshy organisms that grow in matted colonies on hard surfaces.)

Once a piece of decorating material of appropriate size has been obtained, one of the chelae conveys it to the oral field: the area near the front of the crab where the mouthparts are. The mouthparts manipulate the piece of material, rotating it repeatedly until its edges are rough. (A long, thin piece of material such as a strand of alga is roughened at one end only.)

To attach the roughened piece of material to its shell the crab takes the piece from its mouthparts with one of its chelae and rubs it against an area of the shell covered with hooked setae. Rows of these curved (and in some instances barbed) bristles are found on the crab's rostrum (a projection in front of the eyes), on the back of its walking legs (and in some instances on the back of its chelae) and along the sides of its carapace, the distribution differing from species to species. The piece of material adheres to the shell because before the crab releases the piece from its mouthparts it turns the piece so that it is either parallel or perpendicular to the rows of hooked setae where it is to be attached. When the crab rubs the piece against the rows of setae with its chela, the piece is entangled or impaled.

A piece of decorating material that does not get quickly affixed is returned to the mouthparts for further manipulation. It has often been suggested that glands in the mouthparts of a spider crab manufacture a glue that this oral manipulation serves to apply. Those glands probably function in digestion rather than decoration, however; I have found that a spider crab can decorate itself normally after they are removed. On the other hand, if a crab's hooked setae are removed, the crab cannot decorate itself, although it will make repeated attempts to attach properly prepared material. (Other kinds of setae on the crab's shell function as tactile sensory structures and probably provide information about the position of the decorating materials.)

A few species of spider crabs are found on soft bottoms consisting of mud or sand, but most of them inhabit hard or rocky substrates anywhere from the high-tide mark on a coastline to the outer edge of the continental shelf. The crabs settle into such habitats after a larval stage in which they float free among other plankton at the surface. Little is known about the life cycle or molting patterns of spider crabs, but after settling on the bottom all the decorator crabs I have observed molted two or three times before they began to decorate themselves. It appears that many spider crabs continue to decorate themselves throughout their lives, although some, such as the male moss crab *Loxo-*

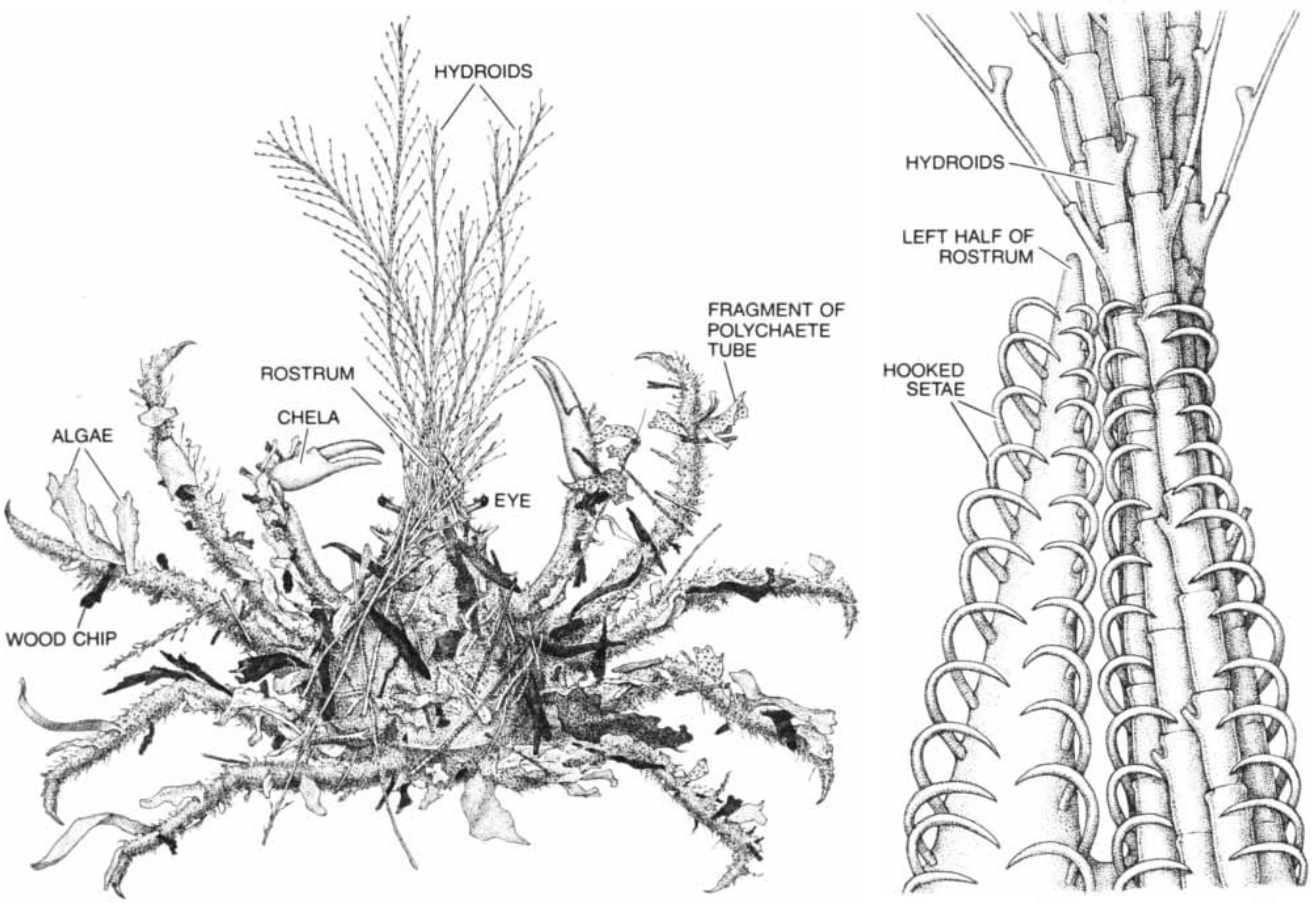
HEAVILY DECORATED CRAB *Oregonia gracilis*, covered by bits of whitish yellow sponges and fluffy branched bryozoans, is barely visible at the center of this photograph. Like all decorating species this crab belongs to the family Majidae, familiarly known as the spider crabs. Spider crabs have a pair of chelae (pincerlike front legs) that in decorating species serve to gather material and attach it to hooked setae: minute curved bristles found on the sides of the carapace (the upper shell), on the rostrum (a sometimes forked projection in front of the eyes), on the back of the long, slender walking legs and sometimes on the back of chelae themselves. (The distribution of the hooked setae differs from species to species.) During the day spider crabs lie on bottom with chelae folded under them, as is the case here.

rhynchus crispatus, stop decorating at about the time they reach maturity. (*L. crispatus,* one of the largest crabs found on the California coast, stops displaying decorating behavior when the width of its carapace reaches about four inches and the span of its legs about three feet. At this size it is presumably immune to attack by most predators.)

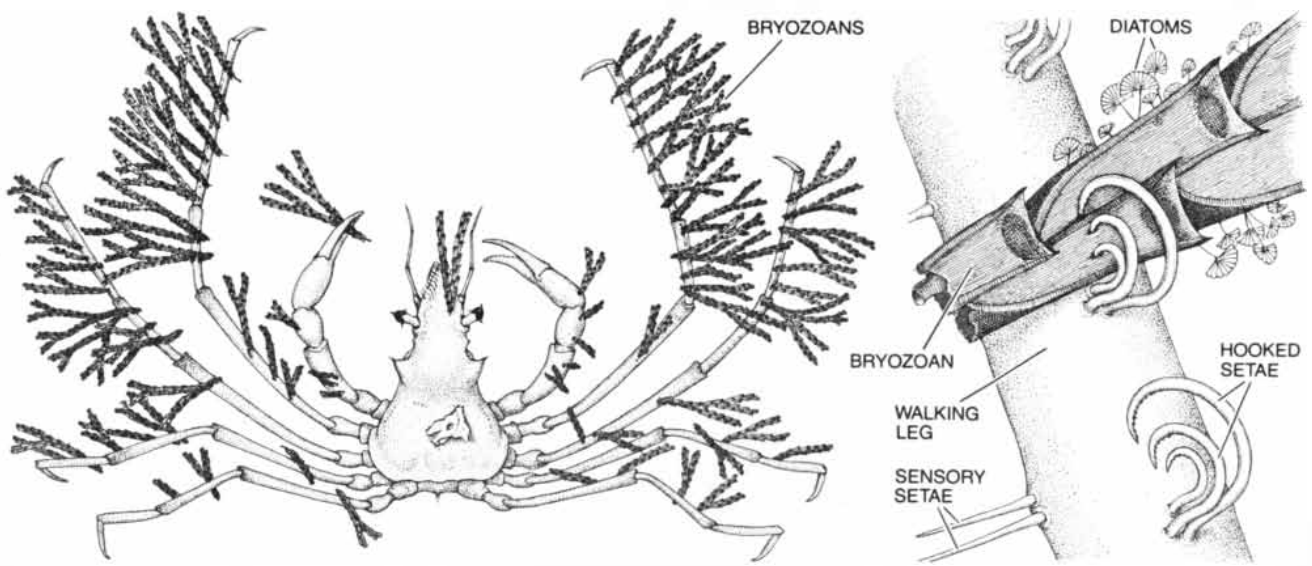
The materials spider crabs generally favor for decorating their shell are flexible, easily torn organisms such as sponges, algae, bryozoans and compound ascidians. The crabs make frequent use, however, of other types of decorating material, including pink or green coralline algae (algae stiffened by a coating of calcium carbonate), branches of brightly colored gorgonians (horny corals such as sea fans), tubes secreted by polychaete worms and even the leaves of land plants. The Caribbean spider crab *Stenocionops furcata* attaches the small striped sea anemone *Calliactis tricolor* to its carapace and legs. In aquariums spider crabs stripped of their decoration have been known to decorate themselves with torn sea pansies, strips of paper, chips of cement from the aquarium wall and even bits of hamburger.

