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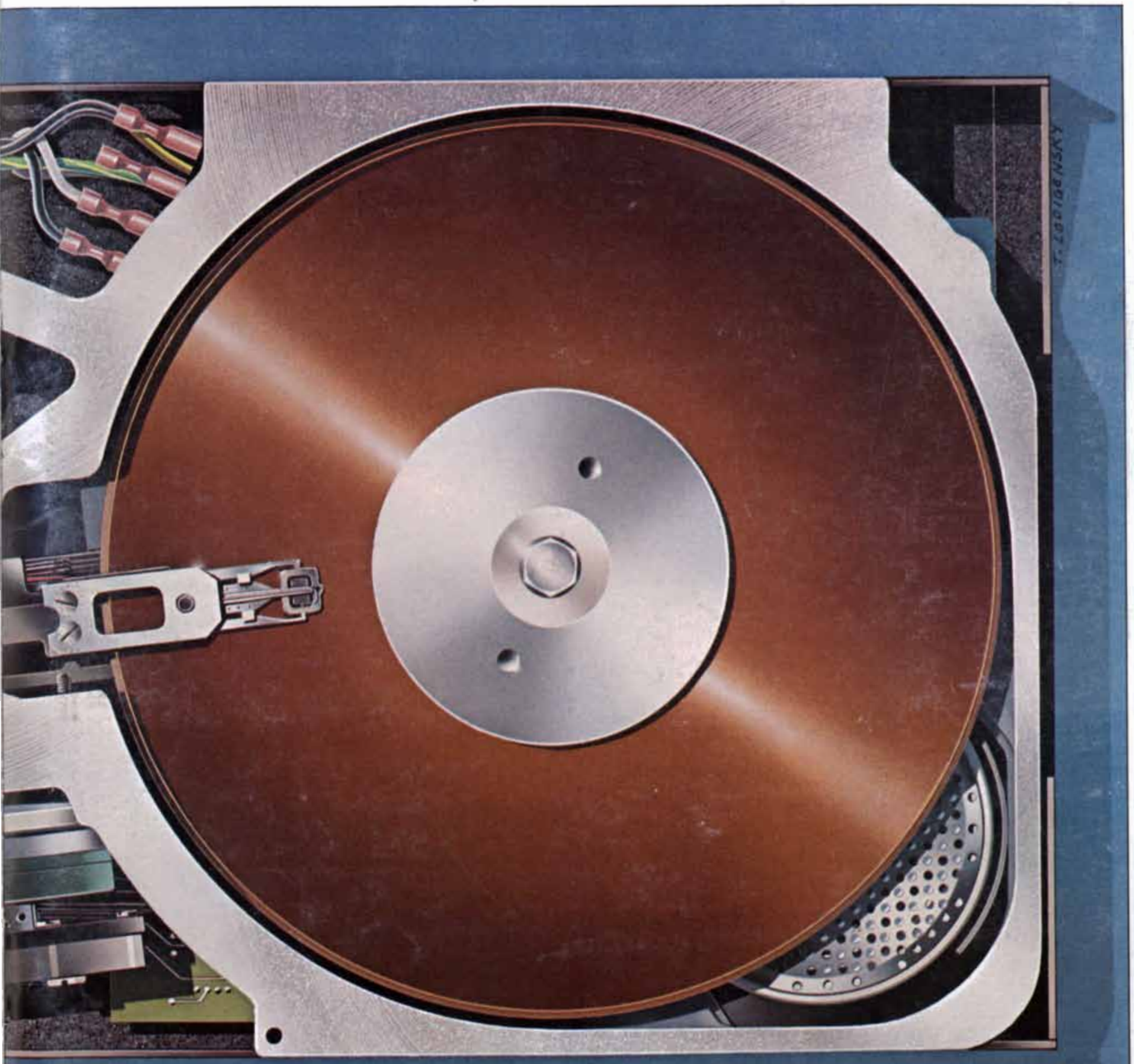

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August 1980

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Tough Ford Courier

OFFICIAL 1980 EPA RATINGS SHOW

	BEST MPG RATING		LONGEST RANGE	
	EPA EST.	HWY. EST.	EST. MILES	HWY. MILES
FORD COURIER	27	37	473	647
BETTER THAN TOYOTA	21	28	338	451
BETTER THAN DATSUN	25	32	423	541
BETTER THAN LUV	25	35	325	455

Use estimates for comparison. Your mileage and range may differ depending on speed, distance and weather. Actual hwy. mileage and range will probably be less than estimated. Fuel tank capacities (gal.) for LWB models. Courier 17.5, Toyota 16.1, Datsun 16.9, LUV 13.0. Calif. estimates lower.

FORD

FORD DIVISION Ford

Established 1845 SCIENTIFIC AMERICAN August 1980 Volume 243 Number 2

ARTICLES

DEPARTMENTS

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executive health

the report that briefs you on what to watch

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Volume XVI, Number 9 • June, 1980 • Pickfair Bldg., Rancho Santa Fe, Calif. 92067 • Area 714: 756-2600

Roger R. Williams, M.D.:

What is your GENETIC risk of an EARLY heart attack?

Why is it that of two men from the same town, with the same lifestyle, one man lives to be 100 and the other has a fatal heart attack at 35?

PUBLISHER'S NOTE: *Dr. Williams is on the full time faculty in the Department of Internal Medicine at the University of Utah College of Medicine. He has designed and directed six major studies of factors leading to heart disease and cancer, with research funding of over $3,000,000. He states that many major diseases (including heart attacks, strokes, diabetes, and some common cancers) result from inherited predisposition coupled with unfavorable environmental factors. In this report he summarizes results from his own studies and others regarding the cause and prevention of heart attacks—the number one killer.*

—Richard Stanton

It is, of course, the most common reason for American deaths—responsible for one-third of the total, for twice as many as all cancers combined.

And the process which leads to heart attack is ubiquitous in America. You can find it at autopsy—advanced—even in most people who die of other causes.

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Leonard Hayflick, Ph.D.: A New Theory On The Cause Of Heart Disease And Strokes . . . Vitamin B_6 may be the key. What new research has revealed that may downgrade cholesterol as the main predisposing factor . . . and why.

John K. Lattimer, M.D., Sc.D.: On that treacherous gland, your prostate — especially as you approach 50.

Stephen R. Elek, M.D. On "The Hurry-up Disease." Why it may be a key factor that triggers heart attacks as early as age 40.

Linus Pauling, Ph.D.: What About Vitamin E? Eminent investigators now suspect it may be one of the key factors to help resist disease and slow the aging process.

Hugh C. Trowell, M.D., F.R.C.P.: A New Dietary Explanation for the cause of Essential Hypertension . . . the dramatic and significant African experience (1929-1958).

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The truth about the right diet and exercise to lose weight safely and stay slender for life.

Alton Ochsner, M.D.: On "The Chair Disease" . . . Why blood clots in your veins are a little-realized hazard of "desk-bound" executives.

James Greenwood, Jr., M.D.: On Osteoarthritis, the "wear and tear" disease . . . Can Vitamin C Help?

If you sit at a desk all day . . . How to avoid a Pot-Belly and Double-Chin (or get rid of them for good!)

Jan Koch-Weser, M.D.: On Systolic Hypertension, more common than diastolic hypertension and as dangerous. What it is, what it does, and what to do about it.

Ewan Cameron, M.D., Ch.B., F.R.C.S. (Glasgow), F.R.C.S. (Edinburgh) and Linus Pauling, Ph.D.: On Cancer and Vitamin C. A consideration of the nature, causes, prevention and treatment of cancer with special reference to vitamin C.

Leonard Hayflick, Ph.D.: On Getting A Good Night's Sleep! What research scientists now know about this mysterious process we so calmly call "sleep."

Albert Szent-Gyorgyi, M.D., Ph.D.: On A Substance That Can Make Us Sick (If We Do Not Eat It!) One of the world's most honored scientists, winner of the 1937 Nobel Prize for Physiology and Medicine explains the fascinating paradox of vitamins.

Denis P. Burkitt, M.D., D.Sc., F.R.C.S., F.R.S.: Is Dietary Fibre Protective Against Disease? The drop in our consumption of potatoes and whole grains may have something to do with the increase in intestinal cancer, diabetes and heart disease—to name a few!

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THE COVER

The painting on the cover shows part of a device that stores data for a computer system in the form of regions of magnetization on the surface of a disk (see "Disk-Storage Technology," by Robert M. White, page 138). In this device the diameter of the disk assembly is eight inches. Hovering above it is a head that not only magnetizes the disk, hence recording data, but also produces a readout voltage in response to the magnetic fields of the data already in storage. The surface visible in the painting stores 2.67 million binary digits, or bits. Three other disk surfaces (and three other heads) cannot be seen in this view. When the device is in operation, the disk assembly spins at a rate of 3,125 revolutions per minute. The flow of air between the disks and the heads then generates an aerodynamic force that "flies" each head. The baffle under the disks at the lower right is part of an air-filtering system. The device was manufactured by Shugart Associates, a subsidiary of the Xerox Corporation.

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LETTERS

Sirs:

"The N-Ray Affair," by Irving M. Klotz [SCIENTIFIC AMERICAN, May], brings to mind a related example of the kind of trap into which even the best minds can sometimes fall.

In the late 1940's Ted Clarke of the Fisher Scientific Company developed a process that consistently produced replica diffraction gratings of exceptionally (for the time) good quality. I was elected to get one of the best blessed by none other than R. W. Wood, the man who showed that the N rays were imaginary.

Professor Wood received me cordially but said he would be very surprised if he ever found a really good replica grating. We descended to his subbasement laboratory at Johns Hopkins, and as Professor Wood proceeded to mount the replica on his spectrograph I wandered around the laboratory. I was soon shaken out of my reverie when he announced in petulant tones: "Here's another for the garbage bucket." I hurried to check the mounting setup, which I had not had the temerity to do while Professor Wood was mounting the grating. I found the spectrum to be foul indeed, showing lines and ghosts for which elements had not yet been discovered. What *I* discovered, however, was that Professor Wood had not removed the transparent plastic cover from the replica! On a second exposure he pronounced the replica "quite good."

What puzzled me at the time was that Professor Wood then said: "It must have been N rays." Only now do I know what he meant; some of us are slow learners.

ANTONY DOSCHEK

Pittsburgh, Pa.

Sirs:

"The Origins of the Water Turbine," by Norman Smith [SCIENTIFIC AMERICAN, January], mentions investigations of reaction wheels done by Leonhard Euler. Your readers may be interested to know more about Euler's contributions, which are of great historical value. The relevant papers of Euler have recently been republished, as part of his collected works, by J. Ackeret (*Leonhard Euler, Opera Omnia,* Series II, Vol. 15) and are easily accessible in university libraries.

Euler was the first to attack the problem of motion of water in moving tubes, particularly in the case of rotation. He applied his results to improve the design of the Segner wheel, the only turbine he could have known about, which is similar in principle to a lawn sprinkler. Euler was the first to apply the method of filaments, which is still in use. Moreover, he was the first to recognize the importance of a guide-vane system, which makes it possible (if friction forces are neglected) to transform the hydraulic potential energy completely into kinetic energy.

Euler's study resulted in a complete design of a reaction wheel. Of course, the design existed only on paper; the technology of the time did not allow a physical realization. For example, wood was chiefly used even for hydraulic machines. Euler calculated the size of turbines in five cases, optimized to the available flow and head of water. He foresaw the phenomenon of cavitation, which appeared in his computations as a vanishing of the absolute pressure. The phenomenon became a matter of interest only 150 years later.

It is not easy to understand why the work of Euler, particularly the 1754 paper, had practically no influence on the design of water turbines in later years. The machine described by Claude Burdin in 1828 is similar to Euler's but can hardly be considered an improvement. J. V. Poncelet, considered the father of the theory of water turbines, does not quote Euler anywhere. Modern techniques made possible an experimental investigation of the properties of Euler's turbine. This was done in 1944 by Escher-Wyss in Zurich under the direction of Ackeret. Trials have shown that the neglect of friction forces has important consequences. Maximum efficiency is attained at a lower speed than the speed predicted by the frictionless model. It nonetheless reaches 71 percent, which engineers consider fairly good for a power of only .15 horsepower and a waterhead of one meter.

PIERRE P. BANDERET

University of Neuchâtel
Neuchâtel, Switzerland

Sirs:

I have a few comments about Martin Gardner's January article on checkers. He writes: "When an expert does win, it is usually because the loser made a blunder or because the winner managed to keep secret... a 'cook' he had discovered." This is completely misleading. Certainly blunders occur and cooks are pulled. Knowledge *is* important in checkers. However, the ability to see deeply into the game is far more important. In his two world-title matches with Asa Long (1948 and 1961) Walter Hellman sprang a great number of cooks from his vast storehouse of knowledge. Yet Long, because of his tremendous analytical ability, made the wins so difficult that Hellman could not find them. Wins between experts tend to be very narrow indeed. In 1922 Long won his first national tournament at the age of 18, besting players who greatly surpassed him in knowledge. He did it on ability, not cooks. One further illustration. In 1876, at the age of 19, R. D. Yates won the world title from James Wyllie. Wyllie had been a great scholar of the game for 40 years and had introduced many important openings and developments. Yet Yates beat him. His games were not a testimony to his knowledge but a monument to his great ability to see deeply into the game.

Finally, a remark about checkers-playing computer programs. I have seen games played by most of them, including six games played by the Duke program. They all play at the very-weak-amateur level. The programs may indeed consider a lot of moves and positions, but one thing is certain. They do not see much! Nevertheless, for 20 years claims have been made repeatedly that there exist programs playing at the master level. It is because of exasperation with such false and aggravating claims that the wager has been made. We are not a fraternity of gamblers. The idea of a stake challenge, however, has become accepted as the only way to effectively expose fakery. Perhaps someday the programmers will have a real breakthrough. But until then let them behave like true scientists and refrain from undue boasting about their offspring.

MARION TINSLEY

World Checkers Champion
Tallahassee, Fla.

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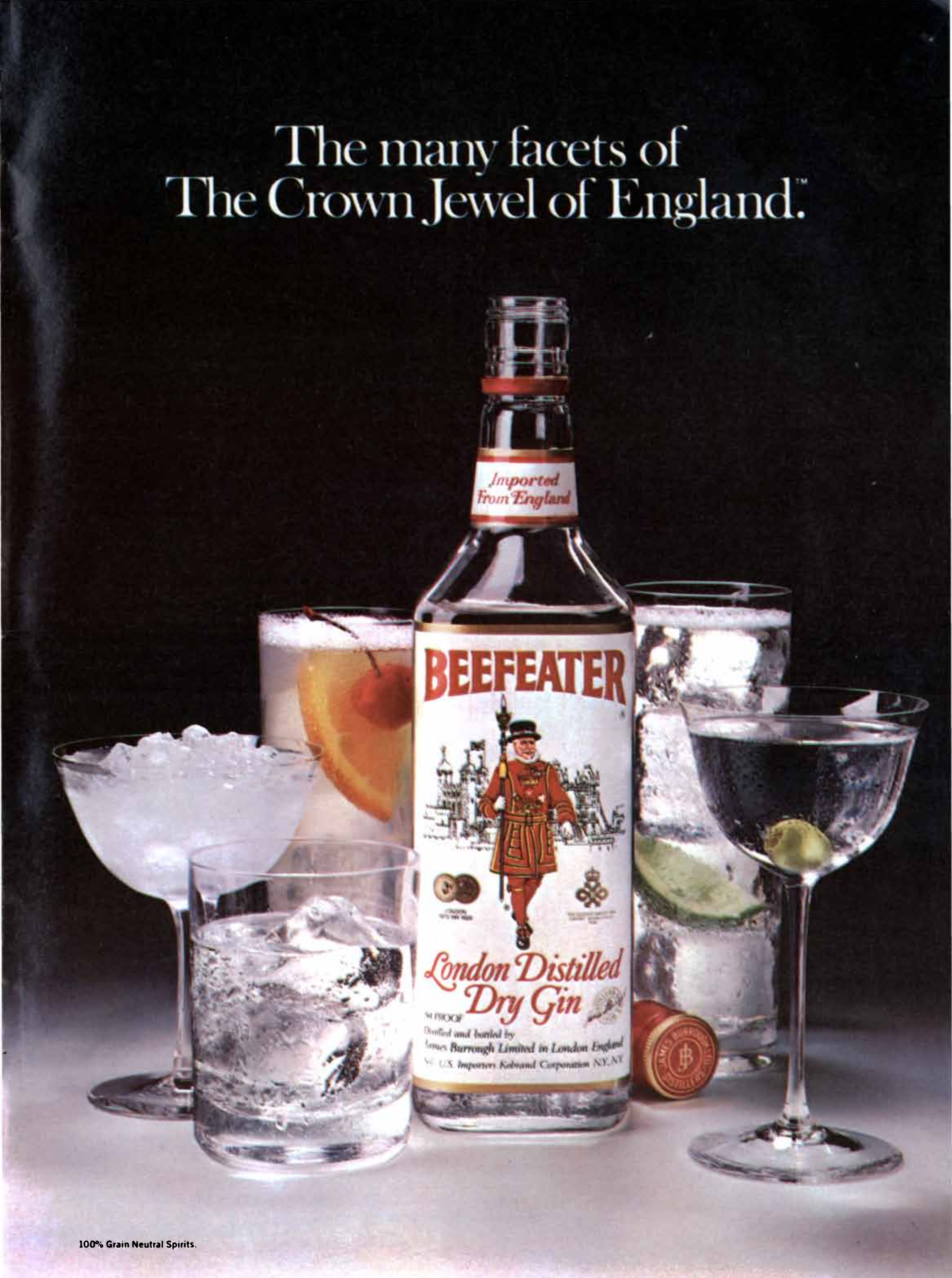
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VOLVO

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

AUGUST, 1930: "Goiter is an abnormal condition of the thyroid gland caused by iodine deficiency. Figures compiled by the United States Public Health Service show that the incidence of goiter is high and is a serious problem in large sections of 23 states. The Northwest in particular has a high incidence. Over the past two years Dr. Roe E. Remington has examined in a laboratory at Charleston, S.C., hundreds of samples of vegetables grown in all sections of South Carolina for their iodine content. He found the amounts of iodine in them enormously greater than those reported by other laboratory workers in vegetables from northern and western states. This discovery, in conjunction with the goiter survey made by the Field Force of the South Carolina State Board of Health, in which it was found that goiter was practically non-existent in the state, led to the definite conclusion that goiter will not occur if foods that naturally contain a sufficient amount of iodine are regularly eaten. Dr. Mazyck P. Ravenel, chairman of the editorial committee of the *American Journal of Public Health*, has expressed the opinion that the laboratory has 'found the solution of the gravest health problem confronting the people of the United States.'"

"The month of May saw the sad crash of Max Valier in a venturesome plane flight propelled by a liquid rocket. The whole fuel charge detonated at once. The internal-combustion engine, the cannon and the rocket are all heat engines operating on the same fundamental calorific principle. A 16-inch shell, for example, has the energy of an express train; a rocket may have the energy of an ocean liner. In the 1890's a German and a Russian (Tsiolkowsky) were developing on paper the concept of space ships, rocket propelled, and in 1913 Robert Esnault-Pelterie, the distinguished creator of the French aeronautic engine, delivered a mathematical paper on 'astronautics' before the St. Petersburg Academy. This science, or art, has been more fittingly renamed by a German 'kosmonautics.' Parallel, then, with the laboratory work of our own Dr. Goddard, a close group of Germans and Austrians, and a corresponding group of Russians of the Hydrodynamic Institute, have been working systematically toward the solution of the problem. Valier was the principal proponent of working toward the space craft from the known forms of surface or air craft."

"In the continued depression of the aviation industry there is one bright spot: the rapid growth of the transport service, mail, passenger and (to some extent) express. We believe that the new regulations of the Department of Commerce regarding transport services will help rather than hinder this growth. These regulations provide that before scheduled operation of passenger air transport is established a Certificate of Authority must be obtained from the Secretary of Commerce. To secure and retain such a certificate the service must provide satisfactory aircraft and equipment, an adequate number of qualified airmen, a high degree of maintenance efficiency, good airways and navigation facilities, and a first-class ground organization. Nothing is so well calculated to inspire the traveling public with confidence as regulations of this character, well and diligently administered."

SCIENTIFIC AMERICAN

AUGUST, 1880: "So long as the production of electricity was confined to voltaic batteries and small, imperfect magneto-electric machines the use of electric currents was necessarily much restricted. In fact, they could only be employed in cases where the mechanical or other sensible effects were small, as, for example, with the electric telegraph and those devices in which purely mechanical arrangements would have been too cumbersome or otherwise impracticable. The improvement of the dynamo-electric generator, however, enables the electrician to deal with very powerful currents and accomplish work on a massive scale. Even in telegraphy the dynamo-electric current is supplanting the voltaic battery for supplying the electric power, and the Western Union Telegraph Company now transmits all the messages from its central office in New York by the current drawn from four Siemens machines. The recent success of the electric light is another triumph for this mode of generating electricity, and new applications open up a vast horizon of possible uses in the future."

"It would hardly be just to dismiss the subject of hard times and business depression on the Pacific Coast without some reference to the Chinese, whose presence there is firmly regarded by a large part of the community as the true cause of all the troubles that have come upon California during the past few years. Chinese immigration began very soon after the gold fever of 1849. The total number now in the state may be safely estimated at 150,000, or more than one-sixth of the entire population. The mistake that lies at the bottom of the anti-cooly movement is the popular idea among white laborers and mechanics on the Coast that if they could only get rid of Chinese competitors, from 100,000 to 150,000 white men would be employed in their place. The truth is that this popular impression is a delusion. In San Francisco and throughout the state white men in the trades receive from two to three and a half dollars per day. But very few are employed at such rates in the trades in which Chinese can be engaged. There are few manufacturers who can afford to pay high wages, and certainly one result of the departure of the Chinese would be the closing up of many manufactories."

"The progress of modern optics is now furnishing observers with telescopes of a power that exceeds the capacities of our lower atmosphere for their constant employment. The obstacles to definition due to the atmosphere have grown to be so nearly a barrier to any rapid progress that attention has lately been given to the conditions of vision it is very commonly supposed will be found to be best on mountain summits. Prof. S. P. Langley was therefore led to make some observations on Mount Etna during a visit there. Prof. Langley concludes that the balance of advantages for astronomical observations is most likely to be found in a dry atmosphere and certainly at a great elevation. On the whole, although the ideal station where atmospheric tremor does not exist and the observer pursues his studies in an ever transparent sky is not to be found on any part of the earth's surface, there is, says Prof. Langley, within our own territory, in the dry and elevated table-lands of Colorado or New Mexico, every condition that experience points out as favorable."

"At a meeting of the Chemical Society, London, Prof. Hartley read a communication 'On the Relation between the Molecular Structure of Carbon Compounds and Their Absorption-Spectra.' It has been shown (1) that every increment of CH_2 in a homologous series of alcohols or acids effects an absorption of the more refrangible of the ultra violet rays, so that the greater the number of carbon atoms in the molecule, the shorter is the transmitted spectrum; (2) that the terpenes always transmit continuous spectra, but polymerization largely increases their absorptive power; (3) that benzene and its derivatives invariably show, in addition to abnormally great absorptive power, the peculiarity of absorption-bands. After taking into consideration the numerous substances examined the conclusion seems inevitable that banded absorption-spectra were caused by the double linking of three pairs of carbon atoms in a compactly closed chain."

THE AUTHORS

GEORGE STERNLIEB and JAMES W. HUGHES ("The Changing Demography of the Central City") are with the Center for Urban Policy Research of Rutgers University. Sternlieb, who is the director of the center, is also professor of urban and regional planning at Rutgers. A graduate of Brooklyn College, he went on to obtain his M.B.A. at the Harvard Business School in 1953. He then worked for a number of years as an executive in a New York department store, leaving in 1958 to help set up a consulting and service firm specializing in on-line electronic data processing. Meanwhile he continued to pursue his graduate studies, receiving his D.B.A. from the Harvard Business School in 1962; that year he joined the faculty of the Graduate School of Business Administration at Rutgers. Sternlieb switched to the department of urban and regional planning in 1968, and the following year he founded the Center for Urban Policy Research. Hughes, who is professor of urban planning and policy development at Rutgers and a research associate of the Center for Urban Policy Research, earned his degrees at Rutgers: a B.S. in 1965, an M.C.R.P. in 1969 and a Ph.D. in 1971. He has been on the faculty there ever since.

GORDON H. PETTENGILL, DONALD B. CAMPBELL and HAROLD MASURSKY ("The Surface of Venus") have a common interest in the mapping of planetary surfaces. Pettengill is professor of planetary physics at the Massachusetts Institute of Technology. He did his undergraduate work at M.I.T. and his graduate work at the University of California at Berkeley, obtaining his Ph.D. from Berkeley in 1955. He then joined the staff of the Lincoln Laboratory at M.I.T., where he worked on the design of high-powered radars for the detection of intercontinental ballistic missiles. This work, he says, "led quite naturally into the field of radar astronomy." After serving for a time as director of the 300-meter radio telescope of the Arecibo Observatory in Puerto Rico, Pettengill returned to M.I.T. in 1970 as a member of the department of earth and planetary sciences. Campbell is currently associate director and head of the radar-astronomy group at the Arecibo Observatory. A native of Australia, he studied physics and radio astronomy at the University of Sydney before going to Arecibo in 1965 to work with Pettengill for a year on the newly completed radar system there. At the end of the year Campbell went to Cornell University to complete work for his Ph.D., after which he returned to Arecibo. Masursky is with the branch of astrogeological studies of the U.S. Geological Survey in Flagstaff, Ariz. He majored in geology as an undergraduate and graduate student at Yale University before joining the staff of the Geological Survey in 1951. Since then he has been involved in a variety of terrestrial and planetary research projects.

PIERRE DUSTIN ("Microtubules") is professor of pathology and head of the department of pathology and electron microscopy at the Université Libre de Bruxelles, where he began his medical studies in 1930. After receiving his M.D. in 1937 he spent the next couple of years as a visiting scholar at institutions in France, Switzerland, the U.S. and Britain. He then returned to Brussels, where following the death of his father, the pathologist Albert P. Dustin, in 1942 he continued the work started by his father's discovery eight years earlier of the antimitotic action of the plant alkaloid colchicine. He has also published research papers on various other subjects in cell biology and pathology, and he is in the process of completing the third edition of a textbook on general pathological anatomy.

PETER BEACONSFIELD, GEORGE BIRDWOOD and REBECCA BEACONSFIELD ("The Placenta") are British physicians who have collaborated for some time on the study of the biological effects of manmade chemicals, using the human placenta as one of their "experimental animals." Peter Beaconsfield is director of the research unit at the University of London of the Special Commission on Internal Pollution, an organization he cofounded in 1971. He holds two doctoral degrees from that institution: an M.D. (1944) and a Ph.D. in physiology (1953). Birdwood was graduated from the University of Cambridge in 1953. After a tour of duty as an army medical officer he returned to civilian life as a general physician and medical writer. Rebecca Beaconsfield, a graduate of the University of London, did her postgraduate work in anesthesiology. She joined the research team of Beaconsfield and Birdwood, she writes, after deciding that "my husband's scientific activities were more stimulating than dozing at the head of an operating table."

PHILIP EKSTROM and DAVID WINELAND ("The Isolated Electron") began to collaborate on the work reported in their article a number of years ago when they were postdoctoral research associates at the University of Washington. Ekstrom is currently a staff scientist at the Observatory of the Battelle-Northwest Laboratories in Richland, Wash., where he does research on both astronomical and geophysical topics. He obtained his degrees in physics from Washington, "with time out for a computer-science degree at the University of Cambridge and for some work as an industrial electronics and computing consultant." Wineland is now a physicist at the National Bureau of Standards in Boulder, Colo. He has a B.A. in physics from the University of California at Berkeley and a Ph.D. in physics from Harvard University.

JEAN-FRANÇOIS JARRIGE and RICHARD H. MEADOW ("The Antecedents of Civilization in the Indus Valley") are archaeologists whose field work is concentrated in the Middle East and southern Asia. Jarrige, who has a doctorate in oriental archaeology from the University of Paris, is director of the French Archaeological Mission of the Indus, which with the Pakistan Department of Archaeology has been engaged for the past six seasons in excavating the remains of a series of early agricultural settlements at Mehrgarh, a site in the Baluchistan region of central Pakistan. Meadow, who has spent the past few seasons working with Jarrige at Mehrgarh, is a graduate student in archaeology at Harvard University. He is particularly interested in the analysis of faunal assemblages from archaeological sites and is developing a program in faunal analysis at Harvard's Peabody Museum of Archaeology and Ethnology.

ROBERT M. WHITE ("Disk-Storage Technology") does research on the physical properties of materials at the Xerox Corporation's Palo Alto Research Center. A graduate of the Massachusetts Institute of Technology, he received his Ph.D. in physics from Stanford University. Before joining Xerox in 1971 he was a member of the faculty at Stanford. He is the author of *Quantum Theory of Magnetism* and *Long-Range Order in Solids*. For the past year, he reports, he has been "on loan" to Xerox' corporate-planning group "with the responsibility of developing a technological strategy to guide Xerox' newly acquired rotating-memory business."