Just as the materials of decoration can differ from species to species so can the decorating style. Compare two crabs that decorate intensively. A juvenile crab of the species *Loxorhynchus crispatus* covers its entire carapace with a thick layer of algae, bryozoans and other organisms; *Oregonia gracilis,* a crab found along the northwestern U.S. coast, covers its carapace and walking legs but also anchors at its rostrum long streamers of algae, bryozoans and hydroids. Among the crabs that decorate themselves more sparingly is the small crab *Podochela hemphilli,* which is often found around California docks and wharf pilings. This crab generally leaves much of its carapace and rostrum uncovered but attaches small bits of algae or bryozoans so that they stick out from its walking legs. The European spider crab *Inachus scorpio* is reported to be even more selective, decorating only its first pair of walking legs.

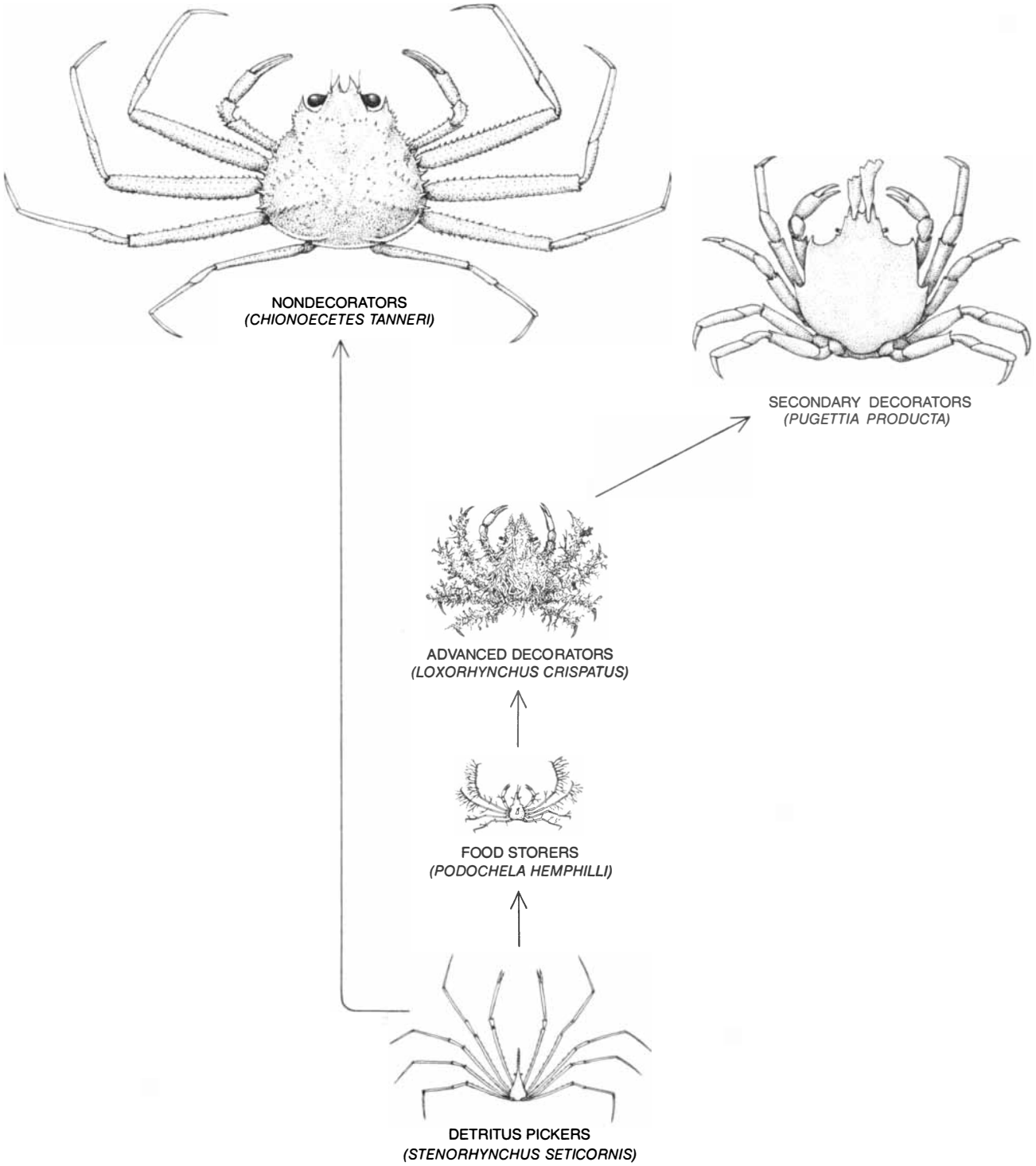
Some of the spider crabs that do little active decoration get covered passively, through the natural accumulation of detritus in their hooked setae or through the attachment of encrusting organisms to their shell. For example, although the sharp-nosed crab *Scyra acutifrons* of the Pacific coast of the U.S. often decorates its own rostrum, much of its carapace is covered by sponges or ascidians that settle there on their own. And as the tiny crab *Pitho picteti* moves across a bottom of sand or rocky rubble in the Gulf of California its hooked setae generally collect a covering of sand and debris. Moreover, small sea anemo-



DECORATING MATERIALS on the carapace and legs of a crab of the species *Oregonia gracilis* in the drawing at the left include short strands of algae, segments of hydroids, wood chips and several sand-speckled fragments of tubes secreted by polychaete worms. The rostrum is decorated with long streamers of hydroids, and the entire surface is covered with a layer of filamentous algae. The chelae pick up or tear off a suitable fragment of material and carry it to the mouthparts, which manipulate the fragment until its edges are rough. Then one of the chelae rubs the fragment against an area on the crab's shell that is covered by rows of hooked setae. Depending on whether the fragment is held perpendicular to the rows of setae or parallel to them, it is either impaled or entangled. In enlarged view of crab's rostrum at right the decoration has been partly removed to show how in this species hooked setae are arranged in pairs of facing rows.



MORE SPARING DECORATION is found on the small California crab *Podochela hemphilli,* shown in the drawing at the left. In this species, which is found around docks and wharf pilings, much of the carapace and rostrum is usually bare, even though there are hooked setae on them. The walking legs, however, are often covered with small pieces of algae or, as is shown here, sections of branched bryozoans. The enlarged view at the right shows how pieces of decorating material are impaled on the small clusters of barbed hooked setae that characterize the species. Also shown in this view are a number of diatoms, which often settle on pieces of branched bryozoans sticking out from the crab's walking legs, and straight setae, which function as tactile sensory organs, possibly for location of decorating materials.



EVOLUTION OF DECORATING BEHAVIOR in spider crabs is suggested by behavior patterns in living species. Because the first activities in decorating (finding a suitable piece of material and conveying it to the mouthparts) are identical with activities in feeding, decorating probably began with early spider crabs that picked edible particles out of detritus. Some of these crabs may have resembled the living species *Pyromaia tuberculata* (not shown), which feeds on debris it finds on the bottom. Others may have resembled the living arrow crab *Stenorhynchus seticornis,* which picks food particles out of debris that collects on its hooked setae. Eventually some of these early spider crabs may have taken to storing food on their hooked setae in the manner of living decorator crabs such as the species *Podochela hemphilli.* The habit of attaching food to the shell may have given a selective advantage to the early crabs by hiding them from predators, and some of them may have made the transition to attaching nonedible materials for camouflage alone. The most heavily decorated living crabs, such as the moss crab *Loxorhynchus crispatus,* seldom eat anything they have attached to their shell and often decorate themselves with materials that few marine animals eat, including noxious sponges and stinging hydroids. The specimen of *L. crispatus* shown here is a juvenile; adult males of the species, one of the largest found on the California coast, stop decorating when they reach maturity. The same is true of both the males and the females of several other large species of decorator crabs. Among the other living species of spider crabs that decorate sparingly or not at all some, such as the kelp crab *Pugettia producta,* may have lost much of the decorating habit in response to environmental pressures (*see illustration on page 152*); others, such as the tanner crab *Chionoecetes tanneri* (whose soft-bottom habitat lacks decorating materials), may never have acquired the decorating habit. All spider crabs shown here are drawn to same scale.

nes and bits of sponges and compound ascidians, however they come to decorate a crab's shell, may remain alive after they have become attached and grow out from the original area of attachment. Many spider crabs of the genus *Pelia,* including the California crab *Pelia tumida,* tend to decorate themselves with small bits of sponges that regenerate and spread out to cover the entire carapace.

Although decorator crab species have been identified in all living subfamilies of the Majidae, many spider crabs do not decorate at all. For example, as I have mentioned, *Loxorhynchus crispatus* does not decorate after it reaches a certain size. Other large spider crabs (species with a leg span of two and a half feet or more) that do not decorate themselves as adults include the California sheep crab *Loxorhynchus grandis,* the Caribbean giant crab *Mithrax spinosissimus,* the Pan-American crab *Maiopsis panamensis* and the Japanese giant crab *Macrocheira kaempferi.* (With a leg span of up to 14 feet, *M. kaempferi* is the world's largest crab.)

Size is not the only factor that may keep a spider crab from decorating itself. For example, species with a knobby shell that already matches the substrate they inhabit generally do not decorate themselves. Hence the lumpy spider crabs of the tropical genus *Mithrax,* which live on a hard, rocky bottom, tend to remain totally free of decoration except for a few encrusting organisms that settle on their own. Spider crabs that live among the stipes, or stemlike parts, of giant algae tend not to decorate themselves, possibly because as they climb through the algae any decorating material would get knocked off. Thus if the brown kelp crab *Pugettia producta,* which is generally found among the giant brown kelps on the California coast, decorates itself at all, it attaches only bits of kelp to its rostrum. The purple kelp crab *Taliepus nuttalli* does not display any form of decorating behavior. Finally, spider crabs that inhabit soft substrates, such as the tanner crabs of the genus *Chionoecetes,* rarely decorate themselves, probably because of the absence of decorating materials on bottoms of sand or mud.

It is important to note that although a motionless, well-decorated crab may be difficult to see in its natural habitat, in some instances the match may be far from exact. I have seen a spider crab encrusted with white ascidians sitting in a field of dark red algae and one decorated with orange ascidians, yellow hydroids, red algae and blue sponges resting on a bed of bright pink coralline algae. *Loxorhynchus crispatus* can usually be detected by looking for patches of dead, bleached bryozoans. Moreover, if in aquariums the Caribbean decora-

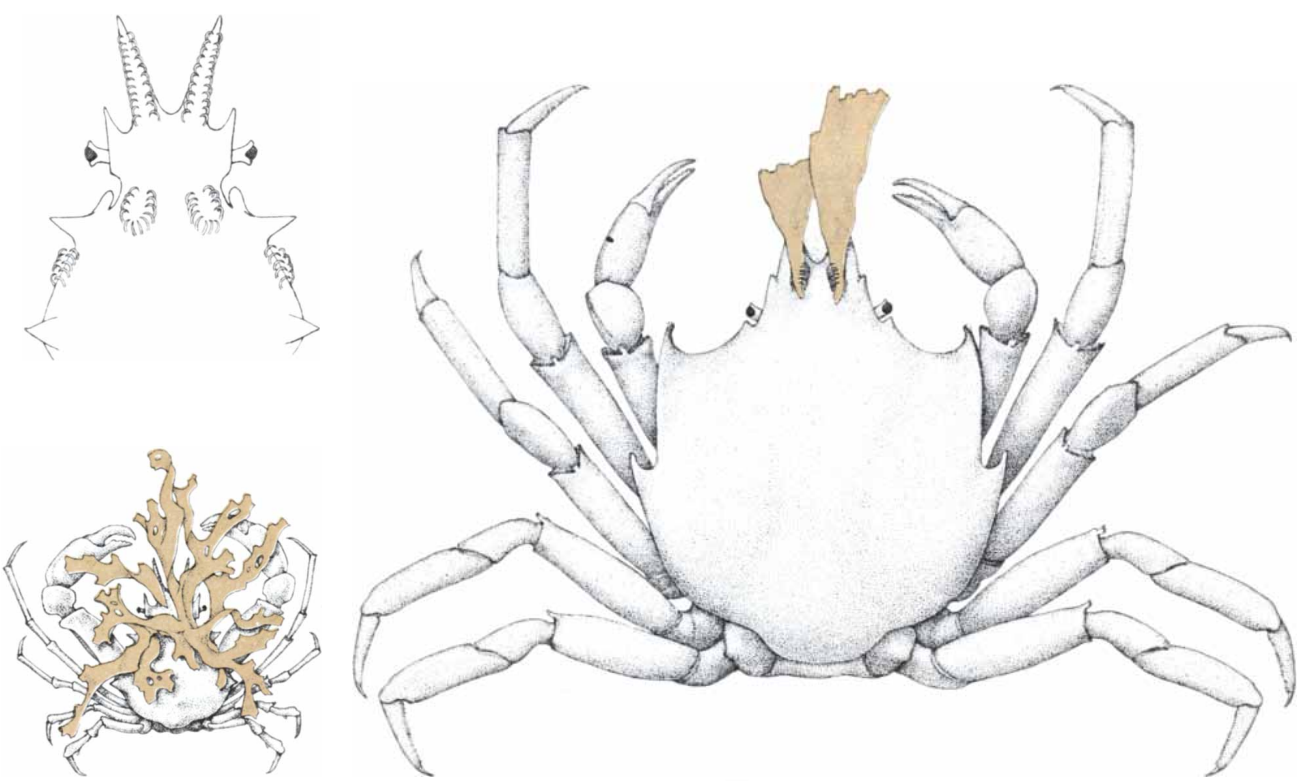
tor crab *Microphrys bicornutus* is placed against a background whose color contrasts with the crab's covering, the crab makes no effort at adjustment. In a similar situation a small crab of the species *Loxorhynchus crispatus* will intersperse material from the new environment among the bits of decoration already accumulated.

These examples probably reflect the fact that crabs living on reefs characterized by a diverse biota would, as they move from place to place, have great difficulty trying to match each different background. More generally, it appears that decorating serves not to make a spider crab invisible but rather to make it look less like a crab. To accomplish this end the crab must expend metabolic energy that could be devoted to other important activities such as feeding or mating. What does the animal get in return, that is, what is the function of decorating behavior?

To begin with, in a number of species the camouflage provided by decorating activities appears to facilitate the capture of prey. For example, in aquariums fishes and other swimming prey have been observed coming close to motionless crabs of the well-decorated European species *Hyas araneus* (a lyre crab) and *Macropodia rostrata* and being captured by them. And in tanks in my laboratory at the University of Southern California another lyre crab, *Hyas lyratus,* has proved to be a voracious predator on smaller crabs, which its heavy decoration often enables it to approach unnoticed. Most spider crabs, however, feed on carrion, on eyeless organisms such as echinoderms (sand dollars, sea urchins, starfishes and so on), on slow-moving organisms such as mollusks and polychaete worms, and on sessile plants and animals such as algae or ascidians. There is obviously no need of camouflage in capturing these organisms, and for the spider crabs that feed on such prey the main function of decoration is probably to provide protection against predators.