STILLMAN DRAKE ("Newton's Apple and Galileo's Dialogue") has written four previous articles for SCIENTIFIC AMERICAN on aspects of Galileo's work. Drake studied philosophy and mathematics at the University of California at Berkeley in the early 1930's, then worked mainly as a municipal-finance consultant in San Francisco until 1967, meanwhile publishing translations of Galileo's scientific books as an avocation. That same year he joined the faculty of the Institute of History and Philosophy of Science and Technology at the University of Toronto. Drake retired in 1978 and is now emeritus professor of the history of science.

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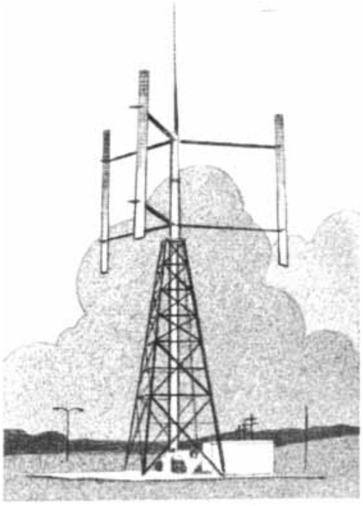

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MATHEMATICAL GAMES

On the fine art of putting players, pills and points into their proper pigeonholes

by Martin Gardner

Can you prove that a large number of people in the U.S. have exactly the same number of hairs on their head? And what does this question have in common with the following problem? In a bureau drawer there are 60 socks, all identical except for their color: 10 pairs are red, 10 are blue and 10 are green. The socks are all mixed up in the drawer, and the room the bureau is in is totally dark. What is the smallest number of socks you must remove to be sure you have one matching pair?

Consider two less simplistic examples. Can you prove that when a common fraction a/b is expressed in decimal form, the resulting number will be either a terminating decimal or one that repeats with a period no longer than b? Can you show that if five points are placed anywhere on an equilateral triangle of side 1, at least two points will be no farther apart than .5? (Hint: Divide the triangle into four smaller equilateral triangles of side .5.)

The quality these problems and thousands of others in both serious and recreational mathematics have in common is that they can all be solved by invoking an old and powerful principle. It is the pigeonhole principle, which some mathematicians prefer to call the Dirichlet drawer principle after the 19th-century German mathematician Peter Gustav Lejeune Dirichlet. The pigeonhole principle is the topic of this month's column, which is written not by me but by Ross Honsberger, a mathematician at the University of Waterloo. He is the author of *Ingenuity in Mathematics, Mathematical Gems* and *Mathematical Gems II* and has edited the anthologies *Mathematical Morsels* and *Mathematical Plums.* All five are excellent sources of unusual problems with a strong recreational flavor. Everything that follows (up to my concluding comments) was written by Honsberger, who calls his discussion of the pigeonhole principle "Can anything this simple be useful?"

Consider the statement "If two integers add up to more than 100, at least one of them is greater than 50." It is far from obvious that the "overflow" principle behind this simple assertion is not trivial. In its simplest form the principle can be stated as follows: If $n + 1$ (or more) objects are to be distributed among n boxes, some box must get at least two of the objects. More generally, if $kn + 1$ (or more) objects are distributed among n boxes, some box must get at least $k + 1$ of the objects.

Even in its most general form this pigeonhole principle states for a set of data only the obvious fact that it is not possible for every value to be below average or for every value to be above average. Nevertheless, the principle is a mathematical concept of major importance and remarkable versatility. Here we shall take up seven of its prettiest elementary applications. Let us begin with a simple geometric example.

1. The Faces of a Polyhedron. Try counting the edges around the faces of a polyhedron. You will find that there are two faces bounded by the same number of edges. To prove that this is always the case it is only necessary to imagine what happens when the faces are distributed among a set of boxes numbered 3, 4, ... n, so that a face with r edges is put in the box numbered r. Since edges separate faces, a face with the maximum number of edges n is itself bordered by n faces, implying that the polyhedron must have a total of at least $n + 1$ faces. On the pigeonhole principle, then, some box must contain at least two of the faces, and the proof is complete. In fact, it is a simple exercise to show that there are always at least two different pairs of faces with the same number of edges.

2. Ten Positive Integers Smaller than 100. Here is an application of the pigeonhole principle that will baffle your friends. No matter how a set S of 10 positive integers smaller than 100 is chosen there will always be two completely different selections from S that have the same sum. For example, in the set 3, 9, 14, 21, 26, 35, 42, 59, 63, 76 there are the selections 14, 63 and 35, 42, both of which add up to 77; similarly, the selection 3, 9, 14 adds up to 26, a number that is a member of the set.

To see why this is always the case observe that no 10-element subset of S can have a sum greater than the 10 largest numbers from 1 to 100: 90, 91, ... 99. These numbers add up to 945, and so the subsets of S can be sorted according to their sum into boxes numbered 1, 2, ... 945. Since each member of S either belongs to a particular subset or does not belong to it, the number of subsets to be classified (not counting the empty set, which has no elements) is $2^{10} - 1$, or 1,023. By the pigeonhole principle, then, some box must contain (at least) two different subsets A and B. Discarding any numbers that are in both A and B creates two disjoint subsets, A' and B', with equal sums. Indeed, because there are 78 more subsets than there are boxes, every set S must actually yield dozens of different pairs of subsets with equal sums.

3. The Pills. For this next application of the pigeonhole principle we are indebted to Kenneth R. Rebman, a mathematician at California State University at Hayward. A physician testing a new medication instructs a test patient to take 48 pills over a 30-day period. The patient is at liberty to distribute the pills however he likes over this period as long as he takes at least one pill a day and finishes all 48 pills by the end of the 30 days. No matter how the patient decides to arrange things, however, there will be some stretch of consecutive days in which the total number of pills taken is 11. In fact, for every value of k from 1 to 30 except 16, 17 and 18 it is always possible to find a period of consecutive days in which a total of k pills were taken.

To prove that a particular value of k is an exception to the rule it is necessary only to find a distribution of the pills for which there is no stretch of days when k pills are taken. Thus the cases $k = 16$, $k = 17$ and $k = 18$ are eliminated at a stroke by the following distribution in which one pill is taken each day except for the 16th, when 19 pills are taken:

$$\underbrace{1\ 1\ \ldots\ 1}_{15}\ 19\ \underbrace{1\ 1\ \ldots\ 1}_{14}$$

Now consider the case $k = 11$. If p_i denotes the total number of pills that have been taken up to the end of the ith day, then p_{30} equals 48 and the positive numbers $p_1, p_2, \ldots p_{30}$ form a strictly increasing sequence $0 < p_1 < p_2 < \ldots < p_{30} = 48$. (The sign "<" is read "less than," and a strictly increasing sequence is one where each element is larger than its predecessor.) Adding 11 to each of the numbers in this sequence creates a new strictly increasing sequence: $11 < p_1 + 11 < p_2 + 11 < \ldots < p_{30} + 11 = 59$.

There are 30 numbers p_i in the first sequence and 30 numbers $p_i + 11$ in the second, and all 60 of these positive numbers are less than or equal to 59. Therefore by the pigeonhole principle at least two of them must be equal. No two p_i's are the same, however, and as a result no two $p_i + 11$'s are the same. Hence some p_i must be equal to some $p_j + 11$, that is, $p_i = p_j + 11$ for some values of i and j. Hence p_i minus p_j equals 11, which implies that precisely 11 pills were taken on the consecutive days $j + 1, j + 2, \ldots i$.

This argument holds for any value of k up to and including 11, establishing the property for the entire block of values of k from 1 through 11. It is somewhat more complicated to dispose of the remaining cases, but the pigeonhole principle is the critical tool throughout. Consider next the cases $k = 31$ through $k = 47$. Although these values of k certainly admit of solutions in many instances, the following family of distributions shows that no one of them guarantees a solution. When n is between 1 and 17, the value $k = 30 + n$ is eliminated by the following sequence:

$$(19 - n)\ \underbrace{1\ 1\ \ldots\ 1}_{n + 11}\ (n + 1)\ \underbrace{1\ 1\ \ldots\ 1}_{17 - n}$$

For example, when n equals 7, the following distribution eliminates the case $k = 37$.

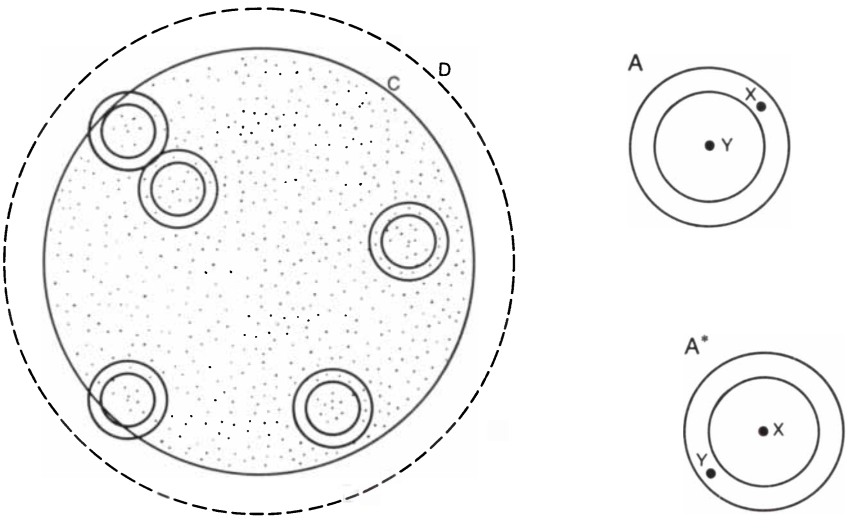
$$12\ \underbrace{1\ 1\ \ldots\ 1}_{18}\ 8\ \underbrace{1\ 1\ \ldots\ 1}_{10}$$

4. 101 Numbers. Suppose some set of 101 numbers $a_1, a_2, \ldots a_{101}$ is chosen from the numbers $1, 2, \ldots 200$. Surprisingly, it turns out to be impossible to choose such a set without taking two numbers for which one divides the other evenly, that is, with no remainder. Proving that this assertion is true provides an opportunity to make use of a rather neat way of expressing integers.

Given a positive integer n, it is possible to factor out of it as many 2's as it contains in order to reduce it to the form $n = 2^r q$, where q is an odd integer (possibly as small as 1). If each of the selected numbers a_i is expressed in this form, a set of 101 values of q is obtained, each value belonging to the set of 100 odd numbers $1, 3, 5, \ldots 199$. On the pigeonhole principle it can be concluded that two of these values of q must be the same. Therefore for some integers i and j, a_i equals $2^{r_i}q$ and a_j equals $2^{r_j}q$. Of these two numbers the one with the smaller power of 2 clearly divides the other.

Similarly, it is not difficult to apply the pigeonhole principle to show that any set S consisting of 102 numbers from the set $1, 2, \ldots 200$ must have two distinct numbers that add up to a third number in S. (Here it is not necessary to employ the form $2^r q$.) I shall turn next to two spectacular applications of the pigeonhole principle in geometric settings.

5. Six Hundred and Fifty Points in a Circle. Consider a circle C with a radius of 16 and an annulus, or ring, A with an outer radius of 3 and an inner radius of 2. Is it not remarkable that wherever one might sprinkle a set S of 650 points inside C the annulus A can always be placed on the figure so that it covers at least 10 of the points? To demonstrate the truth of this assertion one could place 650 copies of the ring A on the region enclosed by the circle C so that each point of S was the center of one of the rings, as is suggested in the figure at the left in the illustration above. For points of S near the circumference of C the corresponding annuli will extend beyond the circle. On the other hand, a circle concentric with C that has radius 19 (equal to the radius of C plus the outer radius of A) will certainly enclose all the copies of A. Call this new circle D. Note that the area of D is $\pi 19^2$, or 361π, and since the area of A is $\pi 3^2 - \pi 2^2$, or 5π, then 650 copies of A have a total area of $3{,}250\pi$.

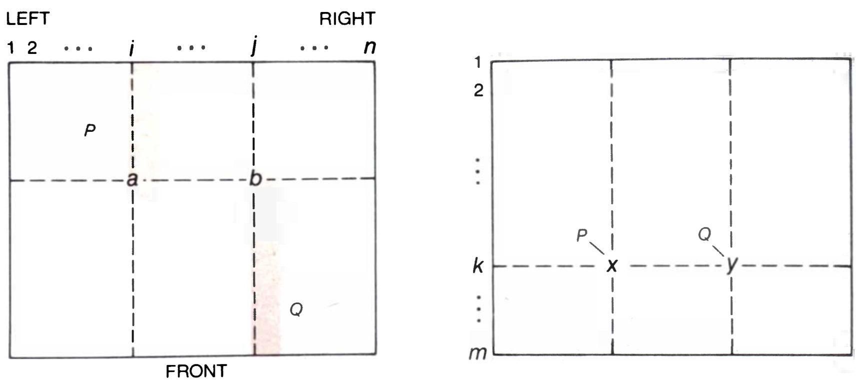


Six hundred and fifty points in a circle

It is at this point that a "continuous" version of the pigeonhole principle can be applied. Each copy of A covers certain parts of the circle D when it is placed on that figure. Suppose when all 650 copies have been put in place, there is no part of D that lies under more than nine different copies of A. In that case the total area of the copies could not exceed nine times the area of D. This, however, cannot be the case, because $9(361\pi)$ is only $3{,}249\pi$, whereas the annuli have a total area of $3{,}250\pi$. The pigeonhole principle, then, implies that some point X of D must be covered by at least 10 copies of A.

Now suppose Y is a point of S that is at the center of one of these 10 copies of A. Then the distance from X to Y must be larger than the inner radius of A and smaller than the outer radius, and as is shown at the right in the illustration above another copy of A centered at X would cover Y. Call this copy A^*. Since there are at least nine other centers like Y, A^* must cover at least 10 points of S, and the assertion is proved. (This problem was proposed by Viktors Linis of the University of Ottawa in *Crux Mathematicorum,* Vol. 5, page 271; November, 1979.)

6. The Marching Band. The next example concerns a marching band whose members are lined up in a rectangular array of m rows and n columns. Viewing



A proof of the marching-band theorem

the band from the left side, the bandmaster notices that some of the shorter members are hidden in the array. He rectifies this aesthetic flaw by arranging the musicians in each row in nondecreasing order of height from left to right, so that each one is of height greater than or equal to that of the person to his left (from the viewpoint of the bandmaster). When the bandmaster goes around to the front, however, he finds that once again some of the shorter members are concealed. He proceeds to shuffle the musicians within their columns so that they are arranged in nondecreasing order of height from front to back. At this point he hesitates to go back to the left side to see what this adjustment has done to his carefully arranged rows. When he does go, however, he is pleasantly surprised to find that the rows are still arranged in nondecreasing order of height from left to right! Shuffling an array within its columns in this manner does not undo the nondecreasing order in its rows.

This startling fact can be proved indirectly, by assuming that it is false and arriving at a contradiction. In other words, we shall assume that after the columns have been arranged there is a row in which a taller musician *a* is placed ahead, or to the left, of a shorter one *b*. Call the column the taller musician *a* is in *i* and the column the shorter musician *b* is in *j*, as is shown at the left in the bottom illustration on the preceding page. Since the columns have just been arranged, it can be assumed that

Q♥	5♥	K♦	9♣	4♥	7♣
3♣	5♦	A♦	4♦	6♦	A♠
5♠	3♠	3♦	2♣	9♠	8♣
10♦	10♣	7♦	J♠	6♥	K♠

4♥	5♥	7♣	9♣	Q♥	K♦
A♦	A♠	3♣	4♦	5♦	6♦
2♣	3♠	3♦	5♠	8♣	9♠
6♥	7♦	10♦	10♣	J♠	K♠

A♦	A♠	3♣	4♦	5♦	6♦
2♣	3♠	3♦	5♠	8♣	9♠
4♥	5♥	7♣	9♣	J♠	K♦
6♥	7♦	10♦	10♣	Q♥	K♠

Demonstrating the non-messing-up theorem every musician in the segment P from a back in column i is at least as tall as a and that every musician in the segment Q from b forward in column j is no taller than b. Moreover, since a is taller than b, it follows that every member of P is taller than every member of Q.

Now consider the halfway point at which the rows have been arranged but not the columns. To get back to this point it is necessary to return the musicians in segment P to their former positions throughout column i and to return those in segment Q to their former positions throughout column j. In other words, the members of P and Q will be distributed over the rows $1, 2, \ldots m$ as if the m rows were boxes. Segments P and Q, however, have a total length of $m + 1$, that is, there is a total of $m + 1$ musicians in the two segments. On the pigeonhole principle two of the musicians must end up in the same row. They could not both have come from the same segment, and so in some row there must be a member x from P in column i ahead, or to the left, of a member y from Q in column j, as is shown at the right in the bottom illustration on page 16. Since x is taller than y, this arrangement violates the already established nondecreasing order of the rows, and the conclusion follows by contradiction.

7. Sub-sequences in a Permutation. This final example establishes an engaging property of every arrangement of numbers from the sequence $1, 2, \ldots n^2 + 1$ into a row. When each arrangement is scanned from left to right, it must contain either an increasing sub-sequence of length (at least) $n + 1$ or a decreasing sub-sequence of length (at least) $n + 1$. For example, when n equals 3, the arrangement 6, 5, 9, 3, 7, 1, 2, 8, 4, 10 includes the decreasing sub-sequence 6, 5, 3, 1. (As this example demonstrates, a sub-sequence need not consist of consecutive elements of the arrangement.)

The assertion that every arrangement includes a sub-sequence of this kind can be demonstrated easily by specifying that for each number i in the row, x stands for the length of the longest increasing sub-sequence that begins with i, and y stands for the length of the longest decreasing sub-sequence that begins with i.

In this way $n^2 + 1$ pairs of "coordinates" (x, y) are obtained for the row of numbers, and if any value of x or y is as great as $n + 1$, the assertion is valid. On the other hand, if every value of x and y is less than or equal to n, there are only n^2 possible different pairs (x, y). In this case the pigeonhole principle implies some pair (x, y) would have to be the coordinates of at least two numbers i and j in the row. But i is not equal to j, and if i is less than j, then the x coordinate of i would be greater than that of j, and if i is greater than j, then the y coordinate of i would be greater than that of

j. In either case a contradiction has been reached. and so the assertion is proved.

Let us close with three exercises the reader may enjoy. The answers will be given next month.

1. A lattice point is a point in a coordinate plane for which both coordinates are integers. Prove that no matter what five lattice points might be chosen in the plane at least one of the segments that joins two of the chosen points must pass through some lattice point in the plane.

2. Six circles (including their circumferences) are arranged in the plane so that no one of them contains the center of another. Prove that they cannot have a point in common.

3. Prove that in any row of $mn + 1$ distinct real numbers there must be either an increasing sub-sequence of length (at least) $m + 1$ or a decreasing sub-sequence of length (at least) $n + 1$.

The counterintuitive result Honsberger describes for the marching band can be demonstrated dramatically with a deck of playing cards. Shuffle and deal the cards face up in any rectangular array, say four rows of six cards each as is shown at the top in the illustration on the preceding page, and then rearrange the cards in each row so that from left to right the six values never decrease, as is shown in the middle in the illustration. (For example, an acceptable arrangement is 6, 7, 10, 10, *J*, *K*.) Now rearrange each column so that from top to bottom the four values never decrease, as is shown at the bottom. Permuting the cards in a column will of course alter the cards in the rows. Nevertheless, after ordering the columns you will find that the rows remain ordered!

A card trick based on this surprising finding appeared in the magic periodical *The Pallbearers Review* (page 513, April, 1972). Deal five poker hands and then rearrange each hand so that its five cards are in increasing order from back to front. Assemble the hands any way you like and then deal five new hands face down in the conventional manner. The hands will be entirely different and will not be ordered. Explain that you are trying to teach the cards to order themselves. Pick up each hand, order its cards once more and turn the hand face down. Assemble the hands by placing the fifth hand (the dealer's) on top of the fourth hand, those two hands on top of the third, and so on. Deal five more hands face down in the usual way. The cards will have learned their lesson: although once again the hands will all be altered, each hand will be ordered!

This result is part of the theory of Young Tableux, a class of number arrays named for the Reverend Alfred Young, the British clergyman who proposed and analyzed them in a paper published in 1900. The arrays have been shown to have important applications in quantum mechanics. In the early 1960's the marching-band problem appeared in various guises in several mathematics journals. David Gale and Richard M. Karp wrote a monograph on the subject titled "The Non-messing-up Theorem," which was published in 1971 by the operations research center of the engineering school of the University of California at Berkeley.

Here are the answers to the problems pertaining to linear games given last month.

In 11-cell linear checkers (beginning with black on cells 1, 2, 3 and 4 and white on cells 8, 9, 10 and 11) the first two moves are forced: Black to 5 and White to 7. To avoid losing, Black then goes to 4, and White must respond by moving to 8. Black is then forced to 3 and White to 9. At this point Black loses with a move to 2 but wins with a move to 6. In the latter case White jumps to 5, and then Black jumps to 6 for an easy end-game victory.

On the eight-cell linear chessboard White can win in at most six moves. Of White's four opening moves, RxR is an instant stalemate and the shortest-possible game. R-5 is a quick loss for White if Black plays RxR. Here White must respond with N-4, and then Black mates on his second move with RxN. This game is one of the two "fool's mates," or shortest-possible wins. The R-4 opening allows Black to mate on his second or third move if he responds with N-5.

White's only winning opening is N-4. Here Black has three possible replies:

1. RxN. In this case White wins in two moves with RxR.

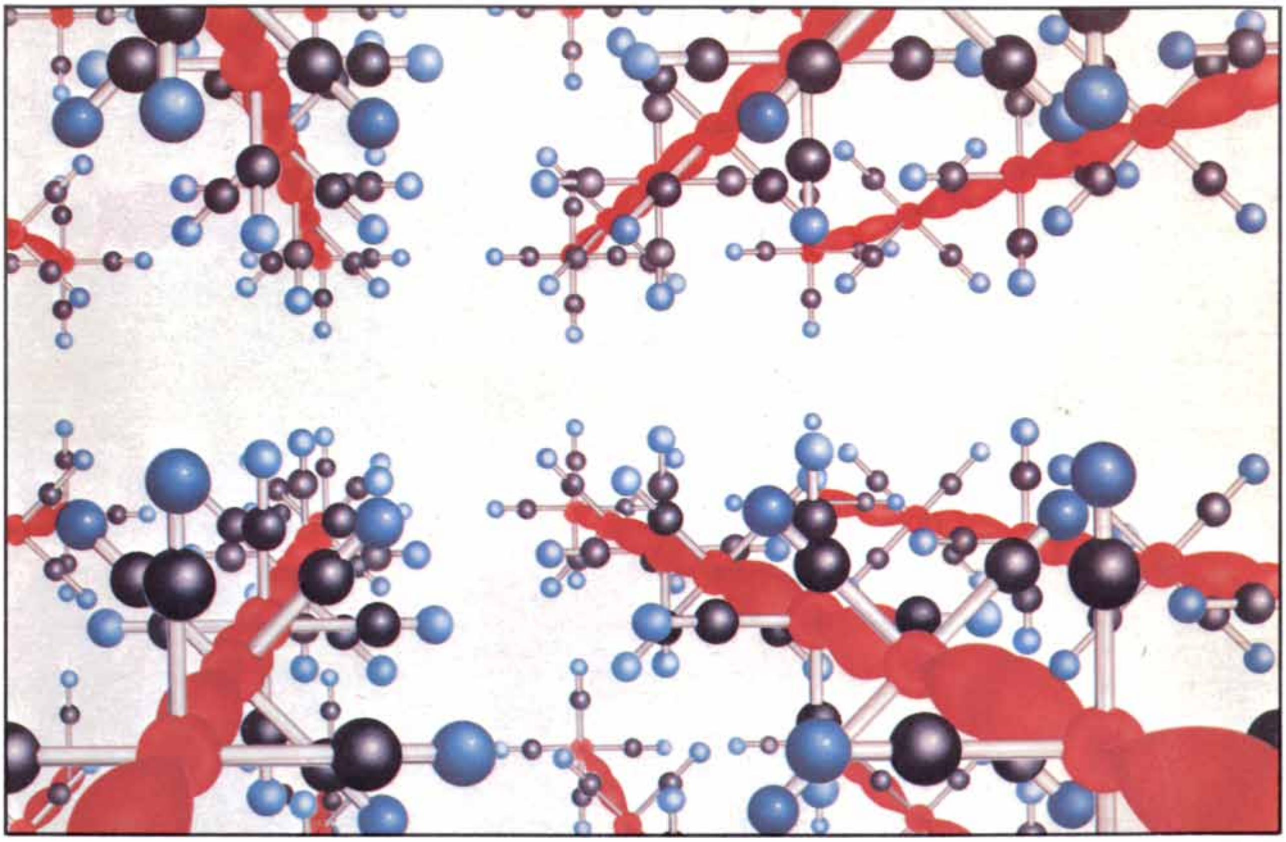
2. R-5. White wins with K-2. If Black plays R-6, White mates with RxN. If Black takes the knight, White takes the rook, Black moves N-5 and White mates by taking Black's knight.

3. N-5. This move delays Black's defeat the longest. In order to win White must check with NxR, forcing Black's king to 7. White moves his rook to 4. If Black plays KxN, White's king goes to 2, Black's K-7 is forced and White's RxN wins. If Black plays N-3 (check), White moves the king to 2. Black can move only the knight. If he plays N-1, White mates with N-8. If Black plays N-5, White's N-8 forces Black's KxN, and then White mates with RxN.

The first player also has the win in eight-cell pinch (linear go) by opening on the second cell from an end, a move that also wins the six- and seven-cell games. Assume that the first player plays on cell 2. His unique winning responses to his opponent's plays on 3, 4, 5, 6, 7 and 8 are respectively 5, 7, 7, 7, 5 and 6. I leave the rest of the game to the reader. It is not known whether there are other winning opening moves. James Henle, the inventor of pinch, assures me that the second player wins the nine-cell game. He has not tried to analyze boards with more than nine cells.

BRITISH TECHNOLOGY for the eighties

The first part of this special section on British Technology was prepared by Business Week's European economic correspondent Edward Mervosh, who provides a financial overview of British industry. In Part Two, David Fishlock, science editor of the Financial Times, examines specific technical innovations in the United Kingdom.



Britain's Technological Challenge

As the birthplace of the industrial revolution, Britain has a keen historical awareness of the importance of technology in fostering economic growth and development. It was the successful commercial application of new technologies in the 18th century that made Britain the leading industrial power well into the 20th century. Now, like the rest of Europe and the US, Britain faces intense competition from the developing countries, Eastern Europe and Japan in traditional industries such as steel, metal engineering, transportation and consumer durable products. The challenge for Britain in the eighties and into the 21st century will be to once again combine new technology and commercial enterprise to radically transform the economy in what is generally regarded as the new industrial revolution.

Britain possesses some impressive resources that could give it an edge in the technological and economic competition in coming decades. First and foremost it has vast energy reserves – not only oil and gas but also coal. Recoverable oil reserves are estimated at between 2,300-4,300m. tons and recoverable gas at as much as 70,000bn. cubic feet. Oil and gas are expected to be flowing into the UK at a rate that will make it self-sufficient at least through the end of this century. Last year Britain produced more than 76m. tons of oil, ranking it in the production league with Mexico, Canada and Indonesia.

Coal resources are even more impressive. Coal that is recoverable through present mining techniques is estimated at 450,000m. tons, enough to last for about 300 years at present rates of consumption. Britain is the single largest producer of hard coal in Western Europe, and ranks fourth in the world in terms of reserves accessible to modern technology.

Britain's human resources are also potentially abundant. Its scientists have been awarded 34 Nobel Prizes for science and medicine – about one in six of all those awarded in those fields. And British universities rank among the best in the world.

It is widely recognised, however, that effectively utilizing these resources will require creative, strong management not only by business, but by government and labor as well. Unfortunately, many people are greatly concerned that there is a serious deficiency of managerial talent and that unless this problem is corrected quickly Britain will not be able to compete in coming decades. "Britain is not competing well now across the board, and the main problem is managerial competence." concludes Christopher Freeman, director

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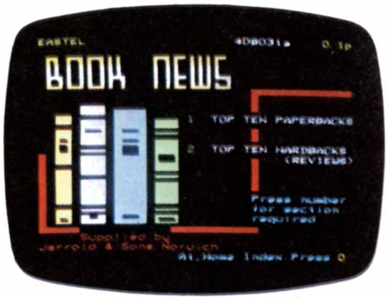

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of the Science Policy Research Unit at the University of Sussex. "It is not a question of having good scientists, but a question of managing the whole process of technological innovation from developing ideas to marketing and negotiating sound contracts. It is here that Britain has been falling behind since the 1930s".

Critics believe that the management problem is rooted in the structure of industry and in the educational system. "In most cases in Britain the board is composed of financial types who are not able to make a reasoned judgement about product innovation", complains Gordon Edge, president of the highly successful Patscentre International, which is in the business of managing technological innovation. "There are not enough trained engineers among top management. And research and development departments tend to be isolated from day to day business".