The animals that prey on decorator crabs include the European lobster *Homarus gammarus,* the sea otter *Enhydra lutris* and a wide variety of fishes, octopuses, starfishes, spiny lobsters, other crabs and even sufficiently adventurous human beings. During the daylight hours, however, most decorator crabs are effectively camouflaged by their shell decoration and their lack of movement. The crabs spend the day lying pressed against the bottom with their chelae folded under them. The only movement is that of the antennae, which extend out from the crabs' ventral surface, and they are generally hidden from view by overhanging decoration. Hence in aquariums well-decorated specimens of *Loxorhynchus crispatus, Pelia tumida* and *Pugettia richi* (a kelp crab found on the Pacific coast of the U.S.) are rarely eaten by predators. Similarly, although sea otters off Pacific Grove, Calif., frequently make a meal of the lightly decorated kelp crab *Pugettia producta,* they have rarely been known to feed on crabs of the species *L. crispatus,* which are also found in abundance there.

A decorator crab's camouflage is not its only form of protection; spider crabs display several types of behavior other than decoration that help them to avoid predators. For example, although many studies of spider crab behavior have emphasized the slow, deliberate movements that characterize the behavior of these animals during the day, at night they can be seen walking openly across sandy bottoms, climbing kelp or foraging on reefs. A spider crab that is threatened by a predator will run, display its chelae, pinch the predator or autotomize, or allow to break off, a limb



SOME KELP CRABS of the genus *Pugettia* seem to have lost decorating behavior. Small species such as *Pugettia dalli* (*left*), which live among low-growing algae or on the holdfasts (rootlike parts) of larger kelps, decorate the sides of the carapace and the rostrum, generally with pieces of kelp (*color*). The distribution of hooked setae on the shell of such kelp crabs is shown in the enlarged view at the upper left. The larger kelp crab *Pugettia producta* (*right*), which lives among the stipes (stemlike parts) of giant kelps, decorates only the rostrum, lacking the hooked setae along the edges of the carapace and behind the eyes that characterize the smaller species. *P. producta* is probably advanced species that lost most of decorating habit as it moved from smaller to larger kelps. Crabs shown here are drawn to same scale.

in the predator's grip. A crab that is fleeing a predator will often drop off an underwater ledge with its legs spread and land on the bottom below. (The European crab *Macropodia rostrata* is the only spider crab known to swim.)

Furthermore, the materials a spider crab attaches to its shell do not protect the crab merely by hiding it. The sponges and the compound ascidians found on the shells of many decorator crabs may be noxious or even toxic to the crab's predators. Hydroids and sea anemones often possess nematocysts, specialized stinging cells that can make a predator drop a captured crab. In aquariums when three fishes that feed on crabs (the cabezon, the lavender sculpin and the California scorpion fish) captured small crabs of the species *Loxorhynchus crispatus* and *Pelia tumida,* they promptly spat them out.

Moreover, to a prowling octopus a furry, well-decorated crab might not feel like a crab at all. Two small specimens of *Loxorhynchus crispatus* in an aquarium with 15 octopuses survived unharmed while crabs of several other species in the aquarium were captured and eaten. One of the two decorator crabs even molted and redecorated itself with bits of the octopuses' crab prey. (Crabs are most vulnerable to attack when they molt or when their shell is damaged. When *L. crispatus, L. grandis* and the New Zealand crab *Notomithrax ursus* molt, however, they immediately remove bits of decorating material from the abandoned shell and attach them to the new one. Molting proceeds at night or in the early morning, when it is difficult to see even an undecorated crab. Within a day the crab has a hard and completely decorated new shell.)

The complicated chain of activities that make up decorating behavior in spider crabs is probably the result of a long evolutionary process. Unfortunately there are not many fossil crabs available to aid in the reconstruction of the process, but consideration of the different behavior patterns displayed by modern species of decorator crabs suggests a possible evolutionary sequence. To begin with, it is interesting to note that the first maneuvers of decorating—picking up materials and conveying them to the mouthparts—are similar to the activities of feeding. It seems likely that the evolution of decorating behavior began with early crabs that picked morsels of food out of detritus. Some may have resembled the modern spider crab *Pyromaia tuberculata,* which picks edible particles out of detritus on the bottom. Others may have resembled the arrow crabs of the genus *Stenorhynchus* and the small California spider crab *Erileptus spinosus,* which perch on gorgonians or other elevated places and by extending their legs into a current gather detritus from which they later pick edible particles.

A later stage in the evolutionary process may have been the storage of uneaten food on the setae. The spider crab *Podochela hemphilli* will eat bits of algae it has removed from its shell. And in aquariums in my laboratory the tropical decorator crab *Camposcia retusa* attached to the hooked setae of its first walking legs bits of chopped fish, which it later ate. The attachment of uneaten food to the setae of primitive crabs may have given them a selective advantage by hiding them from predators.

Species such as *Loxorhynchus crispatus* and *Pelia tumida* generally do not eat anything they have attached to their shell. Indeed, these species often decorate themselves with noxious sponges, ascidians, sea anemones and other things few marine animals eat. This suggests that at some point the early food storers must have switched from attaching to themselves edible materials to attaching inedible ones providing only camouflage.

The decorating patterns of the kelp crabs of the genus *Pugettia* suggest a further evolutionary sequence away from decoration. The small species *Pugettia richi, P. hubbsi, P. dalli* and *P. gracilis,* which live among low-growing algae or on the holdfasts (the rootlike parts) of larger kelps, decorate their rostrum and the sides of their carapace. The larger crab *P. producta,* which lives among the stipes of giant kelps, decorates only its rostrum. *P. producta*'s lack of lateral hooked setae, the square shape of its carapace and its large size all suggest it is an advanced species that may have lost the decorating habit as it moved from small algae to large kelps. Similarly *P. venetiae,* which inhabits sandy bottoms, does not decorate itself at all. It may have lost the behavior pattern as it moved to a habitat where decorating materials were scarce.

In studying the relations among different species of birds and mammals behavioral comparisons have frequently proved to be of great value. It is possible that the application of similar methods to the study of decorating behavior would also be revealing. A deeper understanding of the evolutionary history of the spider crabs could be gained by comparing in different species the sculpturing and distribution of the hooked setae, the patterns of attachment of decorating materials, the types of material chosen, the degree of decoration achieved and the variations in decorating behavior according to size, sex or age. At present information about the natural history of most species of spider crabs is scant. In order to make meaningful, quantitative evaluations of their decorating behavior much close observation remains to be done.

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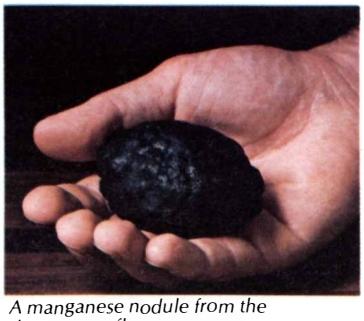

A manganese nodule from the deep ocean floor.

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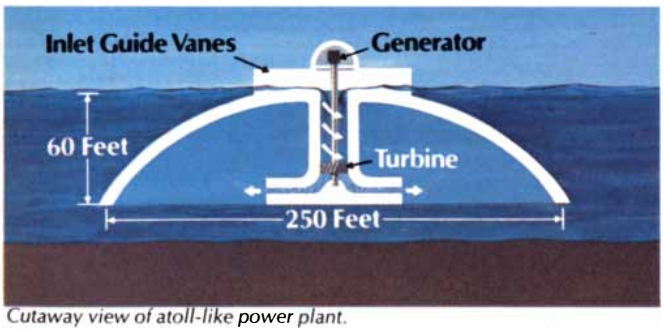
How artificial atoll would look anchored in place.

of the ocean.

The world's largest, most advanced mining ship puts to sea.



Cutaway view of atoll-like power plant.

The concept is similar to the action of waves hitting atolls. The waves don't just sweep by those small islands. Instead, they wrap themselves around them in a spiral pattern.

So, what the Lockheed scientists have done is design a small, artificial atoll that bends the striking waves into a whirlpool. This vortex within the domed structure becomes a powerful flywheel of water. It drives the one moving part: a submerged turbine wheel. The end result is an outpouring of electricity, a potential bonanza of power.

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Easy ways to make holograms and view fluid flow, and more about funny fluids

by Jearl Walker

Many techniques have been employed to make holograms, the intriguing three-dimensional photographs that give a viewer the same sense of parallax and depth that seeing the actual scene would. Recently a new arrangement was sent to me by John Osborne and Bob Waterman of the South London Science Centre. Their technique is the simplest one I have seen. It also is quite insensitive to vibrations, which plague other methods of making holograms.

Conventional photographs record the light scattered from an object and focused onto a strip of film. The result is a flat picture with no apparent depth. Holograms are different because they record not the focused image of an object but the interference between the light scattered from the object and some of the direct light from the source illuminating the object.