It is also argued frequently that Britain suffers from a shortage of qualified engineers. "We have been way behind for 50 or 100 years because we still believe that engineers only need part-time training, a system left over from the early days of the industrial revolution", says Freeman. In addition it appears that people with scientific training regard applying their skills to product development as intellectually inferior to pure research. "There is a problem getting talent and money put into applied research", complains Ian Campbell, chairman of Transmark, the international consulting group for British Rail. "This country has always depended on technology and there is no future unless we are adventuresome with technology. But too few people understand that yet".

Such blistering criticisms are certain to arouse indignation in many successful industries. It is indeed true that British industry has chalked up many successes in such fields as aerospace, railway transportation, nuclear energy and electronics to name only a few. But the final test of a country's technological prowess is how well its economy performs, and by that measure it would appear that some of the criticism about the failure of management is justified.

During most of the postwar period, Britain's economic growth has been considerably slower than that of its main competitors. During the sixties, real gross national product (GNP) grew at annual average rates of only 2.8 per cent compared with 4.5 per cent in Germany, 5.6 per cent in France, 10 per cent in Japan and 4.1 per cent in the US. The strong performance of Germany, France and Japan during the sixties in part reflects the continuation of rebuilding following the war. Thus it is even more significant that Britain's relative performance weakened even further during the seventies when that catchup process was over. Over the past decade, Britain's growth slowed further to an average annual rate of only 2.4 per cent.

This poor showing is largely the result of the steady weakening of Britain's international competitiveness. Exports account for about 24 per cent of GNP, making Britain one of the most heavily trade-dependent countries in the world, exceeding even Germany and Japan. But since the early sixties Britain's share of world manufacturing exports has fallen dramatically according to a study by economists at Cambridge University. More recently, the Organization of Economic Cooperation and Development (OECD) estimated that imports as a percentage of GNP had risen from less than 7 per cent in 1963 to 18 per cent in 1978. The OECD also estimates that the real trade balance in manufactures as a percentage of GNP has deteriorated by about 4 per cent over the past two decades.

Thus even though Britain in company with the US benefits from huge oil reserves that help offset its oil bill, the balance of payments has been almost continually in the red during the past decade. Self-sufficiency in oil is expected to help eliminate that deficit, but Britain's weak performance in trade generally underscores the problems the country faces in keeping up with more technologically advanced countries.

The deterioration of Britain's international competitiveness has been caused by a deadly combination of rising labor costs and weak investment. What is most disturbing is that the loss of cost competitiveness in manufacturing has increased sharply since 1976. The index of relative unit labor costs, which compares Britain's costs with other countries, has risen by more than 30 per cent since 1976.

Unlike its competitors, Britain has not been investing heavily to upgrade its industry to offset rising costs of labor and raw materials. The real growth of fixed capital formation actually declined during the seventies. As a result gross fixed capital formation currently accounts for about 18 per cent of GNP compared with 21 per cent in Germany, 23 per cent in France and 30 per cent in Japan. Only the US among major countries does worse.

The main cause of weak capital investment is not hard to find. The profitability of British industry has been declining steeply for the past two decades, reflecting the shift of income from capital to labor and the government. The rate of return on capital employed has declined from around 11 per cent in the early sixties to about 4 per cent at the end of the seventies.

Poor profits are also a major reason for the sharp decline in spending on research and development during the sixties and seventies. Business spending on research and development dropped from around 2.3 per cent of the domestic product of industries in the early sixties to about 1.75 per cent in the seventies. By the mid seventies, Britain was spending about half as much on R&D as Germany and Japan. "Britain is the only major country where there has been a large decline in spending on research and development in absolute terms", notes Yvan Fabian, director of the Science and Technology Indicators Unit at the OECD. "The decline in spending on a strategic sector like machine tools has been spectacular. British industry either doesn't believe in R&D or it doesn't have the money".

Some British businessmen believe it is a combination of both. "Britain has not yet learned that it has to earn its living in an increasingly competitive world", says Stephen Baker, managing director of British Electricity International. "Management has been lulled into a false sense of security".

Almost everyone, however, believes that the government's policies regarding research and development and technology in general have failed. Although direct government financing of industrial research and development is relatively high compared with other major industrialised countries, about 50 per cent of it is directed toward defense. A major conclusion of a recent book by the Science Policy Research Unit at the University of Sussex entitled "Technical Innovation and British Economic Performance" is that the government spends "far more on defense and prestige-type projects than on the technologies which matter most for industrial competitiveness". The book points out that the Germans and Japanese spend much more on R&D in industries such as machinery, electrical goods, electronics, instruments and chemicals which are critically important in world trade.

The role of government in aiding technological development is certain to become increasingly controversial since the sums needed to finance projects in energy, aerospace, telecommunications and other advanced industries are enormous. "It will cost billions of dollars to change over Britain's telephone system to the new switching system", predicts John Sharpley, managing director of British Telecommunications Systems. The National Coal Board is spending about $1.2bn. a year on capital investment including research and development and expects to continue to do so for years. "Government provides only very limited assistance especially for research and development", says Sir Derek Ezra, chairman of the National Coal Board. "That puts us at a disadvantage with Germany, France, or Belgium where the assistance is much greater".

"The lead times needed to develop energy projects create enormous

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Fuel costs keep going up. In 1979 alone they rose no fewer than five times.

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problems", explains Gordon Evans, chief executive, group research and development at British Petroleum. "You need to commit huge sums without any guarantee that technological advance won't overtake you even before you are finished". "The US and Germany are investing hundreds of millions of dollars in coal conversion plants with substantial government support. It is hard to spend that kind of money in private enterprise given the high risks".

Just how much of a role government should play in the critical area of technological development will certainly be a prickly issue for the Conservative Government of Prime Minister Margaret Thatcher. A basic objective of Mrs. Thatcher's economic policies is to reduce the role of government in order to allow the marketplace to more freely allocate resources. To achieve this objective Mrs. Thatcher is trying to cut government spending sharply and would probably be unwilling to underwrite development projects for industry that could cost billions. Indeed the Government is moving in the opposite direction by selling off its shares in state-owned industries such as British Aerospace and British Petroleum.

The key to the success of Mrs. Thatcher's policies however is to curb inflation and to revive economic growth. The Government has imposed a very restrictive credit policy which is designed to put the economy through a rather severe recession. The hope is that this will sharply cut inflation which has been running in double digit figures for the last three years. A slowing in inflation is expected not only to help restore industry profitability but also to help the Government cut spending even further and therefore enable it to cut taxes to encourage capital investment.

Mrs. Thatcher's policies are revolutionary and in a sense her Government is conducting an economic experiment in much the same way that a scientist tries out new ideas in a lab. For these policies to succeed the economy will probably have to grow slowly for several years and unemployment will have to remain very high. There is no guarantee that high unemployment will achieve the purpose of dampening wage demands as the latest round of wage negotiations indicate. And many economists question whether businessmen will undertake risky investments in new technologies and new products if the outlook for the growth of markets is highly uncertain. Finally, fighting inflation mainly with tight credit policies and high interest rates could make it too costly to embark on very costly investment projects.

Despite the risks inherent in the Government's economic policies, most businessmen and the public as well seem to support Mrs. Thatcher's bold new initiatives. There is widespread agreement that the policies of the past have failed and new directions must be taken. It is the new awareness of the seriousness of the problems confronting Britain that may make it possible for them to be solved. Indeed, despite the candid self-criticism and warranted concern the British express about their formidable problems, considerable investment is underway in new technologies, in energy, chemicals, electronics, military equipment, aerospace and transportation as the following analysis details.

Britain's Technological Successes

Britain's annual expenditure on research, development and demonstration (R,D-&D) is close to $10bn., of which central government is providing more than 50 per cent.

After defense, energy is the biggest single sector of R,D&D. Sir Alan Cottrell, Master of Jesus College, Cambridge, and the last occupant of the post of chief scientific adviser to the government, believes that the 2 per cent of gross national product (GNP) which most nations were allocating to energy in the 1950s and 1960s will rise to about 15 per cent of GNP. Already it is between 5 and 10 per cent. In Britain, it is about 12 per cent. "But we are rather exceptional partly because we already put a strong effort into energy supplies – North Sea oil and gas, coal, nuclear – but also because we have a particularly poor productivity, so that our economic output is unusually low for the amount of energy we consume", says Cottrell.

In the latter half of the 1970s the British Government replaced its chief scientific adviser with a team of 15, drawn from government, industry and academia, known as the Advisory Council on Applied Research and Development (ACARD). ACARD has produced a series of pithy reports in the past two years, critically examining the technological base of the nation. A recurring theme, to quote its chairman, Dr. Alfred Spinks, is that the nation "cannot support any technology of any substance on the British market alone".

Vickers, one of Britain's biggest engineering groups, with sales last year exceeding $850m., is in many ways a microcosm of British manufacturing industry. Its order book used to be dominated by government business. "But prolonged out-bursts of peace left us in considerable difficulties", says Sir Peter Matthews, its chairman. Today it is a highly diversified "engineering conglomerate", technologically very strong in medical engineering, machining centers and printing plate manufacture. As Matthews sees it, these subsidiaries of Vickers are "what small businesses are all about – being right up at the front in their own technology". The problems lie with the large, more traditional areas of engineering which still dominate the activities of the group – and of Britain.

At both corporate and national levels attempts are being made to review the technological opportunities open to Britain, and choose those whose pursuit seems most likely to pay off. The government's Research Councils, with a budget of about $700m. a year for the support of university science, have been cutting back hard on support for high-energy physics and astronomy, both highly capital intensive, in favour of such areas as engineering research and "genetic engineering". ACARD is urging the government to channel more resources into manufacturing technology, both to help raise productivity and to open fresh opportunities for new products.

When and how to stop a project is one of the most difficult problems for the management of research. One way of approaching it is to assign priorities to the research program. The most highly developed attempt Britain has made to assign priorities to an entire sector of R,D&D is in the energy technologies. The resulting "league table" may well serve as the model for other sectors to follow.

ENERGY TECHNOLOGY

Britain is investing about $12 bn. a year in energy production. Late last year the government published a table of energy technologies in which it assigned priorities – ratings from one to five stars – according to their importance to Britain. Behind this table lay several years of research following the OPEC oil price increases of 1973. The scientific advisers knew that Britain could not afford to bring to fruition all the possibilities open to them. Their studies show that technology can offer no way of returning to the pre-OPEC era of cheap energy. It can only help to ameliorate the effect of rising energy costs.

But the scientists have introduced the concept of energy insurance, in case one of two mainstays of long-term energy supplies for Britain fails to come up to expectations. In those circumstances the nation might conceivably be willing to pay the much higher costs expected for, say, electricity generated from waves or wind. So they also assign priorities to such sources as "energy insurance" against future mishaps. In this way some research on, say, wavepower is justified even though it rates only a single star in the "league table" – a rating which implies that it is not expected to be yielding more than 1m. tons of coal-equivalent a year for Britain within the next 50 years.

Coal

Britain's industrial base was built on coal, still the dominant fuel today, fulfilling about 40 per cent of primary fuel demand. Britain is rich in coal but the seams are

BRITAIN'S "LEAGUE TABLE" OF ENERGY TECHNOLOGIES.

	Technology	Importance as Essential or Supplementary Technologies
Primary Energy Technologies	**Energy Conservation**	
	Conservation in Industry	✱ ✱ ✱ ✱ ✱
	Conservation in Buildings	✱ ✱ ✱ ✱ ✱
	Conservation in Transport	✱ ✱ ✱ ✱ ✱
Conservation	**Electricity**	
	Electricity Utilisation	✱ ✱ ✱ ✱ ✱
	Electric Heat Pumps	✱ ✱
	Electric Traction	✱ ✱
	Conventional Generating Plant	✱ ✱ ✱ ✱ ✱
	Advanced Coal Fired Plant	✱ ✱ ✱ ✱
	Bulk Storage of Electricity	✱ ✱ ✱
	Transmission & Distribution	✱ ✱ ✱ ✱ ✱
	Pipeline Gases	
	Gas Utilisation	✱ ✱ ✱ ✱ ✱
	Gas-Fired Heat Pumps	✱ ✱
	Transmission & Distribution	✱ ✱ ✱ ✱ ✱
	Gas Storage	✱ ✱ ✱
	SNG from Oil (Peak-Load Plant)	✱ ✱
	SNG from Coal	✱ ✱ ✱ ✱ ✱
	Liquid Fuels	
	Liquid Fuels from Coal	✱ ✱
	Solid Fuels	
	Coal Combustion	✱ ✱ ✱ ✱ ✱
	Industrial Fuel Gases from Coal	✱ ✱
	Metallurgical Cokes from Coal	✱ ✱ ✱ ✱
	Heat	
	Combined Heat & Power	✱ ✱
	District Heating	✱ ✱
	Nuclear Heat	✱ ✱
	Heat Storage	✱ ✱
	Chemicals	
	Chemicals from Coal	✱ ✱ ✱
Energy Use and Supply Technologies	**Nuclear**	
	Thermal Reactors	✱ ✱ ✱ ✱ ✱
	Fast Reactors	✱ ✱ ✱ ✱ ✱
	Nuclear Fuel Cycle	✱ ✱ ✱ ✱ ✱
	Fusion	✱
	Oil and Natural Gas	
	Deep Water Extraction	✱ ✱ ✱ ✱ ✱
	Enhanced Recovery	✱ ✱ ✱
	Coal Extraction	
	Deep Mining	✱ ✱ ✱ ✱ ✱
	Novel Methods of Extraction	✱ ✱
	Renewable Energy Sources	
	Solar Heat	✱ ✱
	Crops and Organic Wastes	✱ ✱
	Geothermal Energy	✱ ✱
	Wave Energy	✱
	Tidal Energy	✱ ✱
	Wind Energy	✱ ✱

NOTE:

Essential technologies are those assigned five or four stars. Supplementary technologies have three or two stars. Technologies with only one star are not expected to make a contribution of over 1 mtce a year within the 50-year time horizon of this orthodox view of the future.

Table courtesy UK Department of Energy.

deep, relatively thin, and frequently faulted geologically. It cuts most of the 120m. tons of coal mined a year in mines averaging 1,600ft. deep. The National Coal Board's Mining Research and Development Establishment is trying to automate Britain's coal mines, in which the state-owned NCB is investing about $1.3bn. a year. It has developed a system of automation called Minos – acronym for "mine operating system" – for controlling the key facets of a coal mine: environment, coal clearance, coal washing, even the coal cutting operation itself. Minos is planned as a family of electronic systems adaptable to the great diversity in shape, size and age of coal mines in Britain, working to common standards of safety, reliability, performance and computer programming.

At least 38 British mines today are equipped with at least one facet of Minos. The ultimate goal is to tie most if not all facets of Minos into a single integrated system automating the entire mine.

The Coal Board is also host to an international experimental facility for exploring a new way of raising steam at high temperatures and pressures from coal without putting sulfur into the atmosphere. The pressurized fluidized-bed combuster – a British invention – at Grimethorpe Colliery in Yorkshire is a $50m. Anglo-US-German project. The 75 MW(th) combuster operates under microprocessor control over the pressure range 6-12 bar (atmospheres), at a bed temperature of 800°-950°C.

Natural Gas

Britain discovered natural gas (methane) in the North Sea in 1965. Today it is landing about 4,000m. cu. ft. per day; a figure expected to rise during the 1980s to about 6,000 m. cu.ft. by 1990. The state-owned British Gas Corporation has invested about $3bn. in some 9,000 miles of high-pressure pipeline to provide Britain with a nationwide transmission grid for high calorific value gas. It reaches about 85 per cent of British homes. British Gas has invested a major R&D effort in guaranteeing the integrity of this high-pressure grid. It has developed a computer-based system of pipeline surveillance, called on-line inspection, using robots which pass through the pipes without impeding the gas flow, in order to certify that there will be no catastrophic failure of the system through the effects of ageing.

Sir Denis Rooke, its chairman, says he became convinced that it needed some way of verifying that no crack in the pipe had reached a size which might precipitate a catastrophic failure after a US accident in which a pipeline split open over an 8-mile length. He called for a system that would "fingerprint" the entire grid, so that the record of subsequent inspections could be compared with the computer-stored master to see whether flaws – old or new – were reaching a worrying size. This year British Gas has introduced on-line inspection as a new advanced-technology service; one it believes it will also be able to license to pipeline operators worldwide. The robots use very sophisticated methods of magnetic and ultrasonic inspection.

Rooke believes that the North Sea will produce more surprises yet before Britain begins to run out of natural gas. But this must eventually happen and to meet the contingency British Gas has embarked on a $650m. R,D&D program spanning most of the next two decades. Its aim is to bring to commercial demonstration a spectrum of technologies developed in its own research centers, able to convert almost any hydrocarbon – liquid or solid – into substitute natural gas (SNG).

For liquid feedstocks, it plans a new development center at Killingholme in Humberside, where by 1982 it expects to be making SNG from the lighter oil fractions – naptha, kerosene, gas oil. Rooke claims he has already demonstrated the technology on plant of a size " the rest of the world regards as rather large-scale development". The technology is catalytic conversion, using highly active catalysts developed by its researchers.

For solid hydrocarbons it is engaged in major developments of the German Lurgi process, known as the "slagging Lurgi gasifier", which overcomes serious restrictions on the quality and size of coal the original process could handle.

Oil

Britain, mainly through Royal Dutch Shell and British Petroleum, has a major stake in the international oil industry. Britain struck oil in the North Sea in 1969 and it has expanded extraction to the point where, this year, it expects to become self-sufficient in terms of tonnage landed. It consumes about 75m. tons a year. It has 12 offshore oilfields in production and another 10 under development. Total North Sea oil and gas investment by 1980 is estimated at $25bn. The government estimates total oil reserves in the areas it has licensed so far for production at 2,030m.-3,220m. tons, of which just over 1,000m. tons are in fields already being exploited.

The outstanding characteristic of the continental shelf around Britain is its hostility compared with most other offshore oil discoveries. This hostility is increasing as exploration pushes into deeper, more turbulent Atlantic waters to the north, west and south of the UK. The capital investment in a new platform is already expected to exceed $1.2bn. An example of advanced oil company technology for deep-water recovery is British Petroleum's single well oil production system (SWOPS), disclosed early this year. It uses a floating platform and a long umbilical through which the oil and gas would be tapped. BP believes that a big tanker might mate with a seabed well head and tap its cargo of crude straight from the well, without need for a permanent platform or sub-sea installation. To try it, BP plans to spend $100m. in converting a tanker of 50,000-60,000 tons and installing an ocean-bed well head (marked by a sonar transmitter) with which it can mate.

Electricity

Britain has a total electricity generating capacity of about 70,000 MWe, for which the dominant fuel is coal. Two-thirds of UK-mined coal is consumed in power stations. Current policy is to build up the country's nuclear electricity capacity – 12 per cent of power generated in 1979 – in order to make UK coal available for SNG manufacture when this is required.

The Central Electricity Generating Board, which supplies most of Britain's electricity, is the world's biggest electrical utility. Its generators are mainly high-speed 500 and 660MWe machines operating on superheated-steam at 3,000 rev/min, designed by GEC and NEI Parsons. The nuclear stations currently under construction use the advanced gas-cooled reactor (AGR), a UK-designed reactor operating at gas outlet temperatures and pressures corresponding with the superheated steam conditions of fossil-fired stations.

Britain has over 5,500 miles of 400-kilovolt "supergrid" operating as one integrated system. By the mid-eighties this system should be joined to that of Electricité de France through a 2,000 MW d.c. intertie buried in the bed of the English Channel. Two systems of similar size will then be able to exchange electricity. Britain will also be tied into the European electricity pool, which has more than 130 interties. Dr. Peter Howard, director-general of the CEGB's transmission division, is developing a novel technology using remotely controlled vehicles working on the seabed to cut trenches 5ft. deep and automatically lay and bury the cables. The two machines – a 114-ton trenching tractor and a 80-ton cable layer – were tried out successfully in the fall of 1979.

Nuclear Power

Britain, which has been generating nuclear electricity for 24 years, plans to expand its nuclear plant capacity from about 7,000 MWe at present to 20,000 MWe by the early nineties , to meet about 30 per cent of electricity demand. The thermal reactor type under construction is the AGR, developed by the UK Atomic Energy Authority. This is a carbon dioxide-cooled system, moderated by graphite, encased in a concrete pressure vessel.

Reactor development during the eighties will continue to be dominated by the fast

breeder reactor (FBR), in which Britain has been one of the pioneers. Focus of interest is a joint proposal on behalf of the electricity industry and the UK AEA, for a demonstration fast reactor in Britain of about 1,200 MWe. This may be built as an international collaboration, believes Sir John Hill, chairman of the UK AEA and the government's chief nuclear adviser. Britain is spending over $100m. a year in FBR development.

The system under development is the liquid metal cooled fast breeder reactor (LMFBR). Its fuel is depleted uranium enriched to about 20 per cent with plutonium oxide. In addition, the reactor core would be surrounded by a blanket of depleted uranium which, by absorbing neutrons, could be used to "breed" new plutonium, for re-use in the core. Britain's confidence in LMFBR technology is based on 17 years of operation of a 15MW experimental reactor, followed by five years of operation of a prototype reactor using fuel of a size and design appropriate for a full-scale reactor. In man-made caverns and caves at Dounreay in Scotland is a reactor in a pool filled with 1,000 tons of molten sodium metal, producing about 200 MWe.

For two decades Dounreay has studied everything that might conceivably happen if the cooling of the LMFBR should fail. Sir John Hill recently gave the first results of experiments with the prototype reactor in which all the cooling pumps are deliberately switched off. They suggest that, even if everything fails, the operators could simply leave the reactor to cool down safely.

Britain is also host to a major international experiment in controlled nuclear fusion: the eleven-nation Joint European Torus (JET) project at Culham, under the direction of Dr. Hans-Otto Wuester. If this $250m. experiment is successful enough to proceed to an "active" stage of operation in the mid-eighties, using tritium as its fuel, it could lead the world in fusion research, Dr. Wuester believes.

CHEMICAL TECHNOLOGY

The $37bn. chemical industry in Britain is strong "because it grew up parallel with the science – it has grown up with and lives by innovation", believes Lord Todd, president of the Royal Society and a Nobel prize-winning chemist himself.

Biotechnology – the application of living organisms to high speed industrial processes – is one area in Britain where "I'm expecting to see quite big developments", says Lord Todd. The latest techniques of genetic engineering "open the way to exploit two decisive advantages of biotechnology – very low energy demand and an ability to make very complex compounds". Britain has one of the world's leading research centers in genetic engineering in its Laboratory of Molecular Biology in Cambridge, which has pioneered the technique of cell fusion and used it to make antibody immunoglobins. These drugs are especially valuable today in disease diagnosis but potentially are of great interest for treating chronic and inborn diseases.

The most dramatic demonstration of the potential for biotechnology is ICI's Pruteen process, developed in the laboratories of its agricultural division and brought on-stream this year in a 50,000-ton demonstration plant. Pruteen is an animal feedstuff grown continously in the world's biggest fermenter – 600 tons and over 60 ft. tall – by feeding a bacterium, *Methylophilus methylotrophus*, on methanol made from natural gas. Bacteria yield 50-80 per cent protein. But in order to maintain a high yield of the organism ICI finds it has to inject the "fuel" very uniformly, at 3,000 points throughout the fermenter. The $80m. plant has been planned as the precurser for full-scale commercial units of up to 300,000 tons capacity, the first of which is now being designed by ICI.

At ICI's corporate research laboratory at Runcorn a team of molecular biologists has been attempting to modify the microbe used to make Pruteen and increase the efficiency of converting methanol into protein. ICI disclosed this spring that its researchers had made a promising discovery by transplanting a gene capable of assimilating ammonia – one of the nutrients needed in the fermenter – more efficiently.

The technology of growing and harvesting single-cell protein has proved much more difficult to exploit than the pioneers in Britain believed in the sixties. BP, which once led the field with two routes for growing protein on oil as an animal feedstuff, has abandoned the quest, partly because of the problems of eliminating the last traces of hydrocarbons from its product.

Mycoprotein

A company which aimed from the start at the still more difficult target of a new human food from the fermenter is Ranks Hovis McDougall, one of Britain's biggest food processing groups. RHM could become the first company in the world to market an entirely new human food. Its interest began in the mid-sixties when its researchers were seeking a way of using the starchy by-product extracted in baking low-calorie bread. The waste was being spread on fields where a micro-organism was converting it into protein. By the mid-seventies it was running a continuous fermenter making protein by cultivating a microscopically small fungus known as mycoprotein.

The product, a porridge of protein–rich filaments smelling faintly of mushrooms, can be combed and rolled into a remarkably fibrous structure. RHM scientists have devised a variety of ways of turning it into nutritious facsimiles of poultry, fish and other familiar foods. Official approval to market the product has been asked for.

Pharmaceuticals

Seminal discoveries by British medical research workers – for example, interferon, encephalins, and the therapeutic significance of receptor sites – form the foundation for a strong pharmaceutical industry in Britain. Its sales exceed $4bn. a year. ICI, the Wellcome Foundation, Beecham and Glaxo, the four biggest British pharmaceutical groups, are spending between them $280m. on R&D this year. The industry claims its R&D expenditure increased more than 2.5 times in real-money terms during the seventies. Several major US and European groups have also based strong research centers in Britain; G.D. Searle, for example, with a team of genetic engineers and a $12m. pilot plant under construction for biotechnology processes.

Sugar Chemistry

Oil is the basis of Britain's chemical industry today but "almost anything you can do with oil could be done more cheaply with sugar", claims Professor A.J. Vlitos, Tate and Lyle's research co-ordinator. Near Liverpool his company – the world's biggest sugar refiner – has just started up a $45m. complex of processes, all using sugar as their feedstock: the only factory of its kind in the world. One process is a joint venture with Hercules Powder, the US fine-chemicals group. All have come out of a research effort Vlitos mounted a decade ago to open new business opportunities for Tate and Lyle.

Knowsley is a novel kind of refinery, taking in sugar and fats (vegetable oil or tallow) and making a family of polysaccharide gums and surfactants, all of potentially high added value, not least because of their low toxicity. The venture with Hercules, for example, is the fermentation of an unusually viscous broth to make xantha gums, destined for diverse uses in food manufacture and oil drilling.

Pesticides

Close collaboration between Rothamsted Experimental Station and major British chemical groups such as ICI and Shell has produced a family of powerful yet remarkably safe insecticides, now beginning to burgeon into a major new product. As an invention of government scientists, these pyrethrin analogues have been protected by over 300 patents applied for by the National Research Development Corporation. The NRDC believes annual sales for the pyrethroids could reach $1bn. a year.

Rothamsted's success first in resolving

relationships between chemical structure and insecticidal activity, and later in synthesizing more powerful yet safer compounds, proved remarkably timely. By the 1970s it had discovered photostable pyrethroids, "probably the first examples of an important new class of pesticides", says Dr. Michael Elliott, foremost among its inventors. They show many of the good qualities of DDT but are rapidly broken down in the soil. They are 10-100 times more active than most other insecticides, he says. They arrived at a psychologically important time, when environmentalists were demanding safer pesticides. The pyrethrins have surmounted regulatory hurdles to reach the market several years earlier than was expected. The US Government, for example, granted emergency clearance for their use on cotton in 1977 and 1978.

Radio-Chemistry

Two state-owned chemical companies set up in 1972 under the chairmanship of Sir John Hill, the government's chief nuclear adviser, have grown into international trading companies with higher sales than any privately owned company in their respective fields. They are British Nuclear Fuels Limited (BNFL) providing nuclear fuel services worldwide and earning about $600m. last year; and the Radiochemical Centre making radioactive chemicals and drugs, and earning more than $80m. last year

"For BNFL the outlook is steadily expanding sales and profits in the 1980s", says Con Allday, managing director. In 1978 the company embarked on a ten-year investment plan expected to cost over $6bn. It includes reconstruction of the Western world's biggest reprocessing operation for spent nuclear fuel. It is also building the world's biggest plant to reprocess uranium oxide fuels, 1,200 tons a year. The $1.3bn. thermal oxide reprocessing plant (THORP) is expected to include major features new to chemical processing operations, including new power fluidic systems for pumping, navigating and regulating flows of highly radioactive liquor by remote control, with no mechanical intervention.

New process technology includes a cheaper way of making uranium dioxide, for which Westinghouse Electric took a license last year. Two new enrichment plants are under construction using the company's developments with the high-speed gas centrifuge to separate the fissile uranium-235 isotope. One will produce highly enriched uranium fuel for nuclear submarines.

Process Plant Design

Fast-rising energy costs, the novel problems raised by British discoveries of oil in the North Sea and Alaska, and growing difficulties with labor relations on large UK construction sites all have a part in a new approach to big engineering projects which has taken shape in Britain since the late seventies. A key figure has been Robert Malpas, formerly ICI's director of engineering but now president of Halcon International in New York. The essence of these ideas is to combine the increasing elegance and sophistication of electronic control systems with a deeper understanding of the chemistry of, say, a complex synthesis, to redesign the process from scratch. ICI itself has already used what Malpas calls "the plant-after-next approach", in developing several plants which operate at much higher concentrations and hence need much less energy to keep chemicals flowing and make much less effluent and waste.

ELECTRONICS

A beckoning finger sketched by a computer drew British TV viewers into a new world in a series of advertisements this spring. Viewers were introduced to the idea of using the TV set as a computer terminal for instant access to information and pictures, in color, ranging from what the stockmarket is doing to where to go for the evening. The technology is called viewdata and was born in the laboratories of the British Post Office. The idea is to harness two pieces of apparatus found in most homes, TV and the telephone, to a computer-based information retrieval system. The result is Prestel, the first public viewdata system in the world, whereby users can interrogate computers.

Prestel is one of Britain's most ambitious new systems for the 1980s. The PO expects to invest about $220m. by 1985. About 100 companies have co-operated in adapting TV receivers, providing computerized information, and knitting it into a network which will embrace 60 per cent of Britain's telephone subscribers by the end of this year.

On the desk of Derek Roberts, research director of GEC, Britain's biggest electrical group, is a viewdata screen. GEC is one of the companies participating in the Prestel project. Roberts and about 30 other research executives at GEC are already linked into their private information network, through which they can also access data about the laboratories themselves – who is expert in what, where the vacancies are, what is the financial status of a project.Roberts, one of Britain's most creative research chiefs, sees GEC as a representative slice of UK manufacturing industry. Its activities range from the most advanced technologies to turn-of-the-century industries. Much of the most advanced technology is found in the Marconi half of the group, a capital goods activity earning about $2bn. a year and


Uranium. Yesterday it was used for colour.
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Micro-electronics

David Speake, technical director of GEC-Marconi Electronics, has no doubts about the pivotal role of the microprocessor in advanced systems design today. "If we don't use the microprocessors we don't do it at all". He believes it will remain the major influence on his industry for the next decade. ACARD, the government's scientific advisers, alerted the government to the crucial importance of the technology in 1978. This in turn catalysed an Anglo-American joint venture in Britain between GEC and Fairchild to develop and manufacture circuits using very large scale integration.

A British manufacturing system which promises to play a key role in very large scale integration in the 1980s is the electron-beam microfabricator, born of pioneering work by Cambridge Instrument Company in electron microscopy and microanalysis. The microfabricator is a way of making chips of a complexity beyond today's products, using electron beams steered by a computer to cut the numerous masks needed to delineate an integrated circuit. A government-funded project involving the manufacturer, the University of Cambridge, and the Science Research Council aims to develop a new microfabricator 10-100 times faster.

One of the most dramatically successful examples of the power of the miniature computer for enhancing a long-established technology is the EMI-Scanner, EMI's invention for medical X-ray diagnosis based on computerised axial tomography (CAT) scanning. The inventor, Godfrey Hounsfield, received a Nobel Prize for physics in 1979. Under his tutilage, EMI built up an inventory of over 500 patent applications worldwide, developing the basic idea before selling the technology to US General Electric this year.

Avionics

Since World War One, when Marconi engineers first overcame the problems of radio reception in the cockpit, the role of avionics – aircraft electronics – has expanded to form 40 per cent or more of the cost of an aircraft. The all-weather capability of aircraft today depends heavily on a number of computer-based systems, capable of automatically controlling, navigating, even landing "blind" in thick fog. Britain has pioneered many of these avionic systems, including blind landing and head-up displays. At its biggest research center, the Royal Aircraft Establishment (RAE), with a dual role in both military and civil aircraft development, the largest sector of work is devoted to avionics.

"We're good at avionics in this country and a lot of the credit must go to the Ministry of Defense", says Derek Alun-Jones, managing director of Ferranti. His company has no fewer than seven avionic systems or sub-systems in the Tornado, the new Anglo-German-Italian warplane, including inertial navigation and laser weapon ranging. Aircraft designers today can extend performance more rapidly through avionics than by engine design. A refit with a new generation of avionics systems can deliver virtually a new aircraft.

Marconi Avionics, Europe's biggest supplier of avionic systems, claims to be supplying systems for 135 different civil and military aircraft currently in service; Tornado alone has eleven. One of its most advanced developments is the head-up display, a concept from the RAE. For many purposes the head–up display is the most important channel of communication between man and machine yet invented for the pilot. It projects information right into his field of view, beyond the windscreen, but without impeding his view ahead. At the touch of a button he can select data generated by a micro-computer, leaving his view uncluttered by unwanted information.

Telecommunications

The biggest and most complex machine to be designed round a computer is a telecommunications switching system. In the 1960s, when almost everything about Britain's future in fully electronic telecom switching was an unknown factor, somebody joked about "System X". The nickname stuck and became the name of the technology Britain began to design in earnest in the late-seventies and will begin to operate in 1981.

System X is the outcome of a unique collaboration between three private companies – GEC, Plessey, and Standard Telephones (British offshoot of ITT) – and the PO. The concept is elegant and essentially simple: a family of solid-state electronic modules which can be rearranged in a great many ways to build an exchange of the capacity and performance specified by the customer. The modules of System X plug into each other to build up the exchange; anything from the simplest telephone switching system to machines more sophisticated than system designers can envisage at present. The PO plans to integrate telecom switching and transmission throughout Britain through the computers of System X.

System X was born of the dual demands of the world's third-largest telephone administration – over 23m. telephones in service, almost double the number a decade ago – and of a manufacturing industry seeking technology with export potential for a long time ahead. A decade of research in a dozen laboratories stands behind the technology. The PO itself has invested over $300m. in R&D and expects its final bill to exceed $400m. But the real strength of System X, says Desmond Pilcher, managing director of Plessey Telecommunications, lies in the fact that four very experienced development teams are pooling resources to develop the vital computer programs.

MILITARY TECHNOLOGY

Defense is a major industry in Britain. The nation spends 4.9 per cent of its gross national product on defense, a higher proportion than any NATO nation except the US. Total expenditure for the year 1980-81 is estimated at $19.lbn., of which $7.6bn. will be spent on equipment. Exports of defense equipment and associated services are expected to amount to $2.6bn.

Expenditure on defense R&D this year is estimated at $3.3bn. Britain has 12 defense research establishments devoted to major areas of technology such as nuclear weapons, electronic systems and aerospace. A significant trend is the rapidly increasing technical sophistication of the Army, with major systems under development such as Ptarmigan, a computer-controlled, fully-mobile battlefield communications system.

Nuclear Weapons

Early this year the government disclosed success with a $2bn. R,D&D project called Chevaline, a new nuclear weapon system for Britain's nuclear strategic force, the Polaris submarines. It is a nose cone which bristles with decoys to confound anti-ballistic missile (ABM) defenses and let the small number of real warheads get through. Chevaline has been under development at Aldermaston, the Atomic Weapons Research Establishment, since 1974. It is expected to enter service with Britain's four Polaris nuclear submarines in the early eighties.

The Ministry of Defense is building three major new facilities in support of an expanding nuclear defense program in the 1980s. One, commissioned this year, is a plant making tritium for thermonuclear weapons, designed and built by British Nuclear Fuels. Tritium for weapons has previously been purchased from the US. Another is BNFL's new plant for making highly enriched uranium-235 as fuel for its nuclear fleet of 16 submarines.The third is a new reactor for development and training, at HMS Vulcan, a naval research center in Scotland; the testbed for cores for submarine reactors the Navy is developing for service in the 1990s.

Combat Aircraft

The biggest single defense investment by Britain in the 1980s will be replacement of three existing aircraft – Vulcan, Buccaneer and Canberra – by the Tornado GR1 all-weather combat aircraft. Tornado is an Anglo-German-Italian joint venture. Over 800 are expected to be ordered by the three nations. At $22m a unit the Tornado GR1 combines a wide range of capabilities: strike, attack, reconnaissance and interdiction of supply lines and communications, and maritime strike/attack. An air defense version will enter service in the mid-eighties.

ACARD, the government's scientific advisers, has stressed repeatedly in its reports that Britain cannot hope to support advanced technologies on its domestic market. Derek Alun-Jones, managing director of Ferranti, believes the joint venture is the best mechanism for overcoming strongly nationalistic attitudes towards defense procurement. "There is no free market in high technology". Ferranti and GEC-Marconi dominate the provision of avionics for Tornado.

One outstanding all-British export success, however, is the Harrier "jump-jet" fighter, with its vectored-thrust engine; the world's only operational vertical take-off fighter. Export sales exceed $660m. The US is making it under license as the AV8-A for the US Marines. HMS Invincible, first of a new class of 20,000-ton anti-submarine carriers, is equipped with the Sea Harrier, a maritime version. The Ministry of Defense plans developments which will keep the Harrier "jump-jet" fighter in service until the end of the century.

Airborne Early Warning

One major project on which NATO failed to get full collaboration in the late-1970s was a new early warning system for air defense. Britain went ahead with its own airborne early warning (AEW), based on a Nimrod Mark 3 aircraft designed as an over-the-horizon radar station, circling the North Sea. Trials with the development aircraft – first of eleven – are planned for this year. They are the first purpose-built British AEW aircraft and will form Britain's contribution to the NATO AEW mixed force. For GEC-Marconi Avionics as prime contractor the over-riding challenge is the human factors problem of marrying computers and men efficiently enough to handle the flood of data from a large hemisphere of airspace. RSRE, the electronics research center of the Ministry of Defense, as special technical adviser on AEW procurement, is developing a computer model to test the system.

AEROSPACE ENGINEERING

Aerospace engineering in Britain is dominated by two big manufacturing groups brought into state ownership in the 1970s: British Aerospace, with sales of $2.3bn. last year, which designs and makes airframes, guided weapons and satellites; and Rolls-Royce with sales of $1.87bn. last year, mainly concerned with the development and manufacture of aero-engines. They are backed by Britain's biggest national laboratory, the Royal Aircraft Establishment (RAE), with its own fleet of 50 R&D aircraft, and a professional staff exceeding 2,000.

Both manufacturing groups are participants in major international collaborations in advanced technology, such as the European Airbus, the European Communications Satellite, and the European Spacelab to be flown by the US Space Shuttle. Dr. Austin Pearce, recruited this year from the oil industry as British Aerospace's new chairman, stresses the importance of "producing the competitive products which the customer wants to buy".

The corporation has seven civil aircraft either in production or, as in the case of Airbus, for which it makes a major part. It makes the high-technology wings for Airbus, of which 221 were sold last year, over 40 per cent of the world's wide-body airliner sales. It is joint partner with Aerospatiale in Concorde, the only supersonic airliner in scheduled airline service. It also has eight military aircraft in production, among them Tornado, two "jump jets" (Harrier and Sea Harrier), and the Nimrod flying radar station for airborne early warning.

Its Dynamics Group was prime contractor for Europe's first communications satellite, an R,D&D project called OTS, launched by NASA in 1979, and used successfully for TV conferences between Switzerland and Britain. This has led to eight further satellite orders – three for the European Communications Satellite system and five for MARECS, part of an international communications network for ships. Europe is helping to fund and to make the NASA Space Telescope and its solar arrays, in exchange for 15 per cent of the viewing time available from the instrument.

The RAE at Farnborough, famous for one of the world's great airshows, claims to have Europe's most advanced windtunnel among its $400m. investment in windtunnel facilities. The newly commissioned tunnel provides a new level of capability in aerospace design, says Mr. Rhys Probert, RAE's director. "We have great confidence that this tunnel can cut the development time of any aircraft".

Aero-engines

Rolls-Royce today is almost exclusively a maker of gas turbines – the famous car, for example, is made by a separate company, Rolls-Royce Motors – and expects to continue as a one-product company. Over 40 per cent of its sales are overseas. Aircraft gas turbines, its main business, demands a higher proportion of research and engineering resources of any established product except nuclear reactors. Rolls-Royce expects to spend over $500m. on "advanced engineering", the R,D&D of new engines, this year. It will be of the order of 20-25 per cent of sales. This figure includes a substantial expansion of "advanced development", as the company calls its R&D.

"For the first time in my life I'm in an industry where I'm damned if I know whether I'm competitive or not" says Sir Frank McFadzean, former Shell chairman who became Rolls-Royce's chairman this year. The company's civil and military businesses are entwined inextricably, McFadzean has found, with military engines accounting for just over half of sales last year.

Unlike his main US rivals, his dominant civil product is not a derivative of a military engine but a private venture. The RB.211 engine was developed originally for the Lockheed Tristar. The company is making about 60 a year but expects output to grow to 300 by 1983. By then the RB. 211 will account for almost all of the civil business. Judged then by the RB.211 McFadzean has no doubt that his company is "very competitive technologically". The best evidence comes from airlines flying the same aircraft powered by competing engines. Qantas saves 6-7 per cent of fuel – worth $1m. a year per aircraft – by flying RB.211 engines in its Boeing 747s, claims Alan Newton, director of engineering. Moreover, as the engine ages fuel consumption rises only half as fast as its rivals.

Two major derivatives of the RB.211, using the original engine core and its three-shaft configuration, will enter service in the early 1980s. One is the RB.211-535, destined for the Boeing 757, for which Boeing has suggested that Rolls-Royce could capture up to half of a forecasted market for 1,500 aircraft. The other is a bigger version of the RB.211-524, designed for 56,000lb. of thrust and destined for bigger Boeing 747s and wide-bodied twins.

Fuel consumption will remain a big target of engine development, says Newton. He believes the RB.211 can still be improved by as much as 15 per cent. One way is by better sealing and control of blade tip clearances. Newton believes this can now be done with microprocessors to give "active control" of the blading, continuously adjusting the clearances as engine conditions change, helped by a digital electronic fuel control system. In military engines, the company's unique contribution to western technology is the Pegasus engine, which provides short or vertical take-off (S/VTOL) through vectored thrust, in which the engine's exhaust gases can be swivelled through an angle of over 90 degrees.

TRANSPORT TECHNOLOGY

British Rail invented high-speed trains at a time when fuel was no problem. Nevertheless its advanced passenger train (APT) has turned out to be a most economical train, claims Ian Campbell, vice-chairman of Britain's state-owned railways and the engineer with special responsibility for introducing the "flying train" into passenger service this year. British Rail engineers at its Railway Technical Center at Derby have trimmed weight and drag substantially. Weight per passenger of the airframe-like aluminium structure is about half that of conventional trains.

The APT will enter service later this year on the 400-mile run between London and Glasgow. Its average speed will be about 100 mile/h. In trials the electrically powered train has reached 161 mile/h. but such speeds would be disruptive to a congested railway system. The whole rationale of the APT is an advanced train tailored to an existing investment in high-quality track and signalling. Above all it had to be able to take the frequent twists and turns of the track at high speeds.

APT was conceived in British Rail's laboratories. The seminal science lies in the way this team unravelled the physics of wheel-on-rail suspensions. The result is a revolutionary bogie design which prevents wear on the wheel flange as the train negotiates a bend. No longer is the wheelset banging from side to side, abrading the flanges. The APT can go round bends up to 50 per cent faster than other trains with no less margin of safety, says Campbell. The limiting factor is not safety but the degree of acceleration acceptable to the passenger. Another major innovation is APT's ability to tilt the passenger "so that he doesn't know that he's being tilted". A hydraulic tilt mechanism actuated by an accelerometer keeps the tilt axis close to the center of the coach (in contrast to the pendulum types of tilt mechanism). It tilts the coach up to 9 degrees to eliminate the side force on passengers at all steady speeds.

The electric APT is at the heart of a major investment program it hopes to undertake in the 1980s. "British Rail is convinced that the case for converting the nation's main public bulk transportation system to electric power is a strong one, making both economic and social sense", says Sir Peter Parker, its chairman. Electric trains are already cheaper than diesels to operate. Total primary energy input for rail traction, starting from coal mining or oil refiining, works out at least 25-30 per cent higher for diesel than for electric traction. As a start it wants to order about 60 APTs to re-equip the electrified spine of the network between London and Glasgow. But ideally it wants to electrify another 10,000 miles of track. In fact, Parker would like to go one step further in the 1980s and link the British and French national railways with a 31-mile tunnel beneath the English Channel carrying a single electrified track.

British Rail has no doubt that electric locomotives can now outperform their diesel counterparts in almost every respect. But in road transport the diesel is "about to enter a period of technological development more significant than any other since its inception", says Dr. Tony Jarrett, technical director of Lucas CAV. The big incentive is fuel economy. The key, he believes, is the microprocessor and the application of sophisticated electronic control and vehicle management systems of the kind his company is developing for the automobile diesel engine.

"The big advantage that electronics offers, apart from faster and more accurate response, is that they are not subject to wear themselves and can even compensate for wear in mechanical components in the total system". Lucas CAV is developing a system based on a "brainless" fuel distributor pump, which just raises fuel to injection pressure and delivers it, backed up by a microprocessor and sensors capable of measuring such factors as mass air flow. Jarrett forecasts success for his researchers by the mid-1980s.

BOOKS

Biographies of scientists, together with one related in the letters of Robert Oppenheimer

by Philip Morrison

ROBERT OPPENHEIMER: LETTERS AND RECOLLECTIONS, edited by Alice Kimball Smith and Charles Weiner. Harvard University Press ($20). DICTIONARY OF SCIENTIFIC BIOGRAPHY, editor-in-chief Charles Coulston Gillispie. Charles Scribner's Sons ($695). Myth has twice enfolded Robert Oppenheimer, first in the image of the awesome mushroom of our fears and then in the drama of the state's unpitying humiliation of the mind that had done the state some service. His human qualities now fade from living memory. His hopeful and admiring teachers, except for a couple of remarkable octogenarians, are gone; his fellow students are now the gray elders of physics; his own students and those he led are at the brink of retirement. But his many-sided talents and his luminous thought are still to be made out in this intimate, carefully documented, honest and affectionate book, a collection of 160 of his letters (and some exchanges) over 25 years, augmented by meticulous identification of allusions, by a good deal of later comment from Oppenheimer himself and by interviews with many correspondents and other contemporaries.

The senior author is the chief historian of the postwar political movement among the scientists and was a personal friend of Oppenheimer's since the 1940's; Professor Weiner is a historian of science whose special interest has been the growth of nuclear physics. To the vividness and variety of the letters they have brought a pervasive sense of order in growth. The celebrated events of Oppenheimer's public life, everything after the last war year, are treated in a few understanding pages of epilogue. This is no wartime or cold-war chronicle; it is the evocation of a remarkable life of science in our country between 1922 and 1945.

We meet Oppenheimer, after a useful introduction, in his first week as a Harvard freshman at 18, in the fall of 1922. He left Harvard three years later with a most irregular but steadily brilliant record, graduating in three years with an A.B. summa in chemistry, a deep love for which was fostered, out of his childhood delight in minerals and their variety, by his science teacher in his junior year of high school. Most of the college letters are written to another influential teacher, his high school English instructor and lifelong friend Herbert W. Smith. Wrote the playful sophomore to Mr. Smith: "I might string you out a lengthy miserere...how Jane has frozen, because it was rude to understand her dismal notes and unthinkable not to...how Jeffries and I miss each other with coy opacity;...how I have come lugubriously to the conclusion that the two people at Wellesley...that even pretend to pursue me are a sorry and worthless lot; how all that has driven me to whorls of stories and notes on the divgrad of an electrical field and French and merely English verses; and how, in a final catastrophe, I projected said verses toward you."

The years sped past around the Widener Library and weekends at Cape Ann, in gas analysis in the chemistry laboratory and in enriching experiences in class and out with Alfred North Whitehead, G. D. Birkhoff and particularly Percy Bridgman. A skilled sailor and no tyro at the laboratory bench, the young Oppenheimer found he was happier still with the thick books of Cambridge mathematical physics. Although he undertook a study of electrical conduction in rutile for Bridgman, he became convinced that "my genre, whatever it is, is not experimental science." Bridgman concurred; he wrote Ernest Rutherford that Oppenheimer had a brilliant record but that "his type of mind is analytical rather than physical." Somehow Oppenheimer reached the Cavendish, struggled bravely in the laboratory, then found his way through R. H. Fowler's good sense and kindness to theory, moving to Göttingen just as the forge of quantum mechanics glowed hot. By the spring of 1928 he had his Ph.D. and had made his mark. With Max Born as his mentor he could choose among offers. Born wrote to Julius Stratton at the Massachusetts Institute of Technology: "We have here a number of Americans.... One man is quite excellent, Mr. Oppenheimer." His vocation was fully in hand; his letters breathe it now in self-assurance, wide acquaintanceships and bubbling plans.

It is sobering to read that Bridgman, a man of perception and limpid integrity, felt compelled to write in 1925 to the Cavendish: "Oppenheimer is a Jew, but entirely without the usual qualifications of his race. He is a tall, well set-up young man, with a rather engaging diffidence of manner." This is about the time of the jacket photograph of this volume, a very youthful poet's gaze at the lens, with an artfully delicate melancholy.

Now times march swiftly. Oppenheimer has chosen to work in Berkeley, with a concurrent appointment in Pasadena. The letters go now mainly to the theorist George Uhlenbeck and to Robert's brother Frank, eight years his juior, himself on the way to a degree in experimental physics via Johns Hopkins and the Cavendish. The world tightens its coupling; the young professor himself becomes the generous focus of a California coterie of students and research associates. He forms close bonds with the experimenters, Ernest Lawrence at Berkeley, William Fowler and C. C. Lauritsen at Pasadena. Here the letters carry the reader into the flowering of modern physics in America. By the early 1930's the theorist's concerns acquire a still familiar tone: electron-positron pair theory, nuclear energy levels, troubles at high energy, cosmic-ray properties (is the meson radioactive?), even neutron stars.

The troubles of the world enter as well; a tithe is pledged to aid the "former colleagues" exiled from Germany, and we hear other echoes of a grievous decade. Literature, although never music, still consoles: "With books it is not so good, new ones. I have reread all Flaubert" and still older works, "the *Meghadhuta* and the *Timaeus*, reading them with a painful pedantry." Spanish and Dutch too were at his command. Only the Sanskrit would have seemed unusual in a well-traveled and cultivated European physicist; in America his fluency was extraordinary. Then the grave final motif sounds far away in January, 1939: "The U business is unbelievable. We first saw it in the papers, wired for more dope." The next week he wrote: "I think it not too improbable that a ten cm cube of uranium deuteride (one should have something to slow the neutrons without capturing them) might very well blow itself to hell."

In time it did, more or less, and took two cities with it. The next period is wartime, "these terrible years." The diffident youth has become the warm, trusted, prescient and tireless leader at 40. He accepts the requirement to form his laboratory under the Army, not under the civilian Office of Scientific Research and Development. "If I believed with you," he wrote to I. I. Rabi in 1943, "that this project was 'the culmination of three centuries of physics,' I should take a different stand. To me it is primarily the development in time of war of a military weapon of consequence, I do [not] think

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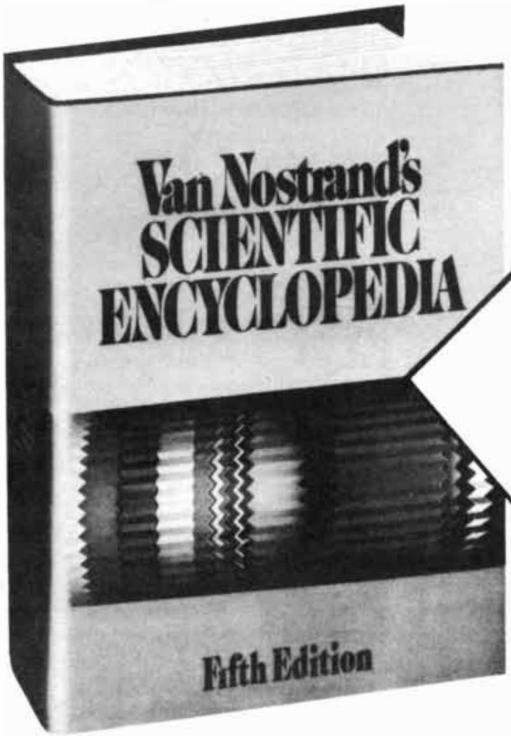

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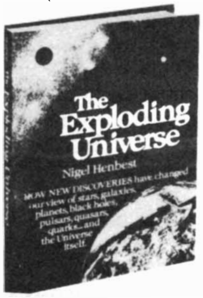

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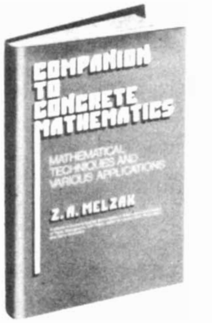

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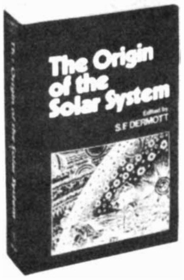

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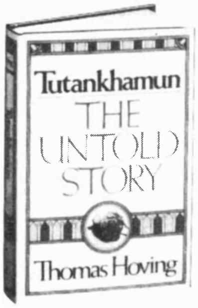

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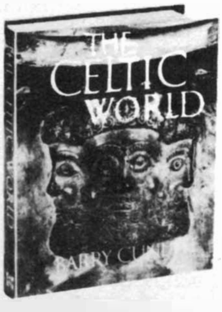

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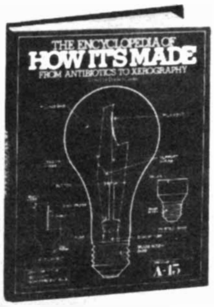

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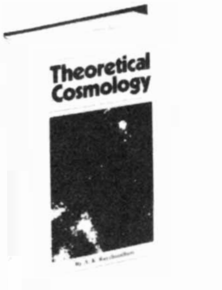

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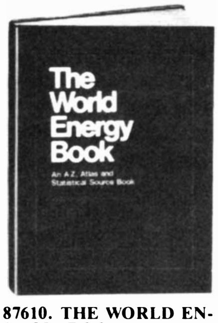

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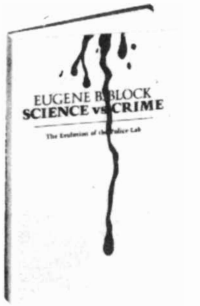

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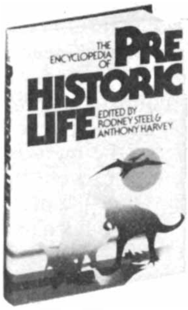

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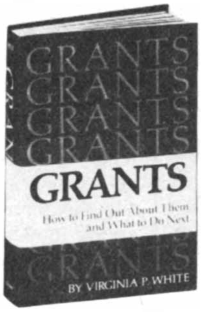

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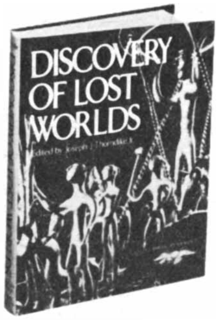

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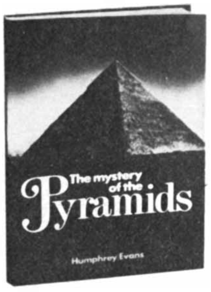

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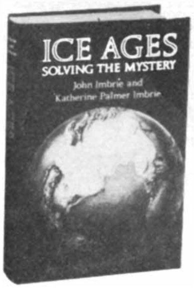

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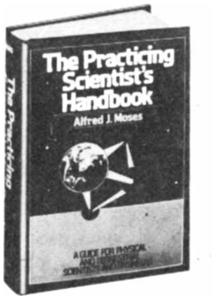

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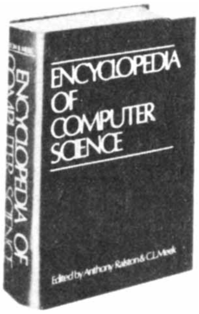

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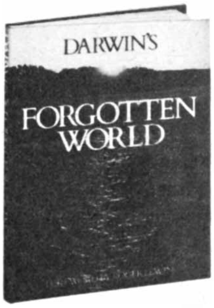

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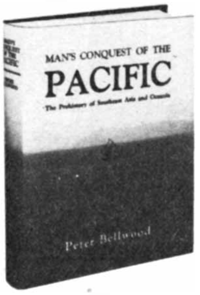

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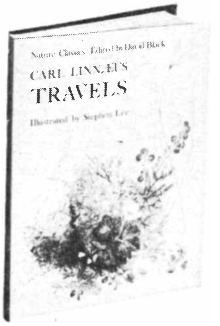

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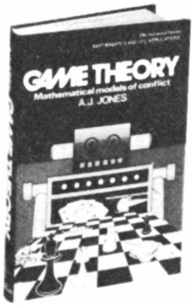

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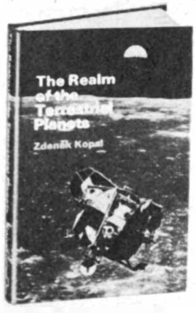

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that the Nazis allow us the option of not carrying out that development." (The only text, a carbon copy, omits the needed *not.*)

By April, 1945, the bomb is a few months from completion, as all believe. The Nazis are done for. At the memorial service for Franklin Roosevelt in the theater on the mesa, Oppenheimer spoke in elegy: "When, three days ago, the world had word of the death of President Roosevelt, many wept who are unaccustomed to tears, many men and women, little enough accustomed to prayer, prayed to God. Many of us looked with deep trouble to the future; many of us felt less certain that our works would be to a good end; all of us were reminded of how precious a thing human greatness is."