In the basic procedure for making a hologram light from a laser is split into two beams by a partially reflecting glass plate. One beam results from the transmission of light through the plate. The other beam results from the reflection of light from the surface of the plate. One of the beams directly illuminates a strip of film. The other beam scatters from the object being photographed. Part of the scattered light also illuminates the film, interfering with the direct illumination. The film is thus exposed to the bright and dark components of the interference pattern, which are mostly too fine for the eye to see directly.

Once the film is developed the interference pattern can be reconstructed by placing the film in the beam of a laser. When one views the film illuminated in this way, the interference pattern creates an image of the object photographed. The image is virtual since its existence is illusory, depending strictly on the observer's eyes to focus the rays of light coming from the film. The illusion can be quite convincing because the parallax and depth in the original scene are faithfully preserved. When one examines the film from a slightly different perspective, the eyes lie in a slightly different part of the interference pattern. Therefore one sees a slightly different perspective of the virtual image, just as if the object were actually present.

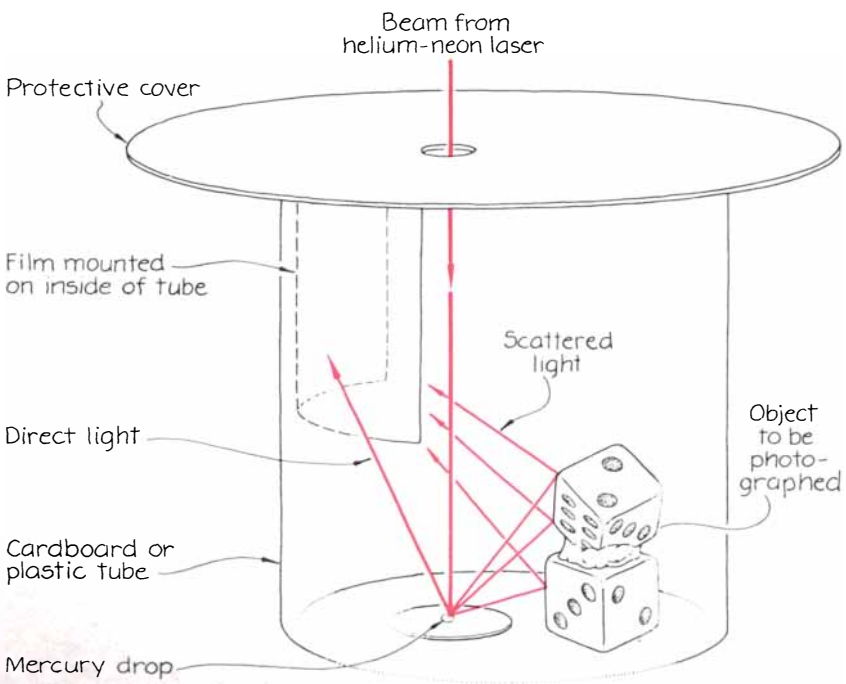
Making a hologram normally requires several lenses, a partially reflecting plate of glass and a sturdy platform. The entire arrangement of the laser and the optical components must be as free of vibration as possible while the film is exposed, otherwise the interference pattern will be blurred on the film. Experimenters with holograms often go to elaborate lengths to eliminate vibration from their equipment.

Osborne and Waterman have done away with the need for lenses and glass plates by a clever arrangement of the laser beam and a shiny drop or bead of mercury. The laser is mounted on a tripod so that the beam is directed downward onto the bead of mercury, which is on a small platform on the floor. (The fact that the apparatus occupies little of the floor accounts for the relative lack of vibration.) The object to be photographed is placed near the bead, after which a cylinder of cardboard or plastic is slipped over the entire assembly. On one side of the cylinder, somewhat above the level of the object, is the film to be exposed.

The laser illuminates the mercury bead, which sends part of the light directly to the film and part to the object to be photographed. Some of the light scattering from the object also exposes the film and interferes with the direct illumination on the film. Once the film has been developed it is a hologram of the object photographed.

To see the hologram one mounts the developed picture in an aperture cut into the side of another cylinder. This cylinder is placed around the mercury bead just as the first cylinder was. When the beam again illuminates the mercury, part of the light is reflected to the film. Receiving this light, the observer sees a virtual image of the object lying somewhere inside the cylinder.

One can re-create the illusion with almost any reflecting surface substituted for the bead. For example, a piece of chalk or white paper will reflect enough light to the film to enable the observer to see the virtual image. One can even eliminate the laser by substituting a small white lamp at the point where the mercury bead is normally placed. (The laser is, of course, still needed for making the hologram.) With the lamp the hologram will be colored but not as clear as it is with monochromatic laser light. The various colors from the white



The setup with which John Osborne and Bob Waterman make holograms

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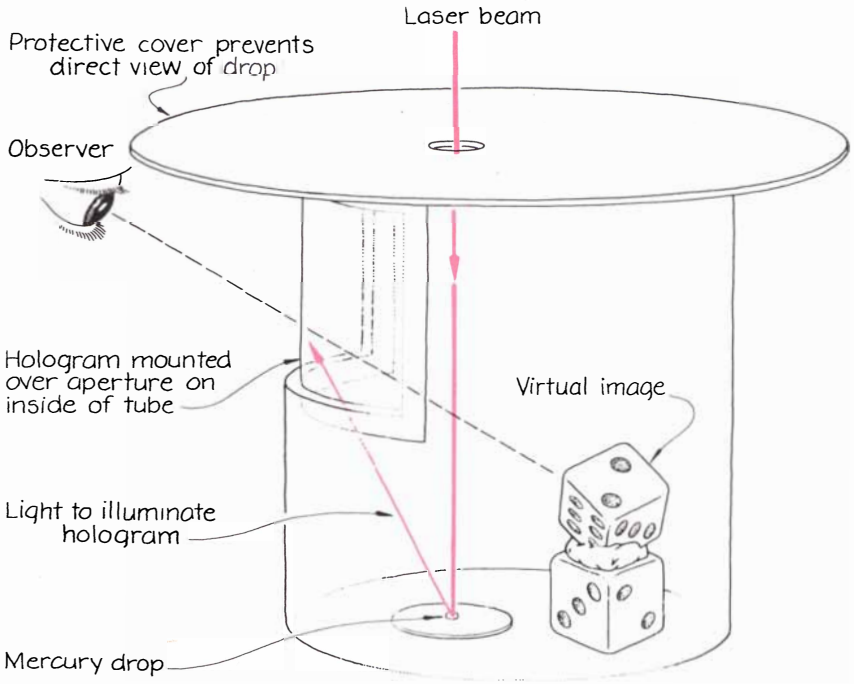


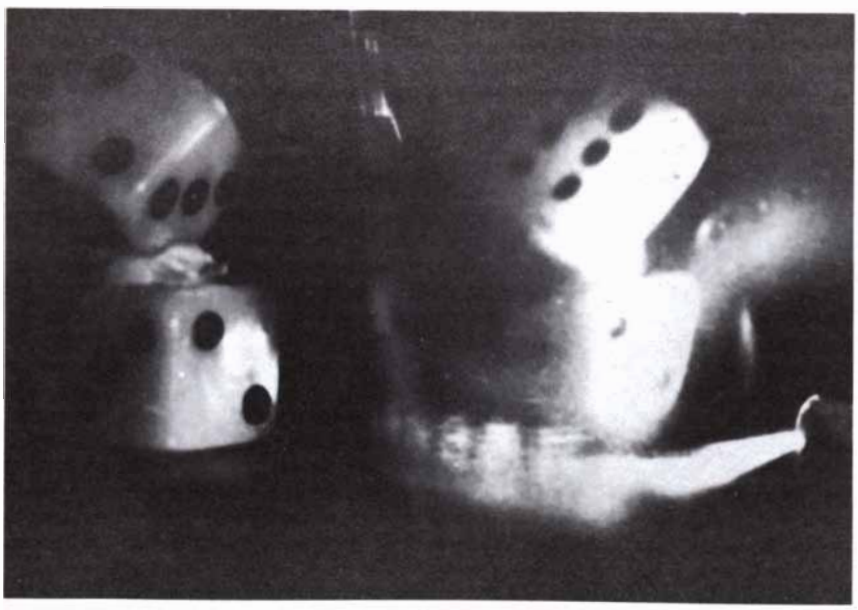
How to view the hologram

light will each create a holographic image slightly shifted in the observer's field of view. Part of the blurring is eliminated if the observer views the image through a colored filter that eliminates all but one color.