So is one reminded on reading this book, rich in the texture of feeling and idea, a bright but erratic beam into shifting components of a mind of power and intricacy and on a world in which ever forking paths of choice have brought us to 1980. We still drift downstream from an accurate fix Oppenheimer took for us 18 years ago: "We are in an arms race of quite unparalleled deadliness—I think this is not the place to speak about the amount of devilment that is piled up on both sides...; on the other hand, we have lived sixteen and a half years without nuclear war. In the balance between the very great gravity of the risks we face and the obvious restraints that have seen us through this time, I have no counsel except that of sobriety and some hope." (The passage is not from the book but from a lecture at McMaster University.) The final published scientific paper of Robert Oppenheimer, on a radiation mechanism in algal photosynthesis, appeared in 1950; his travail began in 1953. He died at his home in Princeton on February 18, 1967, after a final year's struggle with a malignant throat tumor, during which he was determined "to maintain as long as possible his connection with physics... and communication with his friends."

Dictionary of Scientific Biography, the second work reviewed here, is at once closely analogous and entirely distinct. It is in some way a grand extension of the notion of the biography of a scientist, but on a scale so large as to lose most, although not all, of the quality of the volume directly on and by Oppenheimer. The fruit of a decade's work by a thousand scholars from almost a hundred countries, it presents a summary of the scientific lives of a selection of the men and women who have made world science, in all its branches, from antiquity to the present, albeit excluding all living scientists. The first volumes appeared in 1970 and were reviewed in these columns in March, 1971. The work is now complete: 14 of its volumes offer an alphabetical array of biographical articles, from Pierre Abailard to Johann Zwelfer. Volume 15 for about half of its pages adds a small supplementary alphabet, pieces for some reason delayed past their proper time of issue; its latter half offers a set of expert topical essays on periods in science without easy biographical attribution: mathematics in Egypt, mathematical astronomy in India, our understanding of Maya calendars and computation, and a couple of others. Volume 16 is a useful overall index, in which the 5,000 biographies are set in a much larger context of entries, from the A.A.A.S. and the abacus to zymohexase. The entire work is 10,000 pages long, a heavy three-foot shelf. A general reader will hardly read it all, nor did this reviewer.

The authority and scholarship of the work is beyond doubt. An entire Sanhedrin of boards and consultants assures us, and the signatures on the pieces bear the names of the best historiographers. Since so many subjects belong to this century, many of the accounts are the work of colleagues, even friends of the person described. Most such pieces are the product of reflective working scientists who take up rather gracefully the stylus of Clio. In fact, with striking exceptions, a general reader is likely to gain more comprehension from these somewhat less professional articles than from the others. Partly this represents the sense of historical proximity, but it arises also from the pervasive method of the text, a style much closer to the scholar's lamp than to the scientist's bench. The authors all work, as scholarship demands, directly from the sources, which they list and categorize carefully. But they give the reader little evidence, not even many equations, almost never citing the phrases or reproducing the data, the graphs, the drawings and the photographs that were the work they describe. It is mainly brought to us secondhand; *totus in verba.* Even diagrams are few; it is a real pleasure to see the annotated facsimile of the Dresden Codex or a photograph of the zodiacal ceiling at Dendera with a careful key. Although the quasi-archaeological articles offer evidence freely, the others rarely do.

To read of the thought of Niels Bohr at the hand of his colleague Leon Rosenfeld, or of Desmond Bernal in a moving account by C. P. Snow, is the unforgettable best of the work. Our careless tendency to neglect Europe past the Elbe is wonderfully countered by an entire battery of articulate scholars from the U.S.S.R. and from other lands of eastern Europe. The brief piece on Aleksandr A. Friedmann, Leningrad master of fluid dynamics, who first set Einstein and the world straight on the expanding relativistic cosmology, is most welcome; we all believe in Friedmann's universe, but we know little of his life. The science of China is left in general to more specialized works, but a few articles on key figures are presented. The essay on the

Sung polymath Shen Kua, who left us so much understanding of the compass and printing, chemistry and astronomy, in a few compact pages of apparently casual comments, is a tour de force of appraisal in a very wide cultural context. (It is by Nathan Sivin.)

Five thousand names are a lot, but still a few are missing. One can find Georges Sagnac, who carefully led light rays still in phase around a circle, but one looks in vain for Cipriano Targioni, who consumed the prince's diamond with a burning glass in Florence long ago. Yet the overall choice is wide and wise. The length of the articles is not under much control: Newton gets the full treatment; Darwin's biography, although expert, is rather brief. Pasteur has a few more pages than even Newton draws and Laplace fills twice as many (60 times the average), the careful work of the editor-in-chief, with some help from his friends. The Laplace article—a small book—is about the most elaborate mathematically; Lagrange, in contrast, does not earn a single integral sign. The contributors have plainly taken over. The entire dish is bulky, nutritious, rather dry, doubtless very good for you and your library; here and there you can pull out a delicious plum. Our assessment of 1971 seems to stand: a tenth of the pages opened to direct citations and to visual matter might have doubled the value of a work that will nonetheless stand as a lasting contribution to the world of scholarly books.

THE ECOLOGY OF VISION, by J. N. Lythgoe. Oxford University Press ($57.20). Looking upward from the underwater world on an exceptionally calm day, a circular clear spot, Snell's window, opens to view. Through it the entire hemisphere above is seen compressed. That window is framed with a reflection of the watery half space below, in this book the green shallows of a mangrove swamp. Whenever the surface is roughened by wind and wave, the darker and the brighter worlds are fragmented and jumbled together. The sun, always high in the watery sky, sends dancing rays down into the water, beams focused by the small-scale ripples into the top meter of water, by the larger ones down 10 meters or more. At 40 meters the sun is softened by the summed absorption and scatter.

The clearest lakes share the deep Mediterranean blue; it is the yellow stuff from the land and the phytoplankton that runoff helps to nourish that provide the greens and the brown-yellows of many natural waters. All of this is made convincing, even quantitative, by the careful graphs and tables of this expert monograph, supported by admirable color photographs taken on the scene in Aldabra lagoon or along the coasts of England. Fine black-and-white photographs display the polarization of sky light on a blue cloudless day, to induce empathy for the polarimetric bees.

Thus the first chapter of this work by a physically oriented marine zoologist of Bristol lays out the environment of natural light: the sun, the moon and the stars, on land, in fresh water and in salt. Most of the work cited is the latest take, in the past decade or so. Then the view shifts. One looks at the receiver: the direction, intensity and wavelength discriminators as a function of the eye. We read of lens eyes and of compound eyes (two types), and we learn of sensitive pigments and their intricate disposition. The eye is somehow poised between reception and transmission. The tapetum—the light-reflecting base under the light-sensitive layers—is the cause of the shining red eyes of an animal caught in a headlight beam. But the shy Norway lobster, which has extended its range toward the too bright surface by living in holes in the soft bottom mud, emerges only at times of subdued light. Its clear golden orange eye glow, shared with certain night-flying moths, is destroyed by light. The colored substance decays in bright light, and the tapetal surface itself is disorganized by any light brighter than midday seen 30 meters down.

On this secure foundation of physics the book builds a discussion of four special visual environments, each one a challenge to the evolutionary engineering process. Sometimes sheer intensity is limiting: there is not enough light to see by. Sometimes it is the turbid medium that hurts, with all contrasts degraded by the unwanted scattering. Foliage-green and sky-blue, and the varieties of color under water, are a distinct and by no means rare problem for the organs of color vision. Finally there is directional light distribution. What are the visual fields of interest? ("A large predator armed in tooth and claw is unlikely to share the same visual preoccupations as a grazing rodent.") Each circumstance is given a chapter, with some account of life forms and their design schemes.

The microstructure of visual systems finds fascinating interpretation. Birds fly mainly by day; they depend with keen eyes on light. Fast-moving images—the world casts only fleeting forms on the retina of a swift flier—are difficult in dim light: there are simply not enough photons to map the world quickly. (A photograph shows a playground scene in adequate light and then again through a dense filter. The well-exposed photograph shows a cheerful child caught in the arc of a swing, but the dim one shows only the stationary mother; the moving swing and the child have vanished into noise.) One night bird, the tawny owl, has been specially studied. Its eyes are tubular, with a fine low *f* number, like an expensive camera. The tiny colored oil droplets in the retina that act as cone-by-cone color filters in most birds are so rare in the owl's eye that some microscopists report none are there. All of this gains the owl about one *f* stop. The owl hunts so well at night only because it can hear so well, with special acoustic directional acuity. To understand the owl one must take into account both its vision and its hearing.

Yellow filters always go with diurnal life. They are universally present in day-active terrestrial vertebrates and almost completely absent in night-active animals. Some fishes have such a filter pigment that goes away in darkness. Most of the yellow filters, however, cannot be removed. The filter acts against the veiling effects of the bluish light most scattered by the air, the bluish light also scattered within the eye and the blue fluorescence of the filtering lens itself in the sun's ultraviolet. It may be that the protection of photosensitive materials against the damaging blue and ultraviolet is the chief purpose of this piece of living optical equipment.

The cellular texture of retinas reflects their specialization for directional acuity. In man the fovea, where his visual field has its best resolution, is circular. The cheetah (like most of its prey species) has a horizontal streak in its retina where the density of the cells is several times the average. Such an animal sees very well out of the corner of its eye. Many birds have two foveas, one for the monocular field of each eye and the other for the forward binocular overlap. Birds of prey have both the twin foveas and a streak joining them. There is still much to figure out.

A final chapter takes a brief look at some still more complex designs: advertisement and camouflage. Puzzles abound, but some results are most satisfying, if less than certain. It seems likely that the earliest flowering plants, with those early blossom commercials, were pollinated by beetles. Only that insect group, among all those able to fold their wings like the planes on the old aircraft carriers, was well developed when the flowers arrived. Modern plants with primitive flower features are still almost invariably beetle-visited. Such flowers are flat bowls with spiral floral parts. The beetles were attracted to pollen; nectar came later with the newly tubular flowers, whose petals are fused to hold and defend the sugary bonus.

Pollen is still mostly for the insects; larger seeds require vertebrate transport and offer fruit. The pollen-heavy flowers first advertised, however, by central blackness; pollen simply does not reflect in the ultraviolet, where most insect eyes work well. A photograph shows a buttercup, a blandly yellow disk to human eyes and to eye-matched photographic emulsions but marked with a big, shaggy black center to the ultraviolet-passing filter—a hyperbolic promise of protein. Coevolution now joins flowers to human art and artifice, but in those more stochastic epochs it was the in-

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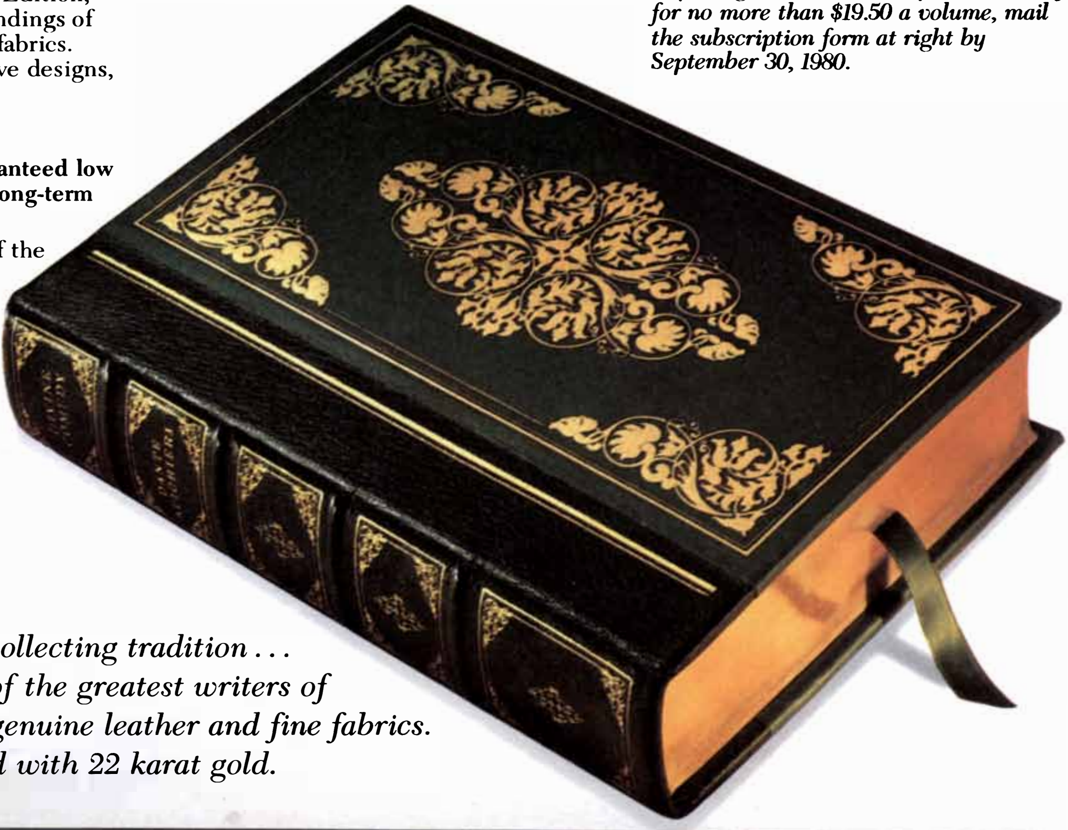

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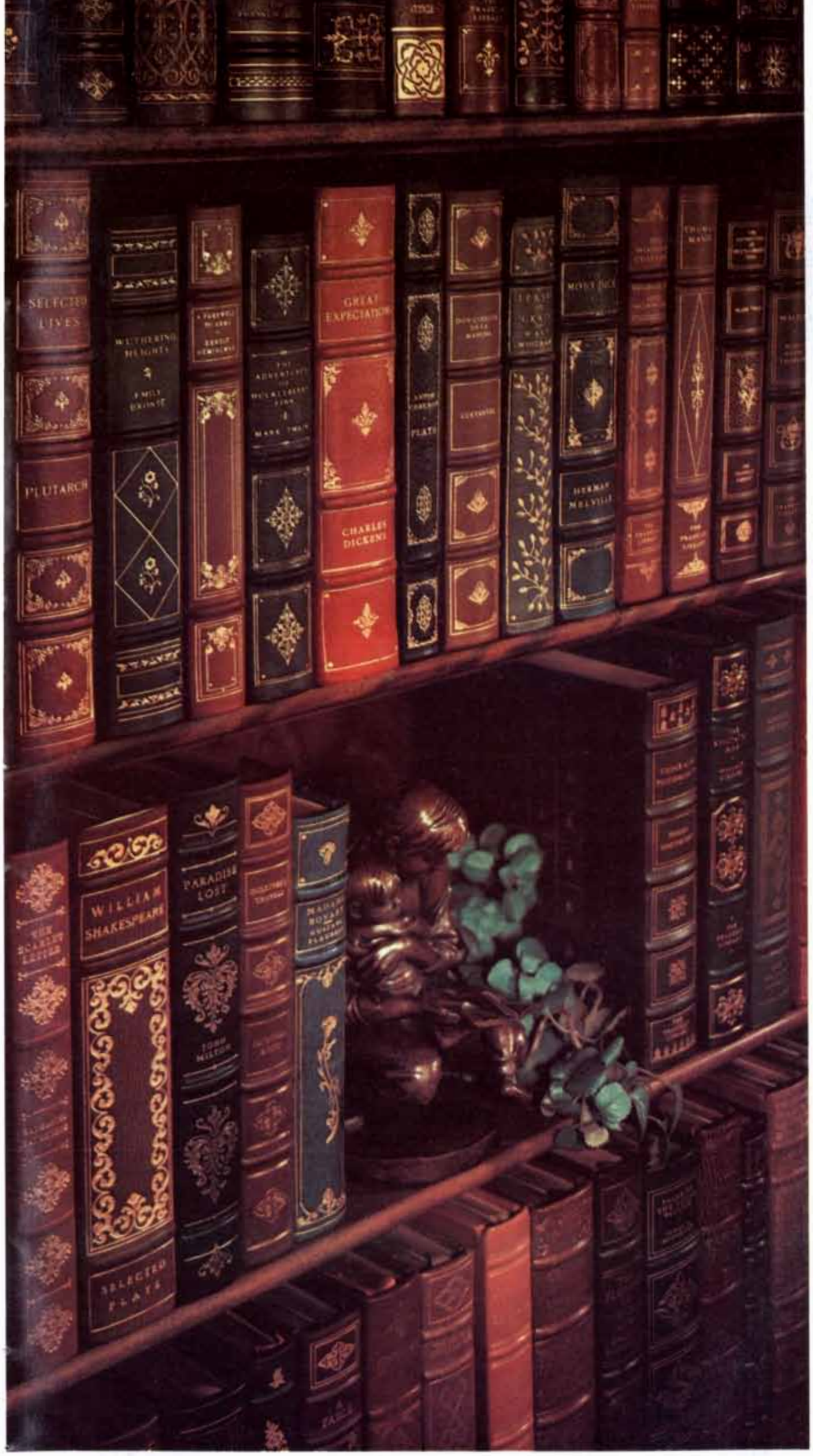

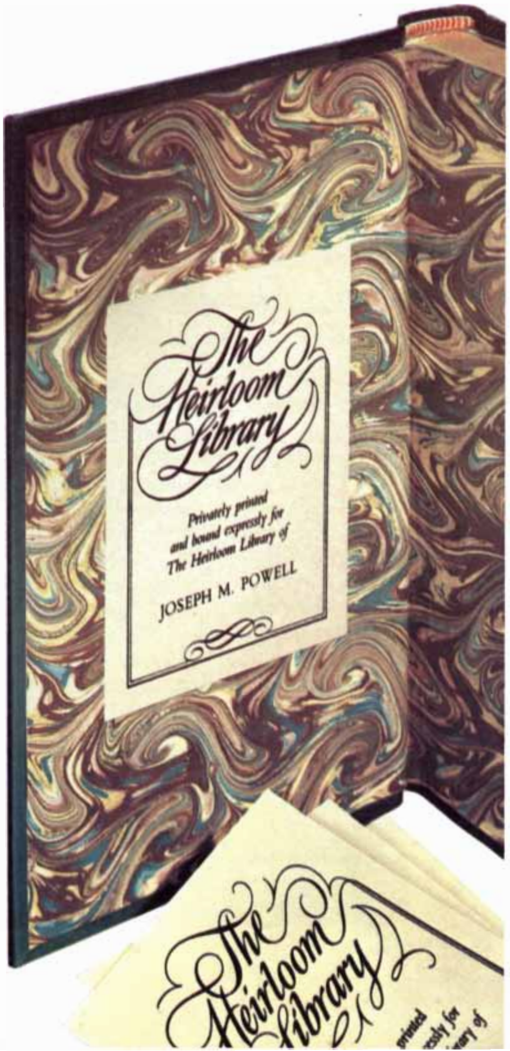

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sect and the blossom that evolved slowly together.

This book is an excellent, if expensive, summary of the optical engineering at work in life. One cannot help noting a contrast between its detailed and quantitative account of the physics of light in nature and the perforce qualitative and tentative application to the steps of the intricate evolutionary history. Both the general reader and the entrant to research will be served and pleased by Dr. Lythgoe's compact and integrating presentation.

AURORA BOREALIS: THE AMAZING NORTHERN LIGHTS, by S.-I. Akasofu. The Alaska Geographic Society, Box 4-EEE, Anchorage, Alaska 99509 ($7.95). Let the enthusiasts of our biggest state brag a bit, but of course the aurora is not all northern. Geophysics professor Akasofu, himself a worthy object of local pride, demonstrates it clearly in this richly illustrated popular paperbound monograph. Two all-sky photographs made from high-flying jets, one aloft over Alaska, the other shooting at the same moment well south of New Zealand, caught similar bands of glow, the two polar auroras. And a shot from the moon shows them both at once! Most witnesses to the phenomenon are in fact northerners; the other polar cap is too thinly peopled.

Nearly a score of pages of color photographs document the form and color of the aurora. Modern representations are not all we see. The finest pictures here are the bold, simple, evocative woodcuts done by Fridtjof Nansen from his ship *Fram*, lying in the pack ice, framed by the "great curl of the aurora borealis." We see diagrams, rockets, time-lapse sequences, old engravings, and we read the rhapsodic lines of M. V. Lomonosov and the tales recorded by Knud Rasmussen. Our author is no less a connoisseur and a collector than he is an analyst; he offers fantastic 16th-century broadsides and the medieval Norse sagas to enrich his story.

Perhaps the clearest account is that of the forms of the aurora. By photograph and diagram (with a wonderful 1975 sketch of an auroral curtain hung halfway around the world drawn by cosmonaut Vitalii Sevastyanov aloft in *Salyut 4*) we come to see the nature of the pattern, a glow found in circumpolar oval, its base 100 kilometers high, of variable height over the base. Sometimes it is a single curving drape, although often the drape is much folded, even doubled. It hangs in a gentle vertical arc along the lines of magnetic field, and perspective and viewpoint can give it the form of a crown of rays or of a high wall in the northern sky. The colors are also clear; it was the Norwegian spectroscopist Anders Ångström (his period photograph is here, in the manner of a serious figure out of Ibsen) who showed the aurora had a gaseous line spectrum back in 1868. The blood red sky shown here glimpsed through an Alaskan radio dish "makes it easy to understand" medieval fears of the rare event, which in our time we put down to the forbidden line of atomic oxygen at very low density.

A nontechnical account of origins is given, with diagrams and analogies. The kilovolt electrons that excite the atomic glows are a current flow down the tubular surface of a bundle of magnetic lines into the atmosphere. That current is generated by the field gradients set up in the cometlike magnetotail of the earth by the active solar wind blowing by. Down the magnetic lines, but not across them, the electrons easily flow; a transverse charged plasma sheet that arises from the swept-out magnetic field, receiving positive charge on the morning side, negative toward the evening, drives the current. The transient, wavelike, rather systematic time course of the process is still unclear in many ways. The entire structure is of course earth-size, yet the total power involved has only the same order of magnitude as the generation of electric power by man.

A final page gives hints on photography; it will not be easy to match the selected images of this agreeable floppy-paged book. The spring and fall of 1981 and 1982 are likely times for spectacular auroras; be on the watch. Keep your ears alert too. There is a persistent belief that a strong aurora can be heard to swish and crackle. The instruments record no such sounds. There are, however, strong acoustic waves generated at subaudible frequencies. Perhaps that energy induces sound sometimes, by a nonlinear response in the ear (even in snow nearby?).

AGRICULTURAL ENERGETICS, by Richard C. Fluck and C. Direlle Baird. Avi Publishing Company, Inc., P.O. Box 831, Westport, Conn. 06880 ($19). In the sweat of his face doth man eat bread, and nowadays in the flow of his wells in addition. This modestly presented brief book is an introductory text for students "from many disciplines" and a valuable and accessible reference for readers at large. It summarizes and organizes the flood of recent studies, mostly from the journals and a few well-known treatises. The book seeks to assess and explain the various energy flows within agriculture in quantitative but simple terms. Here after all is the chief and central use of solar energy to date: the U.S. food system is a vast scheme for making available current solar income by a drawing down of solar capital stores (mainly petroleum and natural gas).

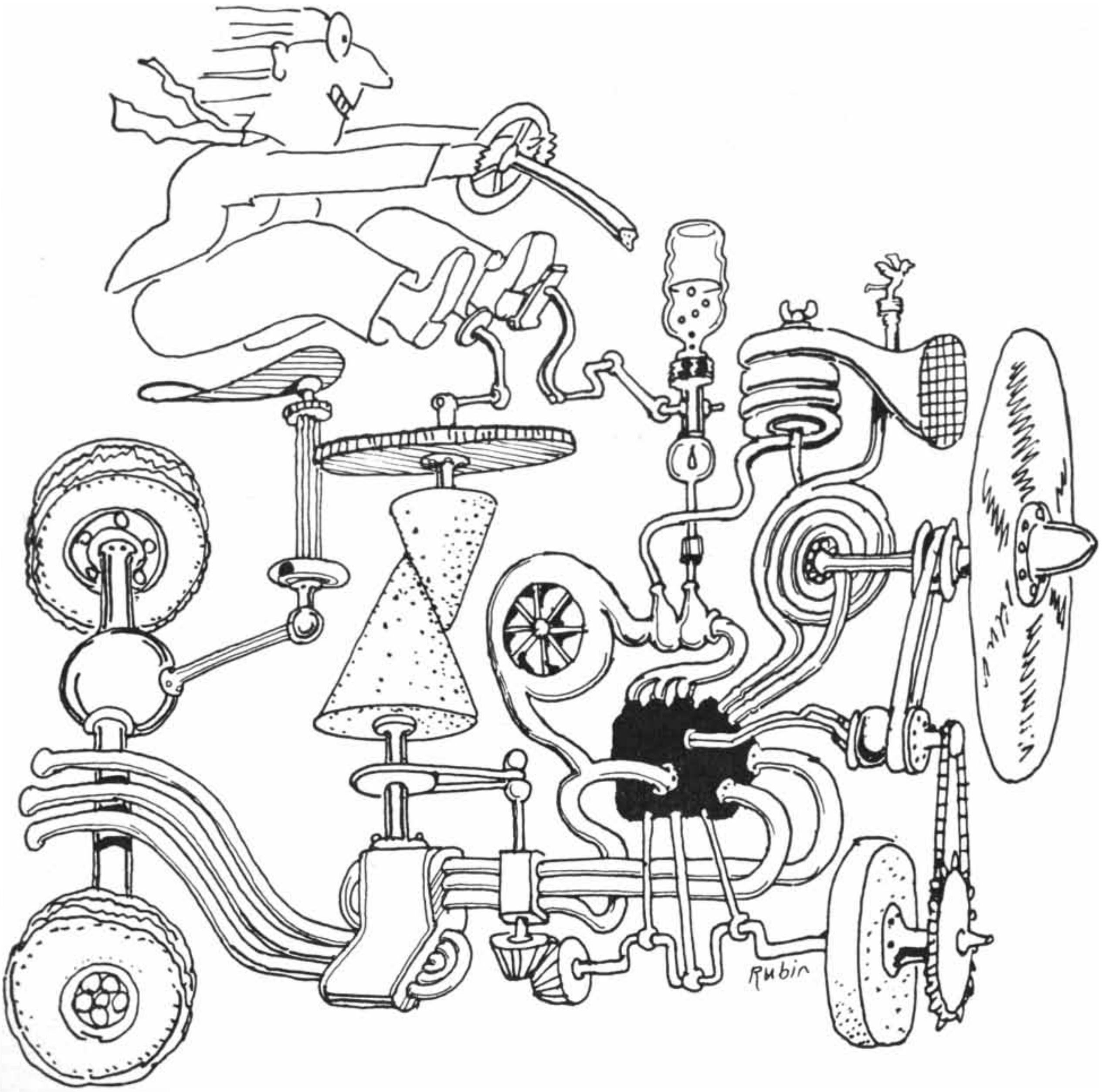
The net energy efficacy of this procedure is no easy number to fix; energy accountancy has its conventions and schools. They are discussed here with some care, although not always reconciled. It is obvious that the U.S. style of food production is costly in solar capital compared with the almost strict annual-income base of the foraging peoples. Even in the appraisal of simple shifting cultivation, however, it is of the first importance to decide whether or not to count the solar capital spent in clearing forest lands by burning them. That single decision changes the net energy yield by nearly three powers of 10!

Ten brief chapters treat of energy use in nonindustrial and in industrialized agriculture, the various bases for assessment, the economic meaning of these inputs and aggregations and the variety of inputs U.S. agriculture needs, from the leading single farm use (the consumption of natural gas to allow the fixation of nitrogen as fertilizer) through irrigation, transport field operations, crop drying, pesticides and frost protection. Specific practices, such as limited tillage, new energy sources and the larger future, are looked at honestly if somewhat sketchily, with useful, often unexpected, data. A few of the data are worth sampling: the chief energy use in the U.S. food system is well off the farm, in the category of indirect manufacturing, with our in-home food preparation a close second.

Man is everywhere a cooking species. Six villages ("vignettes of Third World agriculture") varied over a factor of five in energy efficiency (food energy/total input); the most efficient of them was an unirrigated subsistence village in Tanzania, without draft animals. Heated northern greenhouses are poor energy competitors to long-range trucking of U.S. winter crops from Dade County or Sinaloa up to the Northeast. Even solar greenhouses would appear to lose out in a straight energy competition, but these numbers should be taken as preliminary. One paper lists the energy productivity for a serving of mashed potatoes, over 10 different preparation modes, from fresh through microwave-dried to frozen. Frozen food is typically high in energy cost, but the result is crucially dependent on the time allowed for storage. It seems plain that the future will see more energy overall fed into the world food system; there are too many hungry people to avoid that change. There will be less energy for lesser uses.