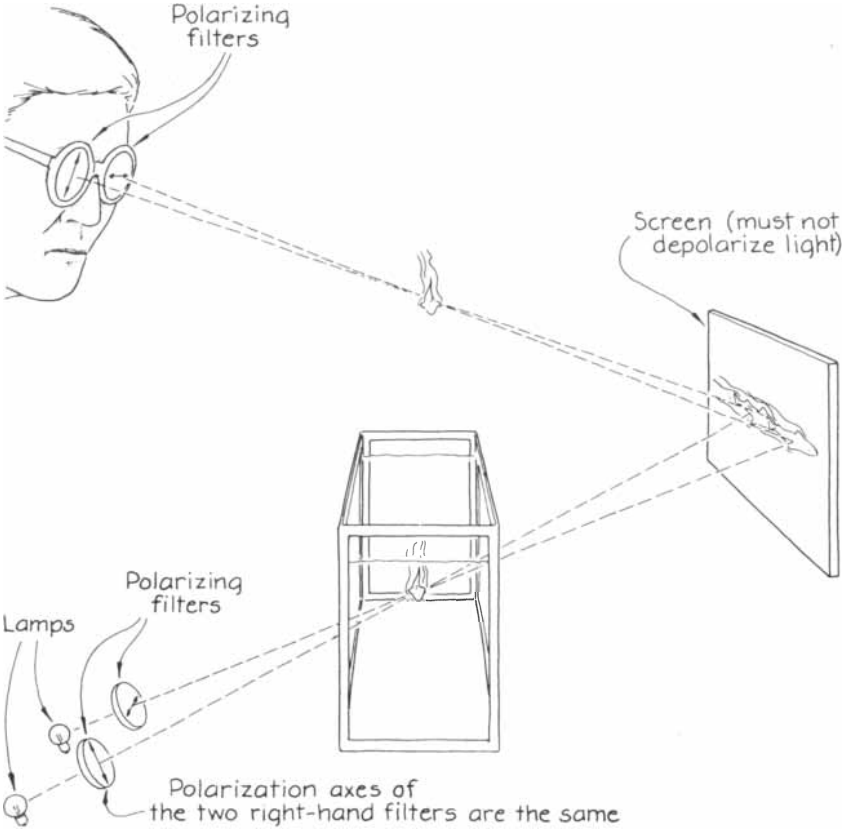
For a source of white light Osborne and Waterman use a two-volt flashlamp bulb of the miniature prefocus variety. The bulb has a small filament and therefore serves well as a point source of light to mimic the original source of laser light from the mercury bead. The lens end of the bulb is blackened so that light shines only from the sides.

The helium-neon laser used to make the exposure does not need to be very powerful. The more power it has, however, the shorter the exposure must be and hence the less vibration will be a problem. Osborne and Waterman use a Metrologic laser with a power of no more than .7 milliwatt, which is at the high end of the range of power of the lasers in school laboratories.

The laser is left running during preparations for the exposure of the film, but the beam is blocked by a shutter mechanism from an old camera. When the preparations are complete, the shutter is



A pair of dice and their holographic image



C. W. McCutchen's arrangement for generating a shadowgraph

triggered by a cable in order to avoid jarring the apparatus. A typical shutter speed is .3 second. An index card could be substituted for the shutter, but the exposure would be a bit less reliable.

This technique of making holograms has four disadvantages. One is that the object must be close to the bead and the film and therefore only a closeup photograph can be made. Second, since the light scatters upward to the object and the film, the arrangement yields an image with a footlighted appearance. Third, optimum adjustment of the intensity of the direct and the scattered light is difficult. Increasing the amount of one necessarily means decreasing the amount of the other. Ideally the two should have about the same intensity at the film, so that an interference pattern of good quality is produced. Finally, much of the light reflected by the bead is directed upward and so is lost.

The bead of mercury should be about 1.8 millimeters in diameter. Clean mercury can be extracted from a thermometer by heat and collected in a small dimple on a thin piece of plastic. When the mercury is not in use, it should be protected from dust to preserve its shine. The best size of drop can be determined only by experiment. The strategy is to

A shadowgraph of a small fish swimming in the "push and coast" mode

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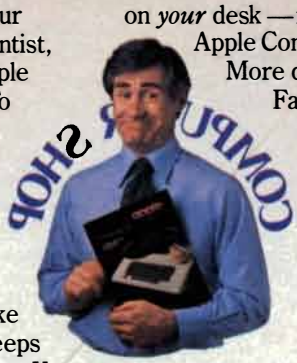

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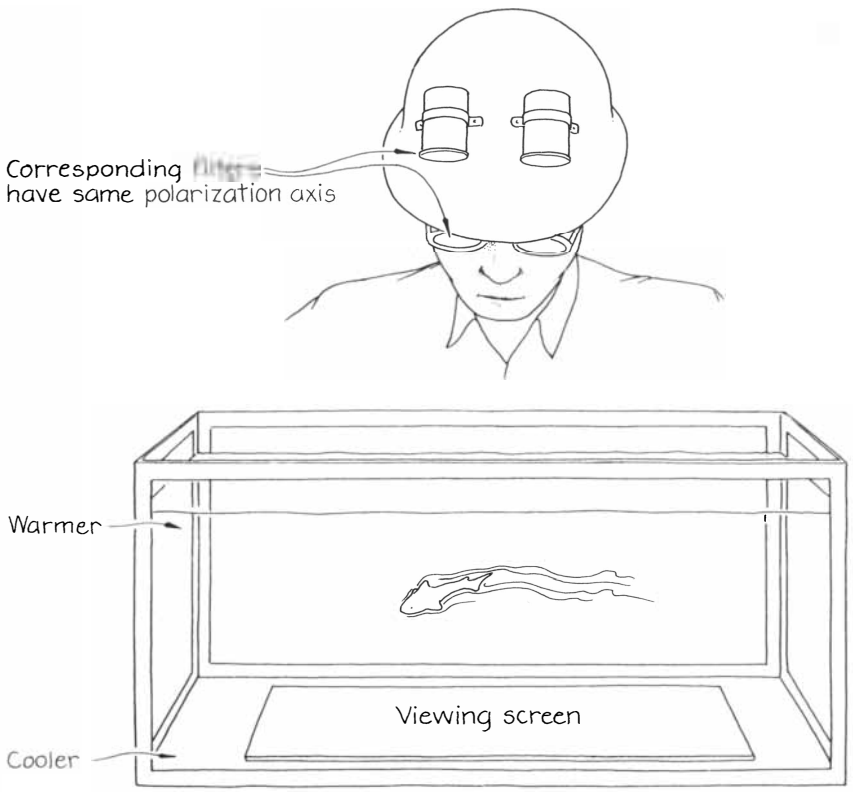

Lamps and polarizing filters mounted on a helmet

obtain the amount of light at the level of the film that yields the proper interference pattern. A larger bead of mercury can be used to illuminate a developed hologram, since it is no longer necessary to split light off to the object.

The best place for the experiment is a concrete floor in a basement. Upper floors will be subject to more vibration. Some experimenters put their equipment in a sandbox mounted on inner tubes. The large mass of sand decreases the vibrations and the inner tubes help to isolate the experiment from the vibrations in the room. (At the finals of the 1979 International Science and Engineering Fair in San Antonio, Susan Tomlinson of Muskogee, Okla., showed me how she made holograms in a sandbox that was originally a bathtub.)

In addition to damping vibrations one should also prevent convection currents and one's own breath from passing through the cylinder during the preparations. Both of them can create variations in the refractive index of the air in the cylinder. The variations would lead to variations in the interference pattern at the film and so to blurring of the hologram.

Osborne and Waterman prefer working with Agfa-Gevaert 10E75AH film (35 by 31 millimeters), but other kinds can be substituted, including 8E75AH and 20E75AH. The film is developed in Agfa G3p developer for five minutes at a temperature of 20 degrees Celsius. The fixer, which is the usual solution for fixing black-and-white photographs, also requires five minutes.

When the apparatus is set up and one is ready to make a hologram, the first step is to check for the proper illumination at the level of the film. With a piece of translucent paper mounted in place of the film examine the illumination reflected by the bead of mercury and by the object to be photographed. If the illumination is not uniform, try a different size of bead (probably a smaller one) or move the bead around in the laser beam.

When the illumination appears to be optimized, remove the translucent paper, block the laser beam with a shutter or an index card, turn off the room lights, take the film out of its container and mount it in the film holder in the cylinder surrounding the apparatus. After exposure the film is developed, dried and then examined in the setup for viewing the hologram. A successful exposure will be achieved only after some experimentation with the illumination and the shuttering of the laser beam. One should try to get a slight darkening of the film.