The many figures and tables are full of interest; it is a small pleasure, with perhaps a touch of disappointment, to note that several of the most vivid diagrams have been taken from the pages of this magazine. The authors have taught the contents of their volume in the department of agricultural engineering at the University of Florida for five years. Theirs is a provocative book that deserves wide reading; it does not attempt to settle all the robust and urgent issues it lays out. The bibliographies chapter by chapter are a survey of a most varied and by no means mature research literature.

Imagine an engine as powerful as eight cylinders but as thrifty as six.



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The Changing Demography of the Central City

Since World War II the suburbs and exurbs of most U.S. cities have grown faster than the cities themselves. Today the decline of population in the central cities is not relative but absolute

by George Sternlieb and James W. Hughes

A term that has been applied to describe what has happened to many metropolitan areas of the U.S. since World War II is "doughnut complex." In many places the hole in the doughnut is a decaying central city and the ring is a prosperous and growing suburban and exurban region. In a few major municipalities such as New York the hole is a core area of the city that is being revitalized and the ring is a surrounding part of the city that is becoming increasingly blighted; the central-city doughnut is surrounded by the usual prosperous suburban area.

The question of what to do about the decay of central cities or major parts of them has occupied the attention of local, state and Federal officials and of specialists in urban planning. Policies such as urban renewal, subsidized housing and aid to mass transit have been tried to a limited degree and with limited success. Some observers see "gentrification" and the possibility of chronic gasoline shortages as forces that might revivify the central cities. Gentrification is the refurbishing of central-city neighborhoods such as Brooklyn Heights in New York and Georgetown in Washington by people who are well educated and well-to-do. It certainly has affected parts of some cities, but the statistics show that it is a minuscule trend compared with the other forces affecting cities. Whether severe and chronic gasoline shortages would impel a large back-to-the-city movement remains to be seen, although in a strongly automobile-oriented society other alternatives seem likelier. Our purpose here is to examine the statistics that reflect the position of the cities and to consider what might be done about the doughnut-complex phenomenon.

The data assembled by the Census Bureau show three major trends affecting the cities. The first trend, which has been in progress for many years, is a movement of population out of the central cities and into the suburbs. The second trend represents a phenomenon that materialized during the past decade. Until about 1970 the historical pattern was that metropolitan areas were the fastest-growing parts of the country and that the general flow of population was from the farm to major urban concentrations, that is, from nonmetropolitan areas to metropolitan ones. The new dynamic is that the nonmetropolitan areas are growing the fastest. The third trend, which accelerated during the 1970's, is the shift to what is sometimes called the Sun Belt; it entails in particular the movement of large numbers of people from the northeastern and north-central regions of the country to the southwestern and western regions.

The simplest and most basic fact is the contraction of the central cities. Their share of the nation's population was 31.5 percent in 1970 and 28.2 percent in 1977. The decline was not simply a consequence of the rapid growth of suburban and nonmetropolitan regions; for the first time it also reflected an absolute decline in the population of central cities. Over the eight-year period the aggregate loss by all central cities was nearly 2.9 million people, or 4.6 percent of the central-city population in 1970. Most of the losses were suffered by the central cities in metropolitan areas with a population of a million or more—the classic monuments to an urban industrialized society.

The growth of the metropolitan suburbs and of nonmetropolitan regions stands in contrast to the decline of the cities. By 1977 the suburbs and nonmetropolitan regions accounted for 71.8 percent of the population. Almost 153 million of the nation's 213 million people lived outside urban core areas.

The trend has persisted in spite of the sharp rise in energy costs starting in 1974. The census data on the migration to and from central cities between 1975 and 1978 show a net outward movement of 751,000 husband-wife families, which was almost 10 percent of the total number of such families living in central municipalities in 1978. In the more affluent subset (with annual incomes of $15,000 or more) three central-city families migrated to the suburbs for every family that went the other way.

The decade of the 1960's was the one in which the relative concentration of the U.S. population in metropolitan areas probably reached its peak. Metropolitan areas grew by an average of 1.6 percent per year, nonmetropolitan counties by .4 percent. Moreover, the nonmetropolitan counties that grew the most rapidly were mainly the ones closest to metropolitan areas.

A distinct change in the trend appears when one examines the data for the period from 1970 through 1977. Nonmetropolitan counties grew at an annual rate of 1.2 percent, metropolitan areas at .7 percent. The largest metropolitan areas (population three million or more) grew the least (.1 percent). And although counties with the highest incidence of commuting to more concentrated areas were at the forefront of the nonmetropolitan resurgence, their growth rates were nearly matched by nonmetropolitan counties that are not contiguous to metropolitan areas. Even nonmetropolitan counties in which fewer than 3 percent of the employed people commute to metropolitan areas grew at 10 times the rate of the previous decade.

To some extent the growth of nonmetropolitan areas can be attributed to what is usually termed exurbanization. This process can be viewed as a continuation of the dispersal from the central city, first to the suburbs and later to more peripheral areas. The growth of communities associated with mining and other energy-related activities is a contributing factor, and so is the development of retirement communities.

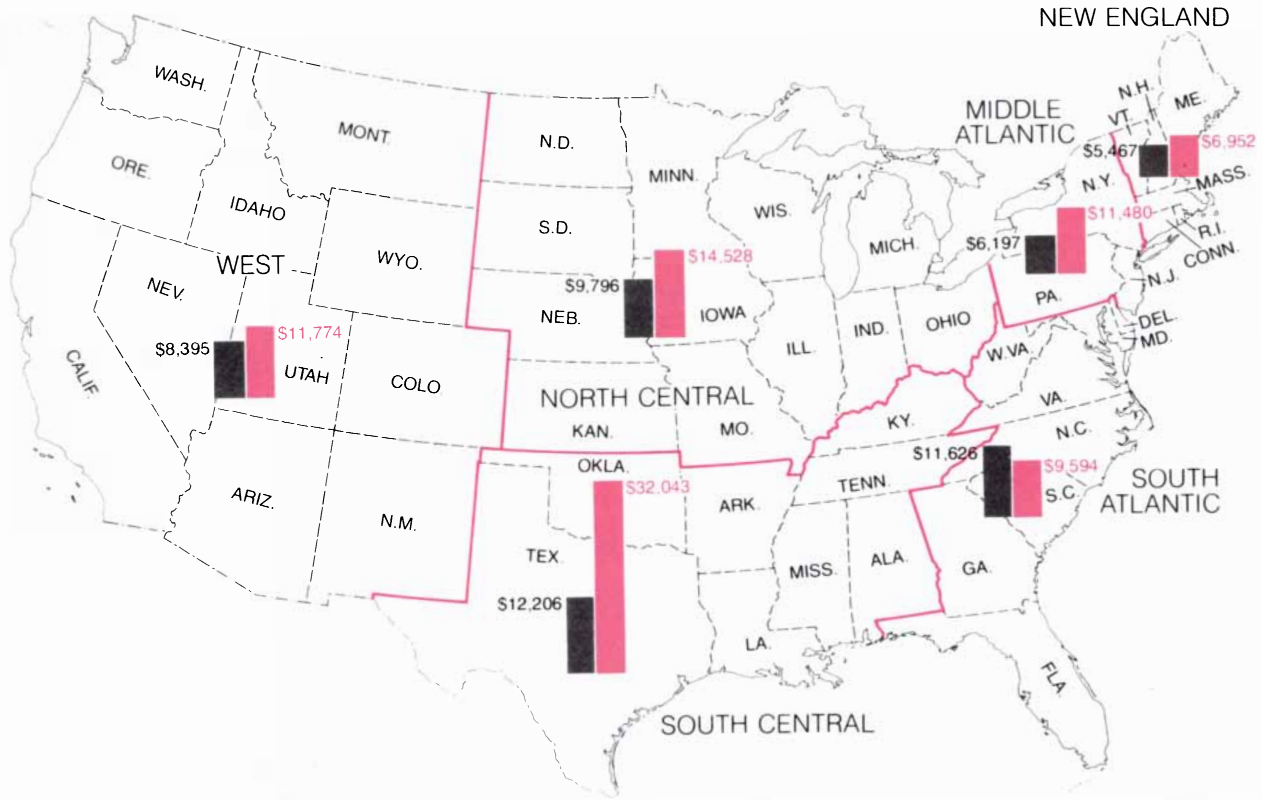
The changing function of the central city must also be taken into account. The major cities of the U.S. were once mainly centers of manufacturing. In contrast the centers of government and administration were often rather obscure, as is shown by the fact that the capitals of New York, Pennsylvania and Illinois are respectively Albany, Harrisburg and Springfield rather than New York, Philadelphia and Chicago.

The industrial city provided a unique focal point for the agglomeration of manufacturing operations. It was the only place that could supply groups of workers with a diversity of skills for the emergence of mass production after the Civil War. Even as late as 1950 almost a third of the work force in New York City was employed in manufacturing. Some of the newer cities of the early industrial era—Birmingham, Pittsburgh and Youngstown, for example—were even more heavily committed to manufacturing. It is the smokestack cities of this type that have been hit hardest in recent years.

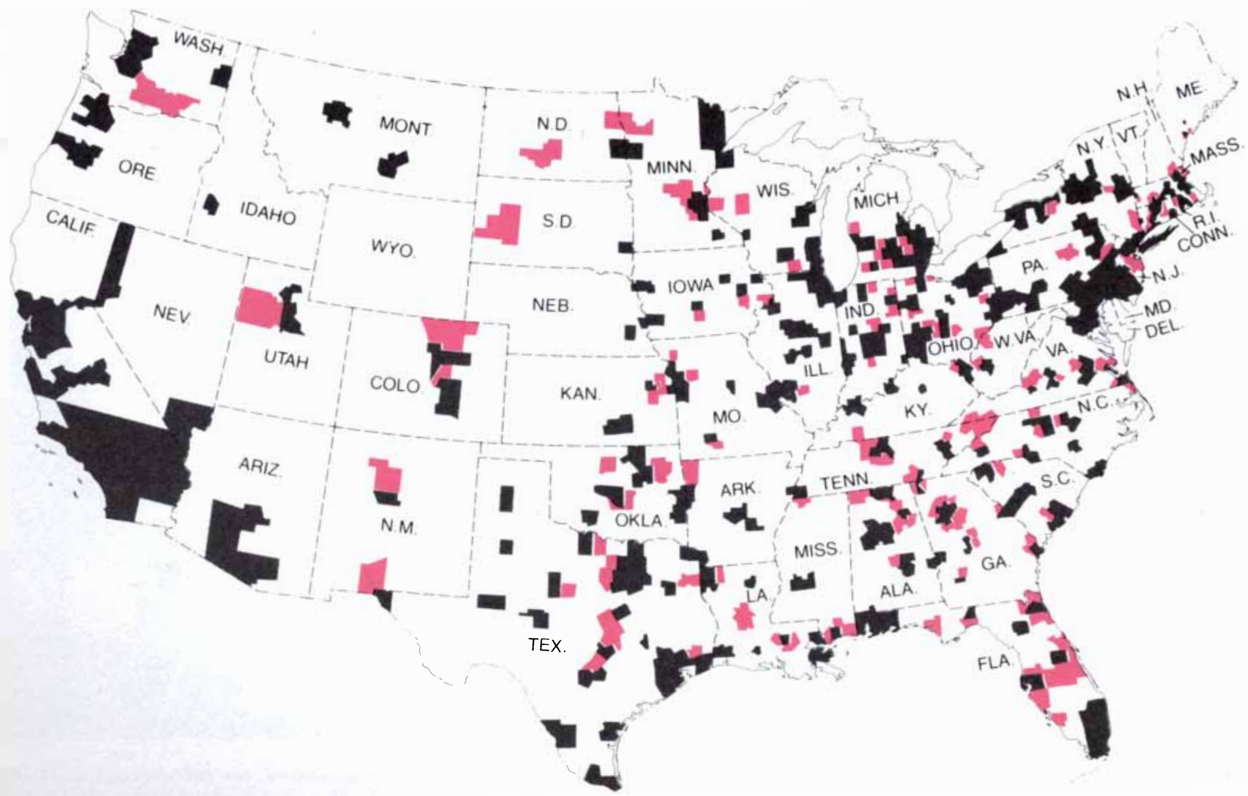
One great change is in the city's role as a source of jobs. In the past there was a synergistic relation between the waves of immigrants, who brought with them little but the cheapness of their labor, and the growth of manufacturing in the industrial cities. The entry-level jobs of yesteryear were not those originating with public policy, as many are today under such Federal programs as the Comprehensive Employment and Training Act (CETA) of 1973 and the national youth-employment program, but rather those of the garment trades, of iron and steel manufacturing and of many other fabricating activities, all situated close to their prime input: cheap labor. The jobs were commonly tedious, sometimes unhealthful and nearly always low-paying, but at a time when the movement from farm to city was taking place at an increasing rate the alternatives were worse. The cities of the U.S. grew because they had jobs to offer.

Today the city is bypassed by the new

"DOUGHNUT STRUCTURE" that has developed in many U.S. cities since World War II is evident in this photograph of a display generated by a computer. The display shows the percent of families below the poverty level in Newark, N.J., on the basis of data from the census of 1970. The number of poor families is largest in the downtown area, which is the hole in the doughnut; the number of poor families diminishes as one approaches the outskirts (the ring). Data for the display were stored in the computer by the Domestic Information Display System, a recently established service of the U.S. Department of Commerce and the National Aeronautics and Space Administration. The bounded areas are census tracts, small areas into which large cities and adjacent sections are divided for statistical purposes.



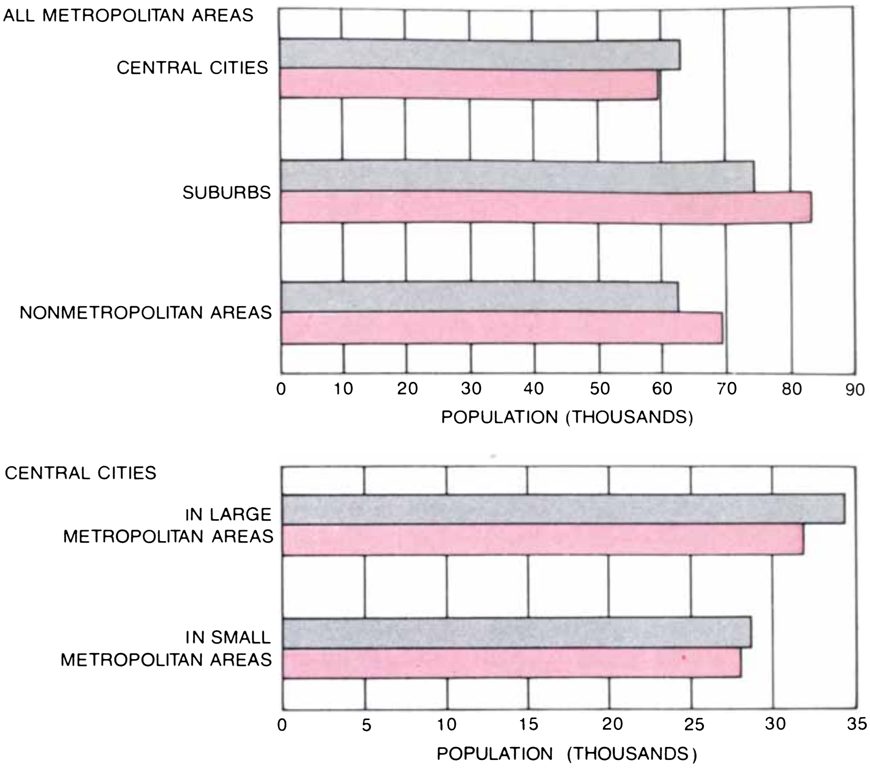
DECLINE OF MANUFACTURING is a major reason for the decay of many urban core areas. In each of the six regions shown on this map the bar on the left represents the average capital investment in manufacturing industries per production worker in the central cities of the region and the bar on the right represents the same data for the surrounding urban counties. As manufacturing and the jobs associated with it move outward, a number of service jobs are moved also and the urban core area loses both population and economic strength.



STANDARD METROPOLITAN STATISTICAL AREAS of the U.S. are shown as they were designated by the Bureau of the Census for 1970 (*gray*) and with the additions or revisions made in 1979 (*color*). Except in New England a standard metropolitan statistical area is a county or a group of counties including at least one city with 50,000 inhabitants or more or "twin cities" with a combined population of at least 50,000. In New England the standard metropolitan statistical areas are made up of towns or cities rather than of counties.

flows of migration of the skilled and has become mainly a disburser of transfer payments, that is, benefits paid by some level of government to the unemployed, the untrained, the elderly, the sick and so on. By 1979 manufacturing accounted for only 20.7 million of 86.7 million nonagricultural wage and salary jobs in the U.S. Much of the manufacturing that was once done in the cities had moved to the South, to Puerto Rico and to other parts of the world. Indeed, arguments over varying rates of regional growth in the U.S. obscure the fact that the country as a whole is losing manufacturing jobs. Much of the garment manufacturing once done in New York is now done in places such as Taiwan; the assembly workers of the old RCA plant in Camden, N.J., have been made obsolete more by the ingenuity of the Japanese than by the development of "Silicon Valley" in California.

It was also once supposed that the city would be a center of innovation. The dense concentrations of entrepreneurs and services in the cities would incubate new functions, nurture them and finally export them to other areas, and so the cities would renew themselves repeatedly. Whatever validity the hypothesis may once have had, it no longer applies. The innovators and the innovations are to be found much more often in the suburbs and the exurbs, as exemplified by Silicon Valley and by Route 128 ("Electronics Highway") near Boston. The old dominant combination of mass industrialization and mass pools of unskilled immigrant labor in the central cities has been replaced by a new synergistic relation of high technology, the environmental preferences of key employees and the concentration of knowledge in suburbia and increasingly beyond it.



SHIFT OF POPULATION away from central cities to suburbs and nonmetropolitan areas is charted for the period from 1970 through 1977. The bars show the populations in 1970 (*gray*) and 1977 (*color*). In 1970 the cities had 31.5 percent of the population; in 1977, 28.2 percent.

The pattern of capital investment in the U.S. confirms this shift. New facilities tend to be more efficient than old ones. When new facilities are established increasingly outside the central city, that city then comes to house predominantly old ones and a kind of self-fulfilling policy is evident. Production within the central city is held to be expensive, and so it is abandoned or avoided; production outside the central city is seen as being more efficient, and so that is where it goes at an increasing rate.

Another hope once held for the economic future of the cities was that they would become centers of a service economy. Some of them have in part, as is evident from the office towers that dominate the skyline in the larger cities. Sometimes these monuments represent institutions that are bound to the city by legislation (banks in certain states, for example) or that are there for institutional selling reasons (some insurance companies), but the phenomenon is much broader: the towers house a great many general office functions. Often sharing the same skyline are the new hotel-convention complexes. They and the office towers together provide an image of rebirth and economic resurgence.

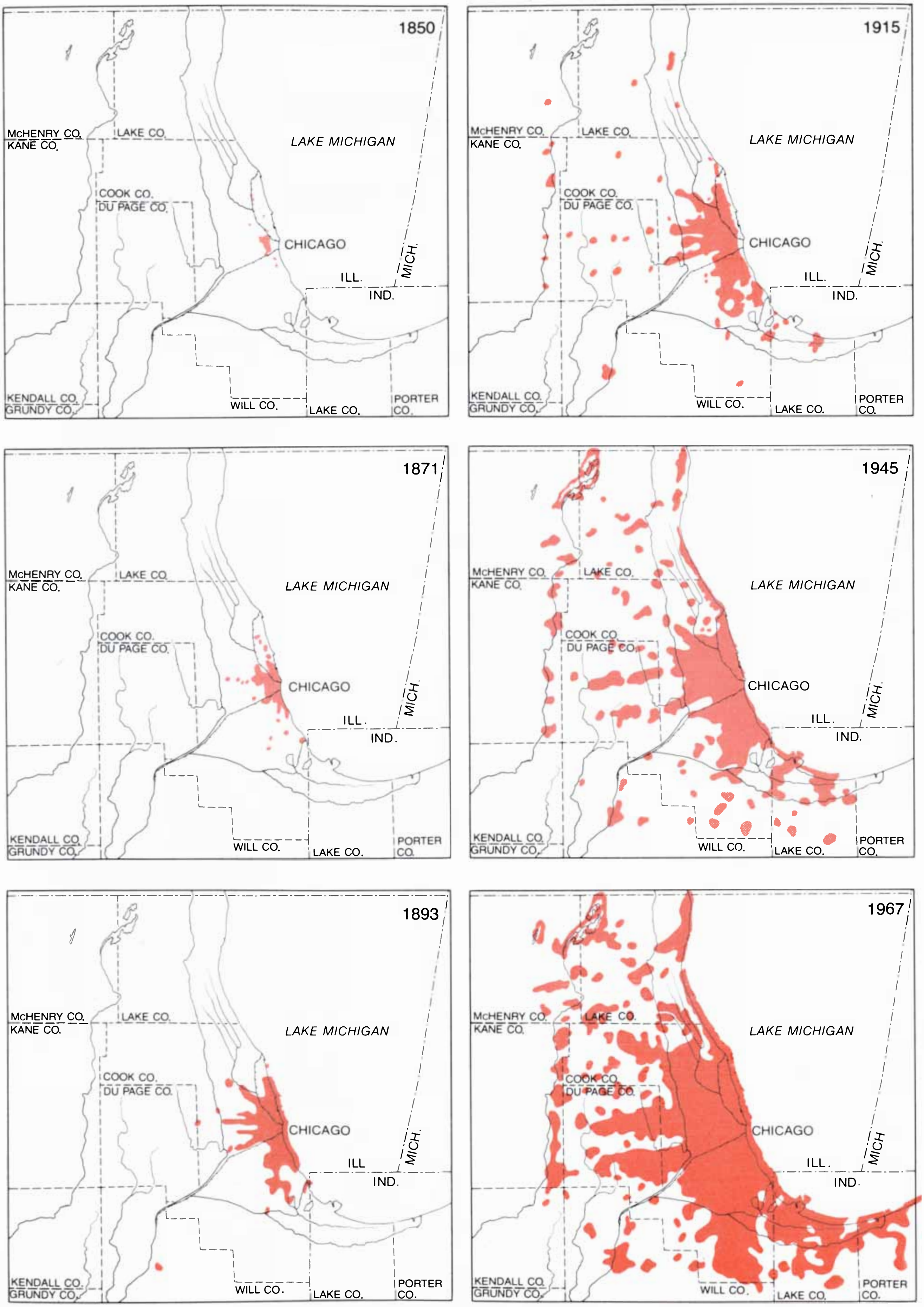
What is striking, however, is the failure of these symbols of the postindustrial service economy to generate anywhere near the number of jobs that have been lost because of departed manufacturing. One reason is the advent of the computer and other electronic aids for the handling of information and paper. Barely a decade ago the New York financial community was convulsed by days in which 15 million shares of stock changed hands; now the stock exchange handles three times that level of trading with less office help. Moreover, many of the new elite jobs of the central city are held by suburbanites. The mismatch between the largely poor and largely black residents of the city and the requirements of the postindustrial job market is increasing, and the city is continuing to lose population.

A second reason for the shortfall of jobs in the central city is that the shifts of population have taken with them many of the service-job opportunities that were once abundant there. The Prudential Insurance Company of America had a peak employment of almost 13,000 people in Newark, N.J. It now has 4,000, and a change of similar magnitude has taken place in the Metropolitan Life Insurance Company complex in New York. The workers of both companies are now decentralized throughout the U.S., mainly in places where they can provide services to the new population centers in the suburbs and exurbs.

The Federal Government is often criticized for allowing its employment in central cities to decline, but here the same forces are at work. The administration of the benefit programs of the Social Security Administration and the Veterans Administration, for example, must be where the population is in order to be most equitable and efficient. A negative multiplier effect can be seen: the drift of population and primary jobs out of the city reduces the number of secondary jobs and activities.

The drift outward is more than passive. When the suburbs reach a certain size, they can support a variety of functions that were once confined to the central city. Thus the large hospital, the major restaurants, the regional shopping centers and the substantial office centers are as likely (sometimes likelier) to be found outside the central city as in it.

These facts trace the evolution of the two-city structure that has appeared since World War II in certain large cities that have partly adapted to the changing conditions. On the one hand are the new centers of consumption, high skills and substantial utilization of advanced technology: parts of Manhattan, North Michigan Avenue in Chicago, the San Francisco wharf district, Society Hill in Philadelphia and others. They provide a central point for people with a relatively


1850
1915
1871
1945
1893
1967
McHENRY CO.
KANE CO.
LAKE CO.
COOK CO.
DU PAGE CO.
LAKE MICHIGAN
CHICAGO
ILL.
IND.
MICH.
KENDALL CO.
GRUNDY CO.
WILL CO.
LAKE CO.
PORTER CO.

high amount of disposable income and serve as headquarters (at least regional and often national and international) for both production and consumption.

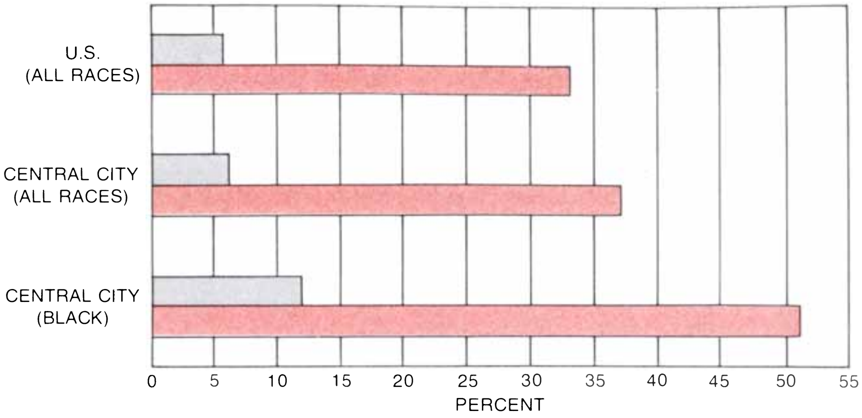
Surrounding them, however, is an increasing wasteland of the bypassed economy. The people there represent the leftovers of previous waves of immigration who no longer find the city of opportunity that existed for their predecessors, however harsh it may have been. The buildings have lost their residential, commercial or industrial reason for being and present a panorama of decay and devastation.

The city of the elite, where it exists, varies in scale from a few blocks in some municipalities to substantial and growing populations in others. It is the city whose inhabitants are matched to the new employment base and do not need or use many of the municipal services that are so heavily burdened by the poor. Typically the people of this city are either childless or sending their children to private schools. They and their families are never to be found in the overcrowded municipal hospitals, and they are certainly not dependent on the city's welfare programs. Although the size of these groups is usually quite small in relation to the rest of the city's population, the groups are conspicuous because they inhabit the city of the tourist and the visitor. And since they represent a fairly new phenomenon, they attract perhaps more attention than their numbers warrant.

The greater reality is the city of the poor, with from a fourth (Boston) to a seventh (New York) of the population on welfare, with staggering crime rates and with truancy levels (vastly understated by the official reports) that make a mockery of the traditional role of public education as an influence for homogeneity and a route upward for the urban young. The data on income and the configuration of households reflect the situation. They show sharp differentials of income across types of household.

Families that include a husband and wife stand at the top of the income ladder (median income in 1978 of $19,340), followed by families of which a male was the head and no wife was present ($15,966). Families in which a female was the head and no husband was present were at a median level of $8,537. Primary individuals, that is, people living alone or in households consisting of two or more unrelated individuals, had a median income of $6,705.

OUTWARD MOVEMENT of population over a period of more than 100 years is depicted for Chicago and its environs in the maps on the opposite page. They show (*color*) the built-up areas that make up the Chicago metropolitan region. The maps are based on information in *Chicago: Growth of a Metropolis*, by Harold M. Mayer and Richard C. Wade.



FOCUS OF POVERTY in central cities is particularly on female-headed black families. The bars show the percent of families below the poverty level in 1977 among families headed by males (*gray*) and females (*color*). From 1970 through 1977 the percent of all male-headed families living below the poverty line declined, whereas the percent of female-headed families rose.

This pattern becomes more significant when the shifting profile of central-city household types is examined. The number of households in the higher income levels is either declining (for whites) or increasing slowly (for blacks). The number of husband-wife families has declined among both whites and blacks. The only type of family expanding in number among whites in the central city is female-headed (no husband present); among blacks that type of family is growing even faster. Nearly 60 percent of the total increase in black households from 1970 through 1977 was in this category. As of 1977 more than four in 10 (41.7 percent) of all black families in central cities were headed by a woman.

The correlation between low income and households headed by women is high. Whereas the median income of all families in central cities in 1977 was slightly below $14,000, families with female heads had $6,658 and black families with female heads had $5,125. Moreover, expressed as a ratio of incomes in suburban areas the central-city incomes are declining steadily.

Female-headed families in central cities have shown the most marked decline in real incomes. The selective migration of blacks to suburban areas undoubtedly underlies, at least in part, the one substantial gain in family income (in constant dollars) from 1970 through 1977; for black families in the suburbs real income rose from $10,745 in 1970 to $12,037 in 1977. The decline of income among blacks in the central city is clearly linked with the outward migration of husband-wife families and the residual dominance of female-headed households.