The hologram should also record as much of the object as possible. For example, Osborne and Waterman have photographed a small toy goat. When the hologram is viewed, the image of the goat can be turned by turning the cylinder holding the hologram or by moving one's head around the cylinder. One can first see the goat face on, then from the side and finally from the rear.

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particularly if it reaches the eye directly. Osborne and Waterman take two precautions to eliminate the possibility that the observer might directly view the mercury bead when it is illuminated with laser light. Over the top of the cylinder they place a cardboard sheet with a hole punched in it for the passage of the laser beam. Hence an observer cannot look into the cylinder to see the bright bead. As a second precaution they extend the top out far enough so that the observer also cannot look directly at the bead when looking through the hologram positioned for viewing.

Experimental techniques to demonstrate fluid flow have always been challenging. Usually they employ dye streamers or small tracers of some kind. The techniques are typically clumsy and difficult to interpret, particularly if the flow involves vortexes. If the object being studied is a swimming fish, the techniques are almost impossible to use. How does one induce a fish to remain stationary before a tracer is released and then, on a cue from the experimenter, to move for only a brief amount of time? If multiple markers are employed, the wake left by a fish may be so complicated that the observer will need computer assistance to make sense of it.

A novel system for avoiding these problems has been devised by C. W. McCutchen of the National Institute of Arthritis, Metabolism, and Digestive Diseases. His system provides just enough information for the observer to easily interpret the flow. It does not require messy dyes or small markers. Best of all, a living specimen need not wait for a signal from the experimenter to begin swimming.

The system employs polarized light from point sources to create a shadow of a specimen and its wake. Two lights illuminate an aquarium containing the specimen. A polarizing filter is mounted on each lamp so that the beams from the lamps are polarized perpendicularly to each other. The strategy is to cast two shadows of the specimen on a screen behind the aquarium. An observer examines the shadows through special polarizing glasses that have the polarization axes of their lenses perpendicular to each other. With the lights and glasses properly oriented the left eye sees only the shadow cast by the lamp at the left and the right eye sees only the shadow cast by the lamp at the right. The brain merges the two images to form what is termed a stereoscopic shadowgram. Although the shadows on the screen are flat, the composite stereoscopic shadow appears to have ordinary parallax and so provides an illusion of depth.

The wake of a moving fish does not cast a normal shadow because water is transparent. To create a shadow of the fluid flow McCutchen begins by arranging for a vertical temperature gradient in the water. When a fish swims through the thermally stratified water, the wake leaves regions with sharp temperature boundaries. Light crossing such a boundary is refracted. As a result the wake throws a shadow on the screen that consists of bright and dark lines. Each lamp makes a shadow of the wake. The visual system merges the two shadows and fills in enough information for the observer to visualize a complete three-dimensional wake. This approach does not require the fish to pause for a cue.

A mild temperature gradient (one or two degrees C. per centimeter) suffices for the experiment. The gradient need not be linear but should extend over most of the depth of the water in the aquarium. McCutchen's scheme for a continuous flow of water through the aquarium entails adding hot water at the top while cold water enters at the bottom. Water is removed about halfway up the sides. Sponges are tied over the inputs to keep the fresh water from mixing the water in the aquarium and destroying the temperature gradient. The water does not have to flow, but without flow the experimenter has only a few minutes before mixing destroys the temperature gradient. That, however, may be enough time for a simple experiment or for observing a fish.

For ease of viewing, the observer can mount the polarizing filters and lamps on a helmet. In this way the proper optics are maintained even when the observer moves to get a new perspective. The lamps are six-volt microscope lamps mounted about 10 centimeters apart. Larger separations increase the illusion of depth. Although the observer also sees the true object, it is soon ignored in favor of the shadows. (Because you are working with water, run the lamps from a storage battery that is not connected in any way to the household current.)

The screen must not depolarize the light or both eyes will see both shadows. McCutchen uses the dull side of aluminum foil, mounted with the length of the strip parallel to a line between the viewer's eyes. The arrangement usually provides shadow images of approximately equal intensities, thereby aiding the stereoscopic illusion. Other metals with a dull finish, surfaces covered with aluminum paint and ground-glass transmission screens will also serve. McCutchen mounts his aluminum foil over a wood embroidery frame. When the assembly is lowered into the water, the wood swells, stretching the foil tight. The screen can be either vertical (to facilitate a horizontal view of the specimen) or on the bottom (to give an overhead view of the specimen). Surface waves may distort the shadows in the latter setup. To avoid the problem McCutchen floats a sheet of clear plastic on top of the water by means of Styrofoam blocks.

The length of time the wake will per-

sist depends on two factors: the buoyancy forces on the parcels of water in the wake and the rate of heat conduction between the parcels. The buoyancy forces result from the dependence of the water density on temperature. Cold water is denser than warm water and sinks in it. With a temperature gradient of about 1 degree C. per centimeter a wake will last for about 15 seconds. After that the sharp temperature boundaries in the wake are smoothed by the sinking and rising of water and by the exchange of heat between parcels of water at different temperatures.

Many of the problems in classical aerodynamics can be investigated with McCutchen's system. For example, a little wing drawn through water leaves a visible vortex sheet similar to the ideal one described in most textbooks. Vortex rings like smoke rings can be created with the aid of a cylindrical plastic container that has a small circular hole punched in the bottom. Filling the container with hot or cold water and giving it a quick squeeze will form a beautiful vortex ring. With several squirts or with several holes one can have vortex rings that interact with one another.

McCutchen has employed his rig to study the motion of a small fish, a zebra danio (*Brachydanio rerio*), which is about three centimeters long. The study revealed a complex variety of propulsion mechanisms, none of which appear to be very efficient. Both the main propulsion and the mechanism for changing course come from a vigorous but brief flick of the tail, which is followed by a period of coasting. During the push the spread of the dorsal and anal fins changes subtly. During the first part of the flick all the fins are spread, but on the return stroke the dorsal and anal fins are less spread. When the fish begins to coast after a stroke, all fins are collapsed; they spread out as the fish slows down. A quick stop is usually executed with the pectoral fins, but sometimes the fish puffs a small amount of water out of its mouth to increase the braking effect. When the fish hovers, it maintains its position by fanning water downward with its pectoral fins and tail.

These motions and others are visible in the shadowgrams, but they are too fast for the eye to follow. In order to slow down the motion and also to make a permanent record McCutchen sacrifices the depth in the shadowgram and photographs the shadow cast by a single light. The setup is shown in the illustration on page 170. One large field lens sends a parallel beam of light through the aquarium. Another such lens focuses the light onto a motion-picture camera. The camera is focused on a spot about halfway to the lens in front of it instead of on the aquarium. McCutchen says this focusing increases the sensitivity of the camera to slight inhomogeneities in the refraction of the light passing

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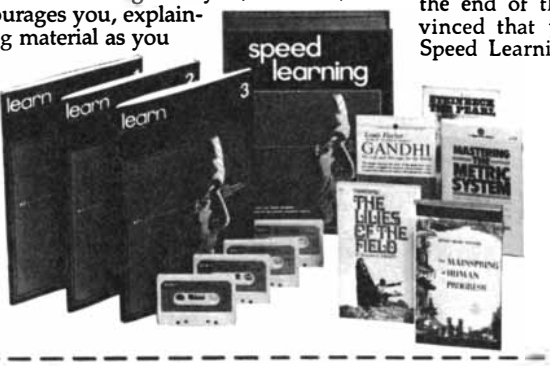

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through a wake. A red filter is inserted into the light so that the camera will not record the chromatic aberration of the field lenses.

The camera is run at about 44 frames per second. Even though McCutchen could slow down the motion, freeze it and reverse it, the fish he studied still moved too quickly for all the details of its motion to be captured. Surprisingly little is known about the propulsion mechanisms of fish, so that if you take up McCutchen's kind of experimentation, you may be able to contribute to that knowledge.

Several people have written to me about my discussion of non-Newtonian fluids in this department for November, 1978. A non-Newtonian fluid is a rather strange substance characterized by the fact that its viscosity changes when the fluid is stressed and sheared. Newtonian fluids, such as water, do not behave this way.

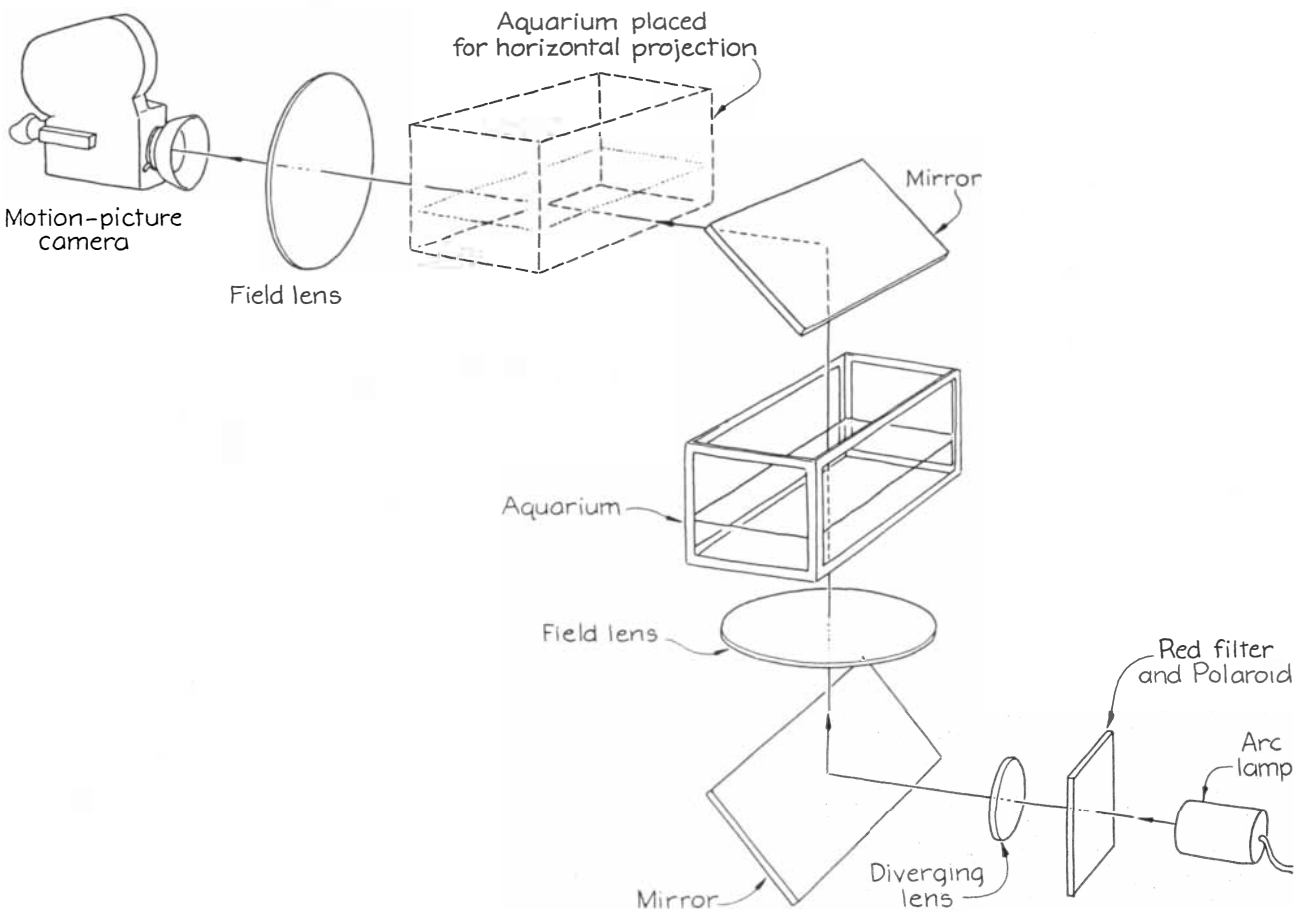
Among my correspondents was I. Slabicky of Newport, R.I., who described how to produce the Kaye effect easily. The effect is a peculiar leap of a stream of viscoelastic fluid when it is poured into a container of the same fluid. Slabicky poured a thin stream (1/16 to 1/8 inch in diameter) of Agree shampoo into his cupped hand from a height of about six inches. By adjusting the height and the width of the stream he discovered a certain combination that produced the Kaye effect almost continuously, giving leaps of up to an inch.

Mary R. Hebrank of Duke University told me about the many important biological fluids that display non-Newtonian features. Within a certain range of shearing rates blood is non-Newtonian, a fact that may be important to some aspects of blood flow through human beings and other animals. Also under investigation are the non-Newtonian aspects of the synovial fluid, which lubricates the joints in vertebrates, and of mucus.

Mucus may play an important role in reducing the drag on some types of fish. According to some theories, this reduction of drag may depend on the non-Newtonian behavior of the mucus (or slime) on the surfaces of the fish. For example, when a fish must swim quickly, some of the slime on its body may be mixed with the passing water. At higher swimming speeds the layer of water near the surface of the fish tends to break up into turbulence, increasing the drag. The addition of a small amount of slime to the turbulent water may increase the viscosity and thereby reduce the turbulence, so that the fish can swim faster.

Many of the demonstrations I described can be seen in a motion picture, *Rheological Behavior of Fluids,* made by Hershel Markovitz of Carnegie-Mellon University. The film is distributed by the Encyclopaedia Britannica Educational Corporation. The film includes several extremely interesting experiments with dye tracers in a non-Newtonian fluid surrounding a rotating sphere. It also beautifully demonstrates the Weissenberg effect, in which a rotating fluid climbs a central rod rather than the outside wall of the container.

Barbara H. Shafer of Greene, R.I., wrote me about the strange behavior of her butternut squash. She usually cooks the squash before a holiday and then freezes it. As she prepares the squash it shows no signs of being waterlogged, but when it thaws after being taken out of the freezer, a noticeable amount of water collects at the top of the container. She heats the squash in a double boiler, but even then the water is not reabsorbed by the squash. Therefore just before serving the squash she stirs it, and the more vigorously she stirs the thicker it gets. The shearing effect of the stirring apparently increases the viscosity of the stuff. Shafer doubts that all squashes behave this way, so that if you want to repeat her experiment, you could try different types of squash.



The optics of photographing the wake of a fish

SCIENCE/SCOPE

A unique "picture-taking" system comprising five separate sensors will help the U.S. Air Force evaluate which imaging methods may be most useful for advanced airborne applications. The Hughes-developed system consists of one sensor that sees only visible light, another that measures thermal radiation (heat), two active laser systems that detect the amount of reflected light, and a millimeter-wave radar. Variations in the gray tones of panoramas made by the sensors, particularly in those made at night and during inclement weather, reveal the advantages and disadvantages of each.

NASA's Pioneer Venus mission has received a bonus with the decision to allow the Orbiter spacecraft to gather data for a second Venusian day. The spacecraft, which already has discovered the largest known mountain and canyon in the solar system, was to operate 243 Earth days, the time in which Venus turns once on its axis. But because the Orbiter performed so well since arriving December 1978, NASA chose to lengthen its mission another eight months. The spacecraft could serve even longer because it has enough propellant to last one Venusian day beyond that. The Orbiter was built by Hughes for NASA's Ames Research Center.

Very thin solar cells now being developed for use on spacecraft promise breakthroughs in weight and power generation capability. The new wafers of silicon and metal measure a paper-thin 0.05 millimeters thick. Virtually as efficient as current production cells in converting sunlight into electricity, they are one-quarter the thickness and one-quarter the weight. In addition, the new cells are more tolerant to the effects of outer space radiation effects. Spectrolab, a Hughes subsidiary, is developing these cells under NASA contract.

Hughes has career opportunities for engineers and scientists to design and build infrared sensors, imaging systems, lasers, electro-optical systems, optical and holographic systems, computers, microprocessors, servos, and control systems. We need electronics and mechanical engineers, optical and control systems engineers, computer hardware designers, computer software developers and scientific programmers, electronic components and materials specialists, circuit designers, product design engineers, and systems engineers. Rush your resume to Professional Employment, Dept. SE, Hughes Electro-Optical and Data Systems Group, 11940 W. Jefferson Blvd., Culver City, CA 90230. Equal opportunity M/F/HC.

Saving money through energy management and preventive maintenance has been made easy by a hand-held infrared viewer, according to a leading manufacturer of zippers. The Talon company reports that a Hughes Probeye® viewer helped save $96,000 in less than a year by pinpointing energy losses due to such problems as leaks in steam machines. The Probeye viewer, which resembles a camera, creates pictures by sensing heat radiated by objects. An operator merely turns on the viewer and looks through the eyepiece. Warm areas appear much brighter than other objects in the surrounding scene. The device can distinguish temperature differences as small as 0.1°C.

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