The result of the increase in both the number and the proportion of low-income households in central cities is growing concentrations of urban poverty. Nationally, however, the incidence of poverty is declining. The data on poverty-level individuals partitioned by family status show that every category was reduced from 1969 through 1976 except for women who were heads of families.

The basic problem is even more sharply focused when the data for central cities are isolated. There is an absolute increase in the number of people below the poverty line. It came about in spite of a reduction in the number of husband-wife families below the poverty level. Virtually all the increase in poverty-level individuals was among women who headed families and among their children.

In the central city black husband-wife families are climbing out of poverty. Black families headed by women are increasingly falling below the poverty line. Moreover, the husband-wife families are declining in number and the female-headed families are increasing.

The increase in the number of such groups has in turn greatly sapped the fiscal vigor of the central cities while increasing the stress on the services provided by the cities. The effect bears more and more on the black people in central cities. Of all blacks in central cities 31 percent were in poverty in 1977, as were more than half (51.1 percent) of the black women who headed families. Those women in turn accounted for most of the children who were in families below the poverty line.

At present there appears to be little in the way of new public-policy initiatives that would counteract these trends. To say that such initiatives are conceivable is not to say that they are likely to be meaningfully achieved in the near future. Up to now the concept of revitalizing urban core areas has been applauded as a goal but has been casually implemented at best. For an entire generation the movement of people and capital has been largely in the other direction. The forces that might reverse this trend are not yet in sight.

The Surface of Venus

Shrouded by clouds, it has now been mapped by radar from the earth and from a spacecraft in orbit around Venus. The images suggest a geology intermediate between that of the earth and that of Mars

by Gordon H. Pettengill, Donald B. Campbell and Harold Masursky

Over the past 15 years the surface of Venus, perpetually hidden by its deep cover of clouds, has been intensively probed by radar signals beamed from the earth, and over the past year and a half it has also been probed by signals from a spacecraft placed in orbit around it. The returning radar reflections reveal that the planet's surface is marked by geologic features suggestive of impact cratering, volcanism and tectonic activity. Because of orbital and rotational synchronicities and other constraints the radar view of Venus from the earth is effectively limited to less than one complete hemisphere of the planet. On the other hand, the Venus orbiter has covered the complete circumference of the planet between 74 degrees north latitude and 63 degrees south latitude. Within that broad band, encompassing 93 percent of the planet's surface, the Venus orbiter can measure altitudes to an accuracy of within 200 meters. The spacecraft has found that Venus is remarkably flat: 60 percent of its surface falls within a height interval of only one kilometer. One feature, however, rises 11 kilometers above the surrounding plain and therefore is taller than Mount Everest. Named Maxwell, it is possibly a shield volcano.

When early telescopes showed that Venus was not only bright but also apparently shrouded in clouds, man's imagination was quick to populate the planet's surface with dinosaurlike creatures living in steamy swamps. The planet is only 72 percent as far from the sun as the earth is, so that one could expect Venus to be substantially hotter than the earth and the clouds to be condensed water vapor. Later, as spectrographs and other instruments showed that the atmosphere of Venus consists primarily of carbon dioxide and is almost devoid of water vapor, most of the early fancies died. One of them, however, was borne out. Measurements of the planet's thermal radiation, made at radio wavelengths long enough to penetrate the clouds, have shown that its surface is indeed hot: 475 degrees Celsius (about 900 degrees Fahrenheit).

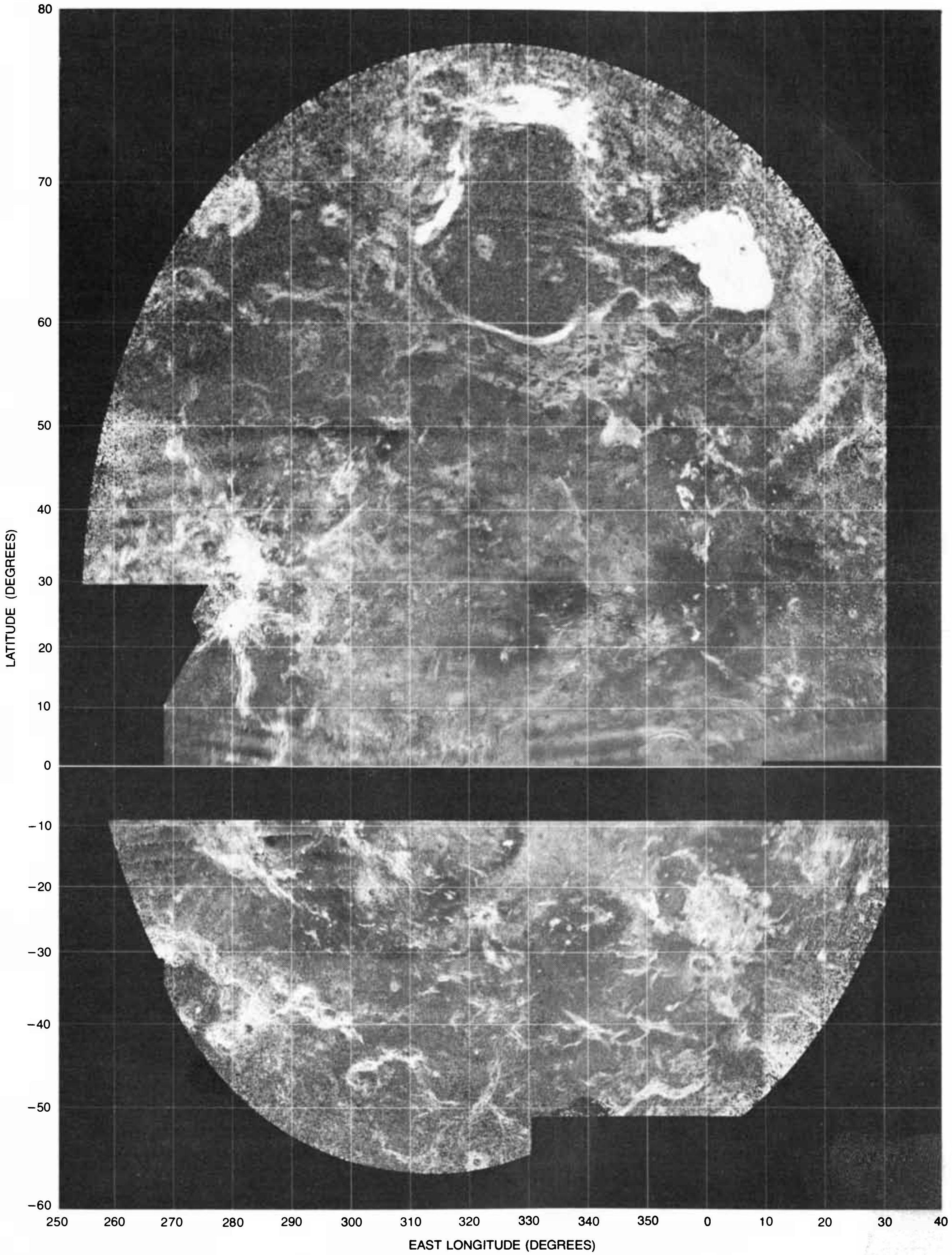
By 1960 radar systems had been constructed with sufficient power to detect radio echoes from Venus on the earth. Operating at wavelengths of between 12 and 70 centimeters, the radar systems penetrated the planet's atmosphere and proved that a true surface exists. Although the early systems lacked the resolution to determine the radius of the solid surface with any precision, they did provide the first clues to two general properties of the surface, namely its mean reflectivity and its average "roughness" at radar wavelengths. The observed reflectivity of about 15 percent is typical of many rocks on the earth.

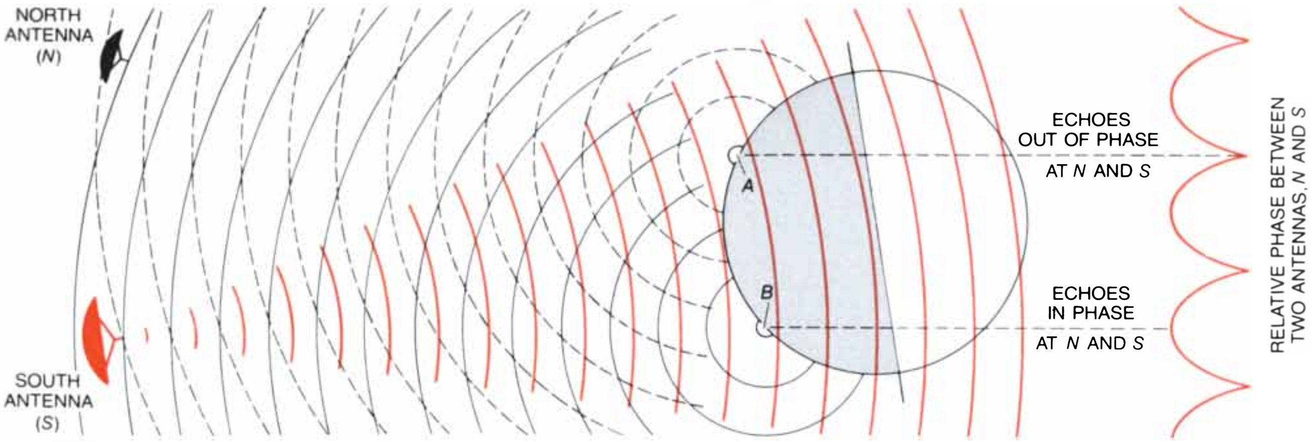
Working with radar observations made in 1961, William B. Smith of the Lincoln Laboratory of the Massachusetts Institute of Technology looked for evidence of frequency broadening in the returning echoes. If Venus is rotating, a differential Doppler shift should be imparted to components of the radar signal that are reflected from different areas of the surface. Signal components that strike an approaching surface will be increased in frequency and those that strike a receding surface will be decreased. The overall effect is to broaden the frequency spectrum of the echoes. Smith concluded that the frequency broadening of the echoes was small and that possibly it decreased as Venus passed between the earth and the sun.

At that time essentially nothing was known about the rate at which Venus rotates. On the basis of his observations Smith suggested that the rotation might be retrograde: in a direction opposite to that of the planet's motion around the sun. A year and a half later, in 1962, Roland L. Carpenter and Richard M. Goldstein of the Jet Propulsion Laboratory of the California Institute of Technology showed that Venus' rate of rotation is very low, having a period equal to about 240 earth days, and that the rotation is indeed retrograde.

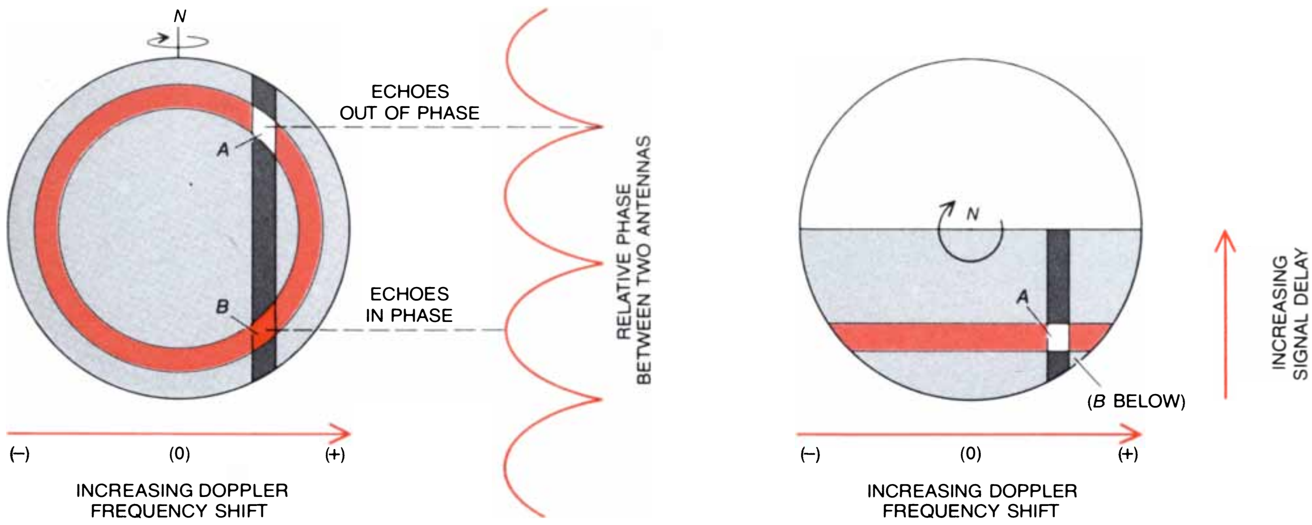
The next major advance in the radar study of Venus came with the completion of the Arecibo radar antenna in Puerto Rico (with a diameter of 300 meters and operating at a wavelength of 70 centimeters), the deep-space tracking antenna at Goldstone, Calif. (with a diameter of 64 meters and operating at 12.5 centimeters) and the Haystack radar system in Massachusetts (with a diameter of 43 meters and operating at 3.8 centimeters). By 1966 the accuracy of the radar ranging of Venus with these instruments had improved to better than within one kilometer, or nearly one part in 10^8 of the distance to the planet. Measurements at this accuracy were carried out over several years at Arecibo by

RADAR IMAGE OF VENUS was assembled from observations made at the Arecibo Observatory in Puerto Rico in 1975 and 1977, when Venus made close approaches to the earth. At such times Venus always presents nearly the same "face" to the earth, so that only slightly less than one hemisphere, the region centered on 320 degrees east longitude, can be successfully mapped. The empty band below the equator is a region where in 1975 and 1977 the imaging method was unable to resolve the radar echoes. Echoes from that region were successfully resolved in observations made during the close approach of this June, but the data are still being processed. The observing geometry in 1975 made the northern hemisphere of the planet slightly more accessible than the southern, as is evident in this Mercator projection. The image brightness is proportional to the degree of surface roughness with dimensions of a few centimeters, except at low latitudes, where meter-scale slopes also influence the reflected signal. The lateral resolution in this mosaic varies between 10 and 20 kilometers. (A degree of latitude on Venus equals 106 kilometers.) The bright area at the upper right, named Maxwell (centered at 65 degrees north latitude, five degrees east longitude), and the area at the left center, named Beta (25 degrees north, 283 degrees east), have nearly saturated the display in this representation. The two areas are shown separately at reduced contrast in the illustrations on page 62.

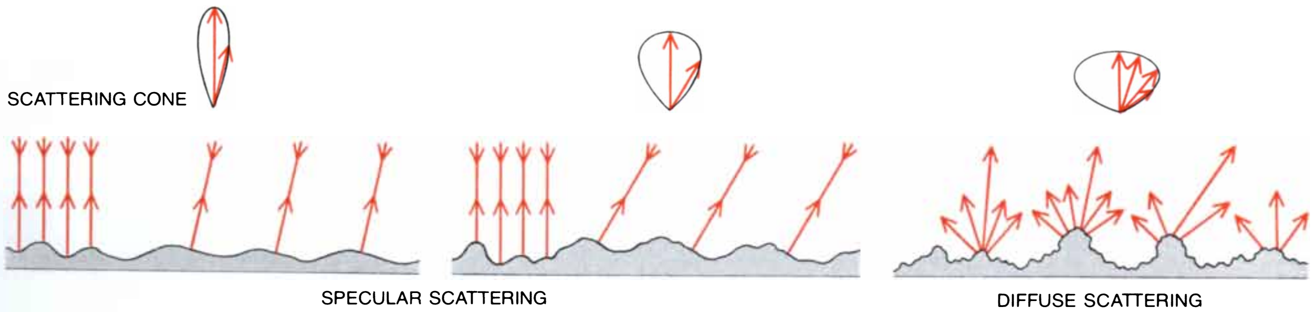

80
70
60
50
40
30
20
10
0
−10
−20
−30
−40
−50
−60
LATITUDE (DEGREES)
250
260
270
280
290
300
310
320
330
340
350
0
10
20
30
40
EAST LONGITUDE (DEGREES)



RADAR MAPPING OF VENUS by the authors and their associates exploits interferometry to distinguish between echoes arising from two separated locations on the surface of the planet. The transmitter in these experiments is at the 300-meter radio telescope at Arecibo. The emitted radio signal has a nominal wavelength of 12 centimeters and a power of 400 kilowatts. The outgoing radio beam (*color*) consists of a continuous-wave signal about five minutes in duration that has been systematically varied in phase. When the radar echoes return from Venus after a round trip of roughly five minutes, the precise travel time can be deduced by searching for the phase patterns that were embedded in the original outgoing signal. The echo is recorded simultaneously at the 300-meter antenna (*S*) and at a 30-meter "passive" antenna (*N*) 10 kilometers to the north. A point on Venus such as *B*, for which the round-trip distances *SBS* and *SBN* differ by an exact multiple of the wavelength, gives the same received phase at the two antennas. Another point, *A*, for which the corresponding paths *SAS* and *SAN* differ by an odd multiple of half wavelengths, gives echoes that are out of phase. (Here the wavelength is much exaggerated.) When the echoes received at the two antennas are combined coherently with appropriate adjustments in their relative phases, one can suppress the echo from either *A* or *B*. Here the signals from point *A* "cancel," leaving only the signals from *B* visible.



ROTATION OF VENUS gives rise to a Doppler shift in the returning signals. Echoes from approaching sites are shifted to a slightly higher frequency; echoes from receding sites are shifted to a slightly lower one. Two sites, *A* and *B*, produce echoes with the same time delay and Doppler shift. The strength of the scattering from a conjugate pair of locations such as *A* and *B* is established by analyzing the radar echo to extract those components with the same time delay and Doppler shift. When *A* is in an interferometer null, only *B* is visible.

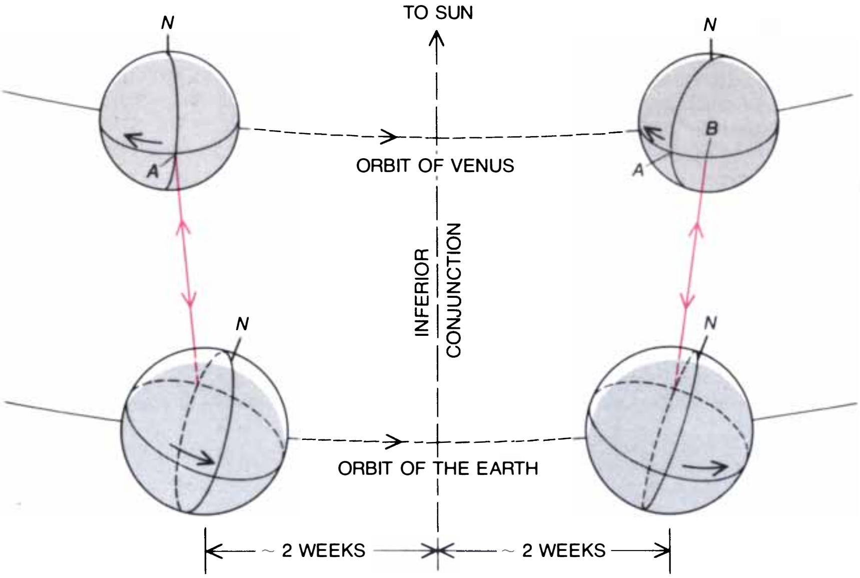


CHARACTER OF A SURFACE can be inferred from the distribution of the scattered power at varying angles. An undulating surface, smooth at the scale of the observing wavelength, scatters back radar energy only where a facet lies at right angles to the observer. For gentle slopes this produces a narrow scattering cone (*left*). Where a surface has somewhat steeper facets the cone is wider (*middle*). A surface that is rough at the scale of the wavelength scatters diffusely with an intensity largely independent of the angle of observation (*right*).

Rolf B. Dyce and two of us (Campbell and Pettengill) and at Haystack by Richard P. Ingalls and one of us (Pettengill). In collaboration with Irwin I. Shapiro and other workers at M.I.T. we deduced that the mean surface radius of Venus is close to 6,050 kilometers. As the orbits of the earth and Venus came to be better known from the fitting of the motion of the two planets to long sequences of radar data it was eventually possible to observe variations in the radius of Venus as the reflecting region migrated around the equator of the planet.

An unexpected dividend of the radius measurement was the contribution it made to determining the atmospheric pressure at the surface of Venus. The pressure determination is a classic example of the power of combining apparently unrelated lines of inquiry. One of the tasks of the 1967 mission of *Mariner 5* was to observe the refraction of the spacecraft's radio signal by the atmosphere of Venus as the craft passed behind the planet. From the refraction data Arvydas J. Kliore and his colleagues at the Jet Propulsion Laboratory calculated the atmospheric pressure and temperature as a function of distance from the planet's center of mass. Because the dense lower atmosphere of Venus is both highly refractive and absorbing, however, Kliore was unable to extend the spacecraft measurements below altitudes where the pressure is more than a few times the atmospheric pressure at the surface of the earth.

An extrapolation to the surface of Venus was made possible by taking account of the surface temperature (from the radio-emission measurements) and the precise location of the surface (from our radar-ranging measurements). The major uncertainty in the extrapolation was ignorance of the composition of the atmosphere near the surface. On the assumption that the composition is dominated by carbon dioxide, Kliore and his colleagues calculated that the surface pressure on Venus is almost 100 times the surface pressure on the earth. This prediction was subsequently verified directly by Russian and (much later) U.S. probes that descended through the atmosphere and reached the surface.



RADAR OBSERVATION OF VENUS WITH HIGH RESOLUTION is limited to a period of about four weeks centered on the time of inferior conjunction, when Venus is on a line between the sun and the earth and therefore at its closest to the earth. A minimum distance to the target is necessary because the intensity of radar echoes falls off inversely as the fourth power of the target's distance. An inferior conjunction comes every 19 months. Since Venus makes one retrograde rotation every 243 earth days, it rotates from east to west (with respect to the stars) about 42 degrees, or 1.5 degrees per day, during the prime four-week observing period. For an observer on the earth, however, about a third of this rotation is canceled because Venus is moving from east to west (with respect to the stars). Thus two weeks after inferior conjunction a point on the surface of Venus, *A* as viewed from the earth, will have rotated only about 27 degrees eastward from *B*, its position two weeks before inferior conjunction.

Hot, dry and under tremendous atmospheric pressure, the surface of Venus is unique in the solar system. How could one examine in detail this remote, beclouded and inhospitable area nearly the size of the earth? Clearly the most feasible approach was again to use radar. The challenge was to extend and increase the sensitivity of the techniques that had successfully defined the planet's radius and rate of rotation.

Since points on the surface of a rigid body move in a highly predictable way as the body rotates, one can correlate with a specific surface location the time it takes a component of the radar signal to make its round trip and the Doppler shift in its frequency at reflection. With computer analysis of the data one can map variations in the scattering of the radar signal over a large fraction of the planetary surface provided only that the radar system has sufficient sensitivity at the desired resolution.

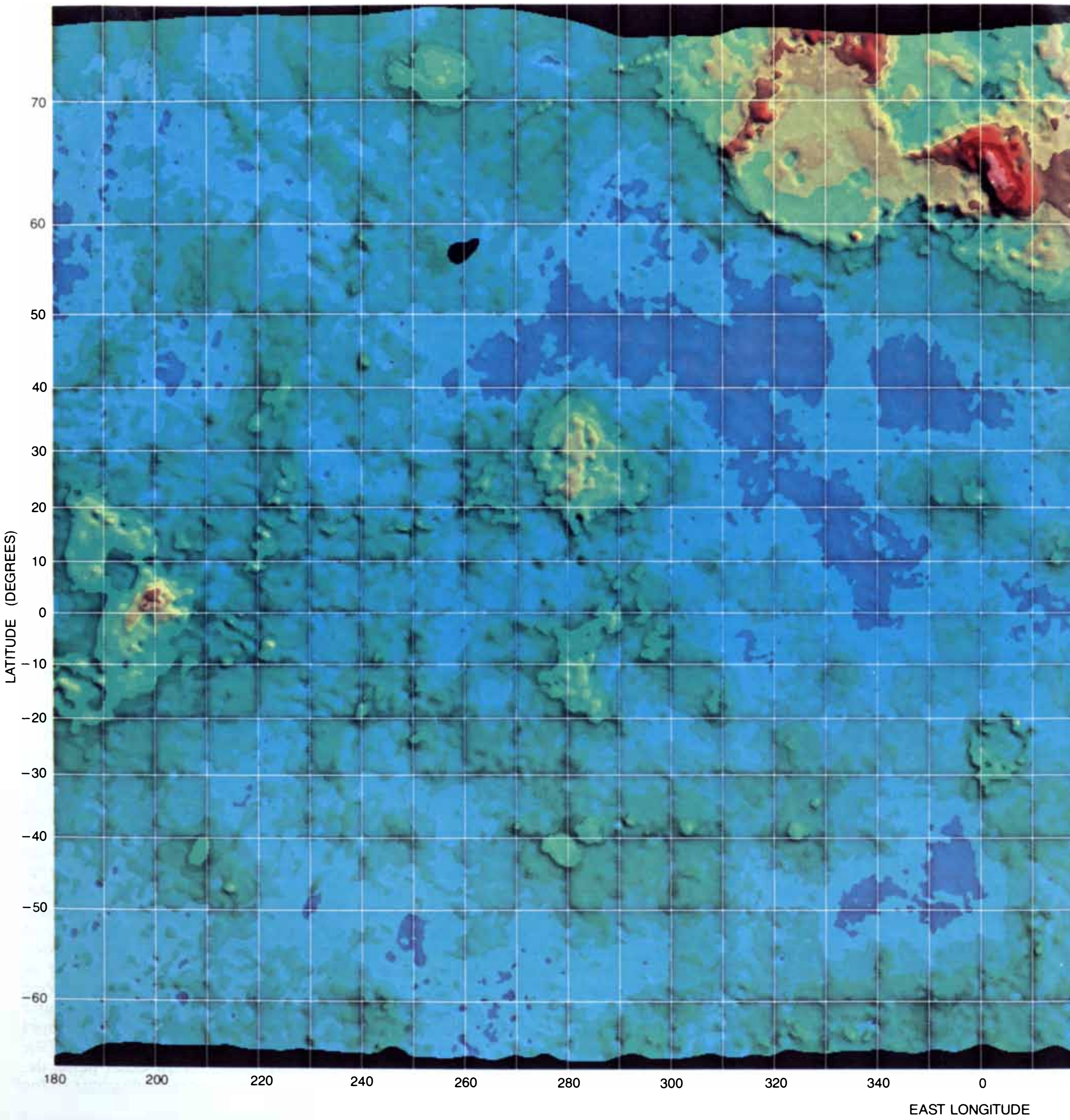
In our studies the outgoing beam is transmitted from the 300-meter Arecibo antenna and consists of a continuous-wave signal lasting for about five minutes that incorporates carefully orchestrated rapid reversals in phase. By searching the echo for a corresponding pattern of phase reversals we can precisely measure the round-trip delay of the signal. When the transmitted beam reaches Venus, it has spread out to about twice the diameter of the planet. The radar echoes are recorded at the Arecibo antenna, whose transmitter is turned off while the signal is being received, and simultaneously at a smaller dish, 30 meters in diameter, that is 10 kilometers to the north. Doppler shifts in the recorded signals are established by frequency analysis. Differences in phase between corresponding components of the echo received at the two sites are then analyzed by computer to help sort out and map the locations of the reflecting surfaces on Venus.

What properties affect the scattering of radio waves? If a surface is smooth at the scale of the observing wavelength, the reflection is specular, or mirrorlike. The radar beam can be visualized as a searchlight. If the radar reflection is viewed by the same antenna that launches the radar pulse, energy that is reflected specularly will be recorded only where smooth facets of the surface lie at right angles to the axis of the antenna. At radar wavelengths the moon, Mercury, Venus and Mars appear to be densely covered by facets that vary in dimension from a few wavelengths to hundreds or even thousands of wavelengths and that are tilted at random to the local horizontal. The same would be true of many points on the earth that are not covered by water or vegetation.

Radar echoes from the inner planets are therefore dominated by specular reflection when the backscattering angle of incidence is approximately perpendicular to the mean surface. The phenomenon can be likened to sunlight glinting from the sides of wavelets on the ruffled surface of a body of water. The rate of decrease in the power of the backscattered signal as the viewing angle departs from the perpendicular depends on the steepness of the slopes of the facets. The total power of the scattered signal, on the other hand, depends primarily on the reflectivity of the surface.

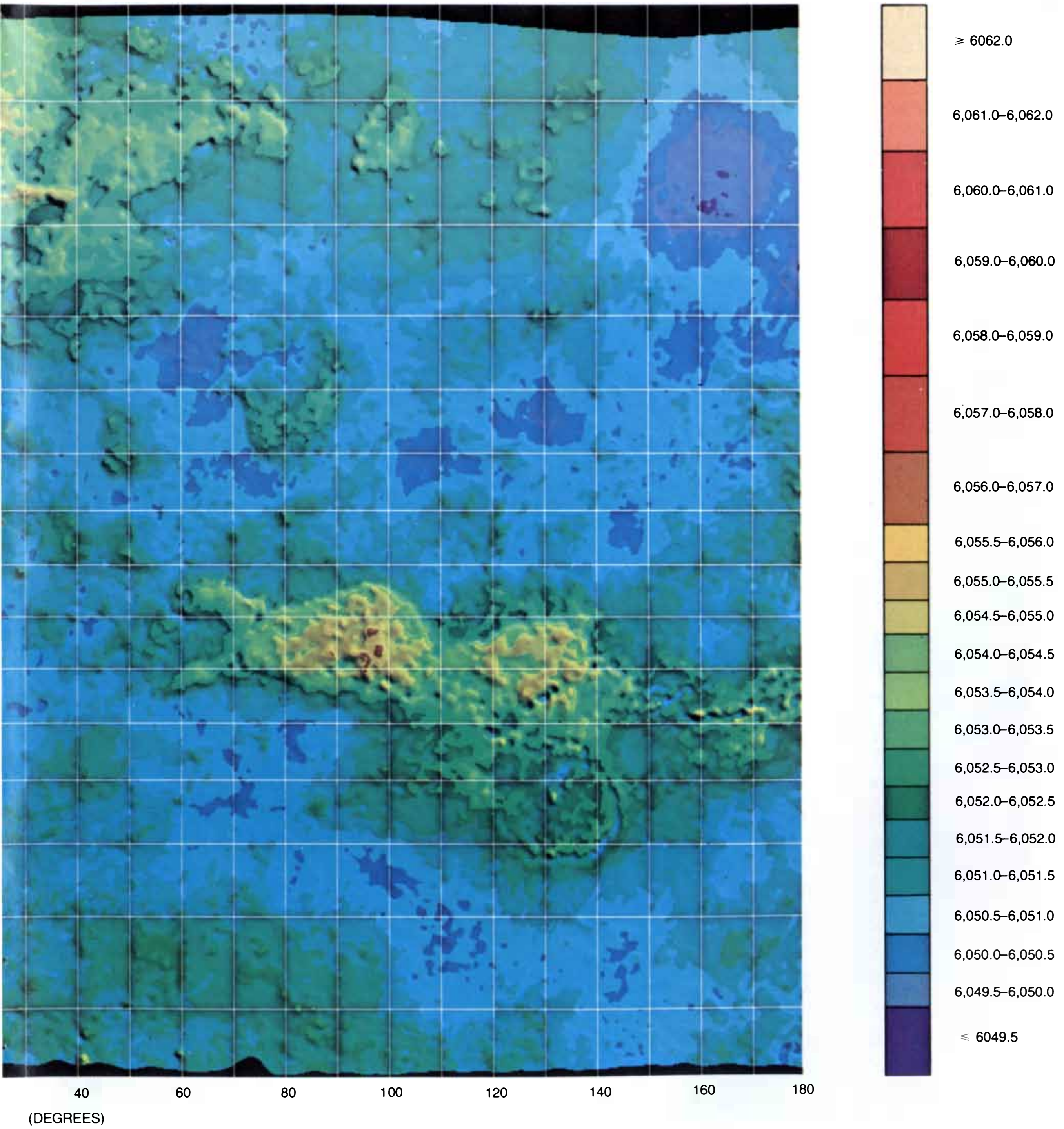
Surface irregularities that have sharp edges or that are small compared with the incident wavelength give rise to diffuse or incoherent scattering that spreads the incident power thinly over a wide range of emerging angles. When the angles of incidence are more than about 20 degrees from the mean local vertical, scattering from small irregularities usually dominates over specular reflection. Accordingly observations of radar backscattering at typical decimeter wavelengths made at viewing angles within 10 degrees of the local vertical are sensitive primarily to surface undulations with dimensions larger than a meter, and observations made at more oblique viewing angles are sensitive primarily to surface structures with dimensions of about a centimeter. By and large the variations in radar scattering seem to be dominated by the geometry of the surface rather than by changes in its reflectivity, which is a function of the dielectric discontinuity between the planet's surface and its atmosphere.

Radar images of Venus made from the earth are assembled from observa-



ALTITUDES OF THE SURFACE OF VENUS have been measured by *Pioneer Venus 1,* a small spacecraft that was placed in orbit around the planet on December 4, 1978. A radar altimeter aboard the orbiter measures the height above the surface of Venus whenever the craft passes below an altitude of 4,700 kilometers on an orbit that carries it from about 150 kilometers at periapsis to about 66,000 kilometers at apoapsis. The orbit limits coverage to the 93 percent of the planet's surface that lies between the latitudes 74 degrees north and 63 degrees south. The raised appearance of this computer rendering is created by modulating the intensity of the color contours, as though the sun were shining on the surface from the upper right, and it serves to emphasize the steeper slopes. Average radius of Venus is 6,051.4 kilometers, coded a blue-green in the altitude color scale. The deepest violet corresponds to a planetary radius of less than 6,049.5 kil-

tions taken over a wide range of scattering angles. The rotational axis of Venus is always nearly at right angles to the line of sight from the earth, so that scattering data from high latitudes on Venus are obtained at large angles of incidence; therefore the variations in surface structure the data disclose have dimensions of less than a wavelength. At lower latitudes, where the radar-viewing angle is more nearly straight down, the scattering is modulated by surface undulations and inclinations that have dimensions of more than a wavelength. With decreasing distance to the poles of the planet coverage is limited by the increasing depth of atmosphere to be penetrated and the resulting high absorption of the radar signal. The backscattering efficiency also drops for radio waves that strike the surface at shallow angles,

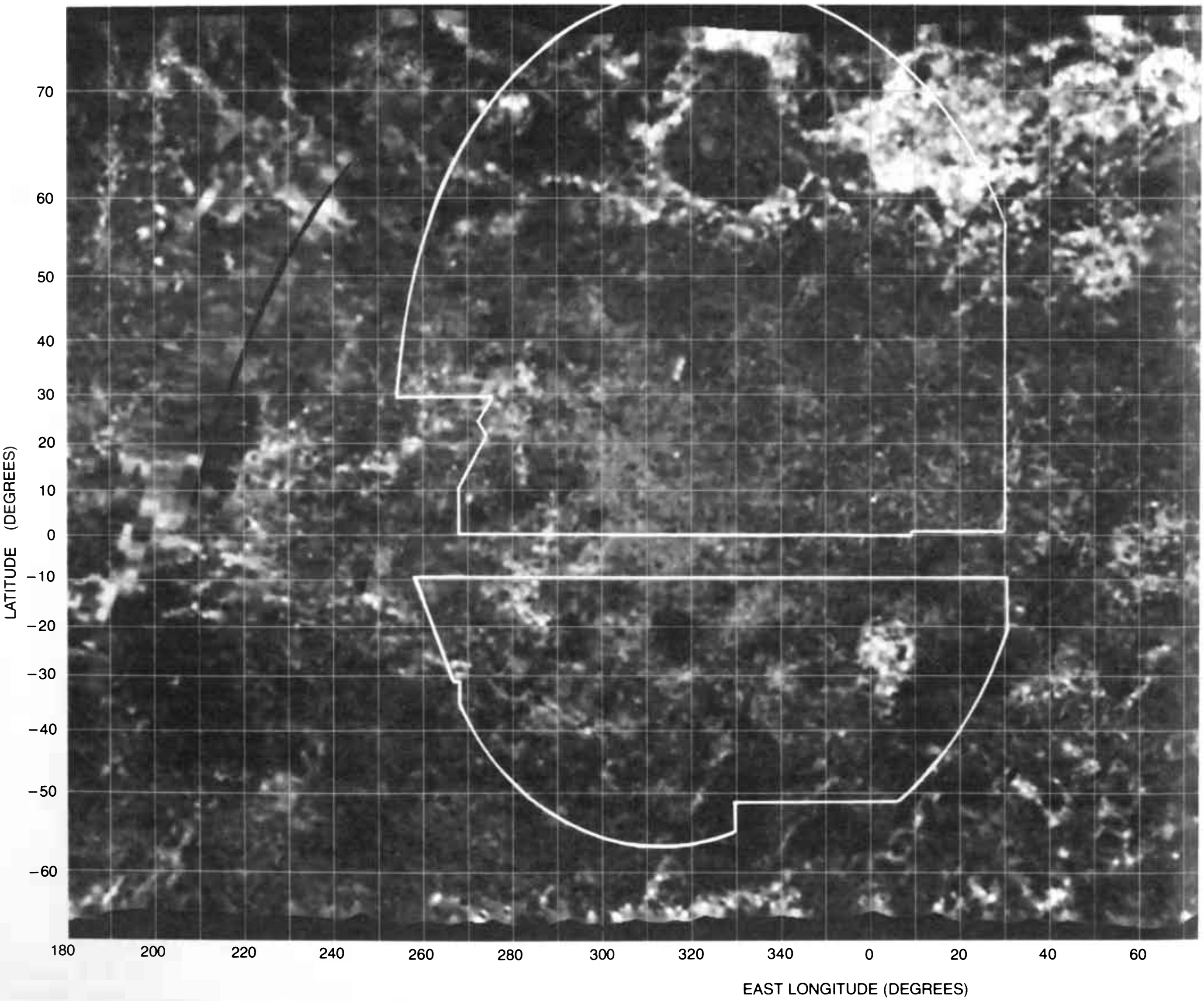


ometers, which embraces much less than 1 percent of the mapped area. The color changes at each half-kilometer interval until brown is reached at an altitude of 6,056 kilometers, beyond which the interval increases to one kilometer. The accuracy of the measurements is within .2 kilometer. The small black area at the upper left should be filled in as the *Pioneer Venus 1* mission continues. The highest elevation so far recorded by the spacecraft lies just above 6,062 kilometers in the white dot in the pink area within Maxwell at the top center. The mountain's 11-kilometer height above the average radius of the planet exceeds by two kilometers the height of Mount Everest above sea level. The region between longitudes 260 degrees and 30 degrees east should be compared with the radar image of the region on page 55. This map and others presenting the Venus-orbiter radar data were prepared by Eric Eliason of the U.S. Geological Survey.

which further reduces the strength of echoes from high latitudes.

Since Venus presents different faces to the earth as it rotates, one might think that in due course its entire surface could be mapped. Such is not the case. The strength of the transmitted radar energy falling on the target and the proportion of that energy received as an echo back on the earth both fall off with the inverse square of the distance to the target, so that the strength of the echo is related to the strength of the original transmission inversely as the fourth power of the distance. High-resolution radar mapping is therefore limited to a few months at inferior conjunction: the time, coming about once every 19 months, when Venus is on a line between the earth and the sun and is therefore closest to the earth. At such a time the combined effect of Venus' retrograde rotation and the planet's westward motion through the sky causes the subearth point on Venus, defined by a line passing through the center of both planets, to change by less than .8 degree per day. Hence in the most favorable observing period there is little apparent rotation. Even so, one would expect the subearth point to migrate systematically from one inferior conjunction to the next. Curiously, this does not happen. Venus rotates almost exactly four times, as it is viewed from the earth, between successive inferior conjunctions. Whether this is accidental or dictated by orbital dynamics is a matter of debate among theoreticians.

The fraction of the surface of Venus that can be mapped at good resolution from Arecibo shows details down to between 10 and 20 kilometers in size [*see illustration on page 55*]. Bright areas represent enhanced radar scattering and therefore correspond to unusually rough areas. The large, extremely bright region centered at 65 degrees north latitude, five degrees east longitude is the one named Maxwell (after the physicist James Clerk Maxwell). It was first noted some years ago in early low-resolution radar observations. When Maxwell is examined in reduced-contrast images, which reveal additional detail, one can see an almost circular dark hole and a distinct "grain" running from northwest to southeast [*see upper illustration on page 62*]. To the west of Maxwell



METER-SCALE SURFACE SLOPES ON VENUS are estimated from the same orbiter radar data used to prepare the relief map on the preceding two pages. In this presentation the darkest tones correspond to average slopes of one degree or less, the lightest areas to slopes of 10 degrees or more. The long black arc at the upper left and the small black area to the right of it should be filled in by the end of the mission early in 1981. In general the continental regions, which are the highest in the topographic relief map, exhibit the steepest slopes. An exception is the Lakshmi plateau to the west of Maxwell. The region outlined in white is the face of Venus that has been

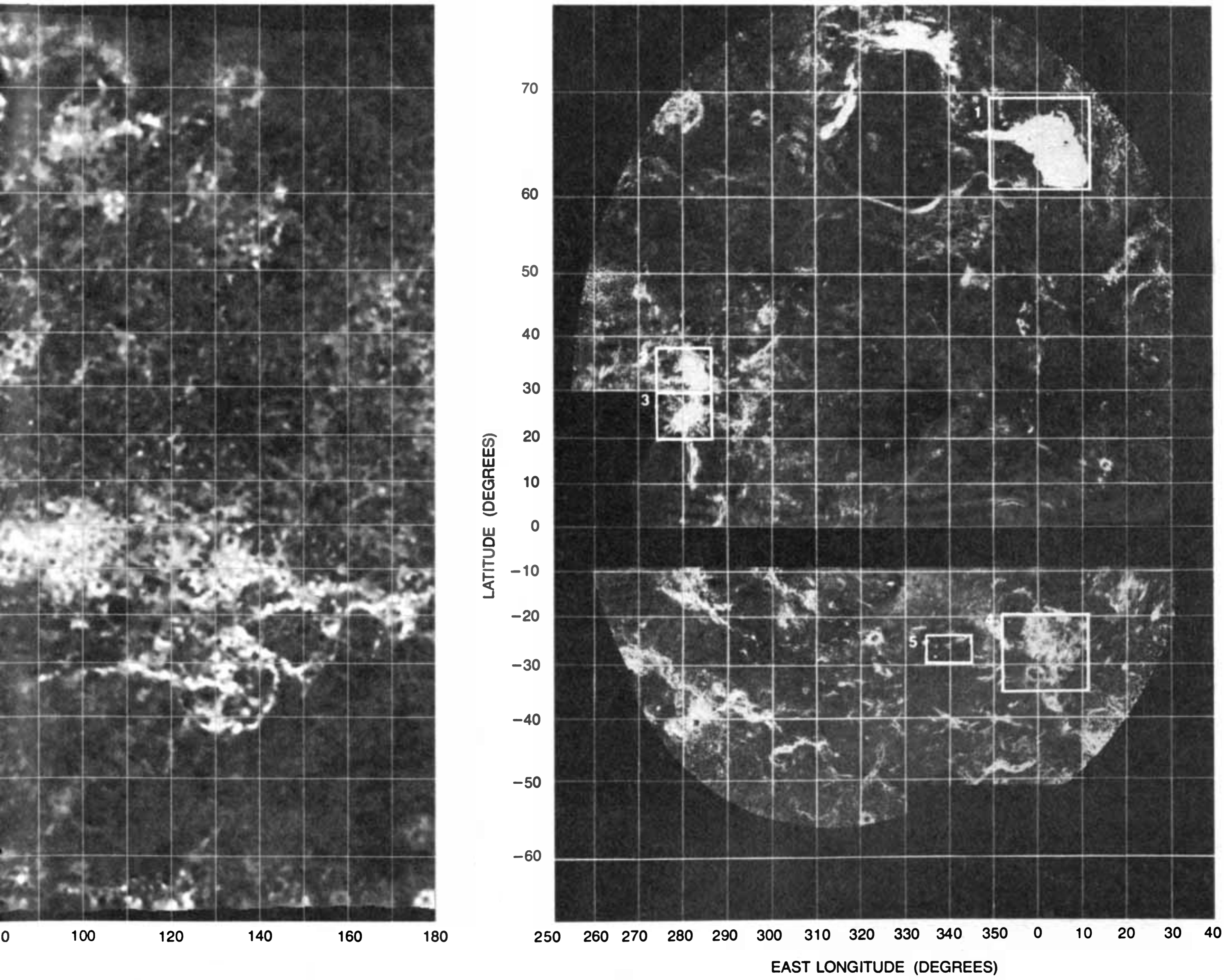
lies a rimmed, pear-shaped, rather dark (and therefore smooth) feature named the Lakshmi plateau (after the Hindu goddess). Because the planet itself is named for a goddess the surface features are being given women's names; the only exceptions are Maxwell and the names of two other sites that have been in use for more than a decade.

Two other bright features stand out. One, called Alpha, is on the zero meridian at about 25 degrees south latitude. The other, Beta, is centered at about 25 degrees north and 283 degrees east. A close-up of Alpha at a resolution of about five kilometers reveals a striking northeast-to-southwest grain reminiscent of the faulted basin ranges found in Nevada and adjacent areas of the southwestern U.S. To the southwest of Alpha, almost exactly on the zero meridian at 32 degrees south, lies a prominent ring-shaped feature with a bright central spot that resembles many impact craters seen on the moon and Mercury. The feature has been named Eve; the meridian that passes through the central bright spot is likely to become the planet-fixed reference origin for the official Venus longitude system.

Beta, a feature with a north-south orientation, includes a central region from which rays extend outward. Radar observations made by Goldstein show the central region to be a broad shield-shaped mountain with a small depression at the summit. R. Stephen Saunders and Michael C. Malin of the Jet Propulsion Laboratory have proposed that the feature is a shield volcano. Nearly 1,000 kilometers across, it is comparable in size to the huge volcanoes on Mars.

Just north of the equator, at about 355 degrees east longitude, a furrowed arc runs for about 1,000 kilometers. Since this feature lies almost directly under the radar beam, the intensity variation in the echo is caused mainly by large-scale tilts in the topography. The feature actually consists of two parallel ridges, each about two kilometers high, separated by a valley 90 kilometers wide. The maximum slope at right angles to the ridges approaches six degrees, an impressive tilt for such a large feature. There are no precisely analogous features on the earth, so that one can only speculate about the feature's origin.

Close examination of the radar im-



mapped by earth-based radar. At the right is a version of the earth-based-radar map at the same scale. One can see considerable similarity in the images that have been produced by the earth-based system and the orbiter one. Evidently the small-scale roughness depicted in the image made from the earth is accompanied in most places by large-scale roughness that shows up as bright in the orbiter image. Rectangles superposed on the image that was made from the earth identify five areas depicted at larger scale on the next two pages. The numbers identify Maxwell (*1*), Rhea Mons (*2*) and Theia Mons (*3*) in the Beta region, the Alpha region (*4*) and three craterlike features (*5*).

ages made from the earth reveals more than two dozen ring-shaped structures that are conceivably highly modified impact craters or perhaps evidence of volcanism. Barbara A. Burns of the Arecibo Observatory has plotted the number of such features as a function of their diameter and has compared the result with similar number-v.-diameter plots for other planets and the moon. For bodies with a surface visible at the wavelengths of light the distribution of craters for selected fractions of the surface agrees broadly with estimates of the number of craters that should have been made by impacting objects over the lifetime of the solar system. Where the distribution of visible craters departs from these estimates one can infer that craters have been erased by the renewal of the surface.

Burns's analysis indicates that the surface of Venus exhibits close to the number of craters with a diameter larger than about 80 kilometers that cratering models predict should have been made within the past 600 million to one billion years. One would expect craters smaller than about 20 kilometers to be much rarer on Venus than elsewhere because the meteorites that make such craters largely burn up in the planet's dense atmosphere before they reach the surface. This expectation cannot be tested because craterlike features smaller than 20 kilometers in diameter are below the resolution of all but an insignificant fraction of the current radar maps. The maps do show that the number of craters with a diameter between 20 and 80 kilometers are distinctly fewer than was predicted. The discrepancy may, however, simply reflect the difficulty in identifying craters of this diameter range in the radar data.

In spite of the apparent agreement with prediction for the number of large craters, the ring-shaped features observed on Venus differ in detail from typical impact craters on the moon, Mercury and Mars. One must therefore remain cautious about identifying the Venus features as impact craters. Topographic profiles of limited regions of Venus, made on the basis of radar observations from the earth, show some of the rim characteristics one would expect from an impact if one also assumes that the hot surface of the planet is capable of plastic deformation. Nevertheless, many of the rims are not quite circular, and the radial extent of small-scale roughness near them is greater than that observed for impact craters on other bodies. A better understanding of the craterlike features on Venus may come with better physical models of the mechanical properties of the hot surface and models that can predict the effects of the dense atmosphere on the patterns of the material thrown out of a crater by either impact or volcanism. Even without such models, however, the genesis of the features may be clarified by radar images made at higher resolution.

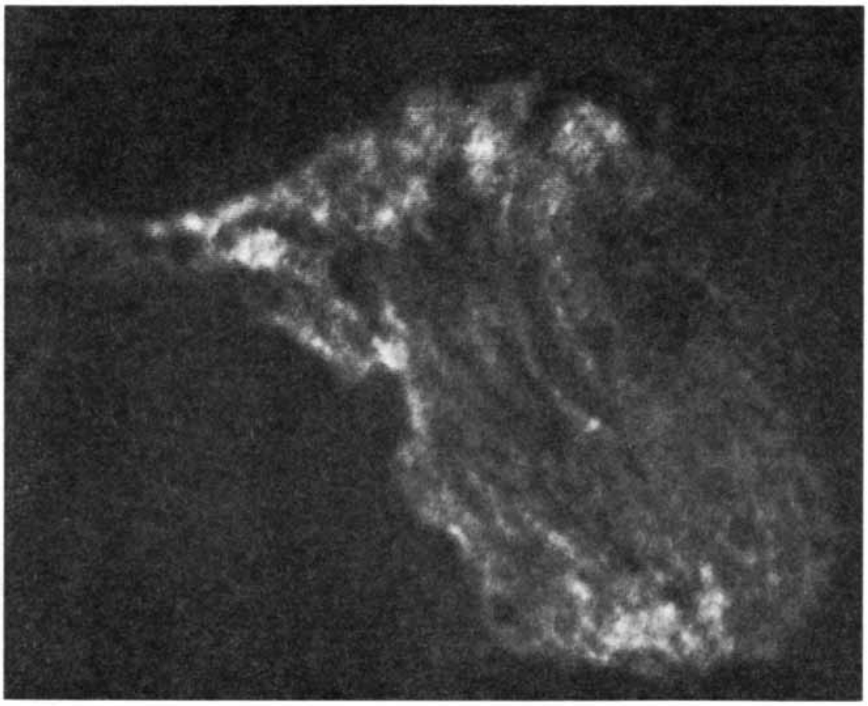
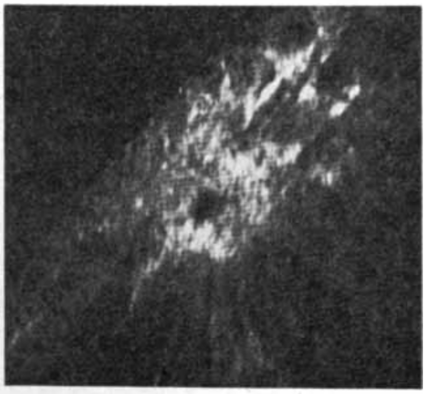
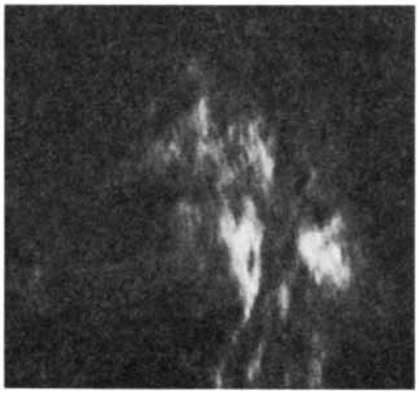


IMAGE OF MAXWELL MADE FROM THE EARTH is derived from the same Arecibo observations as those used to produce the large mosaic on page 55 but is shown here at reduced contrast to bring out interior detail. The surface resolution is about 10 kilometers. Maxwell, which measures about 750 kilometers from north to south, includes the planet's highest elevation: 11 kilometers above the planetary mean. The region exhibits a distinct grain from northwest to southeast. Dark circular "hole" at right center may be a crater partly filled with lava.





BETA REGION, also mapped by radar from the earth, contains what may be two volcanic peaks. Theia Mons (*left*) has been identified by its gently sloping circular shape as being a massive shield volcano some five kilometers high. The dark central region is presumably a volcanic caldera; the streaks radiating outward may be lava flows. (The featureless black area at the upper left has not yet been mapped.) Rhea Mons (*right*) is just to the north of Theia and may also be volcanic, but the large furrow running through its center makes interpretation uncertain.

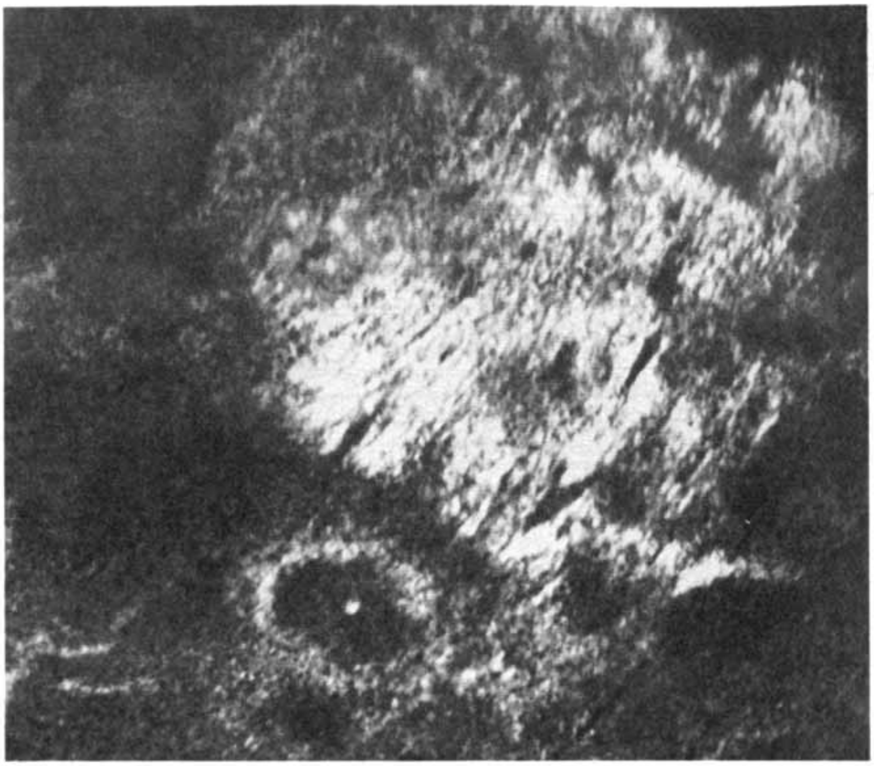
Information on the surface relief of Venus is largely missing in the radar observations of Venus made from the earth. Goldstein and his colleagues at the Jet Propulsion Laboratory have successfully applied multistation interferometry to map the relief of a few small areas of the planet, and earlier several groups determined some topography by direct radar ranging. Both types of measurement, however, have been limited to regions near the equator and have not helped to clarify the nature of the large features seen in the images of surface roughness and texture. Knowledge of a feature's relief is crucial to an interpretation of its nature and an understanding of its origin and evolution.

With this need in view the National Aeronautics and Space Administration approved the inclusion of a small radar altimeter aboard the spacecraft *Pioneer Venus 1,* placed in orbit around Venus on December 4, 1978. As the altimeter goes around the planet it measures the distance to the surface below. Simultaneous tracking of the spacecraft from the earth establishes the orbit with respect to the planet's center of mass. Subtracting the spacecraft's altitude from its distance to the center of mass yields the planetary radius at the surface point observed. Although the spacecraft experiment lacks the resolution of the best observations made from the earth, it has yielded an almost global picture of the surface relief with a vertical accuracy of about 200 meters and a "footprint" resolution typically of 100 kilometers.

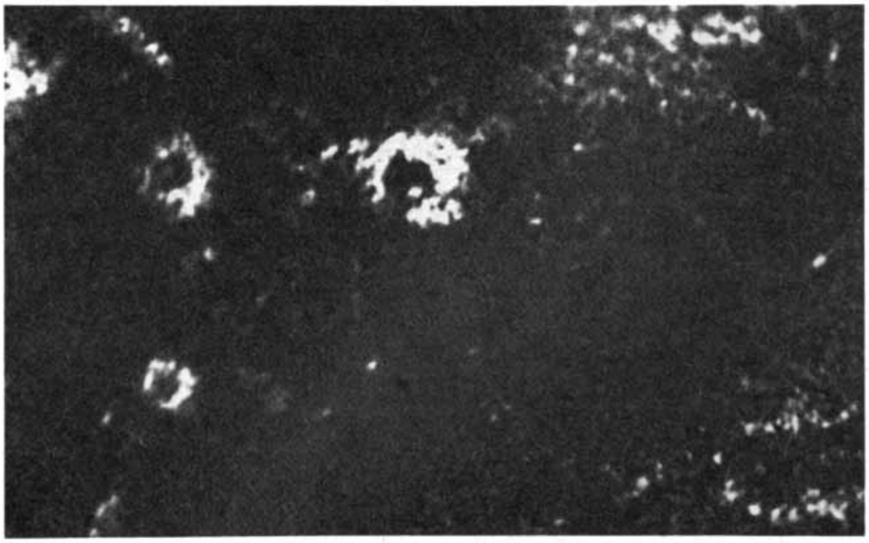
The *Pioneer Venus 1* mission was designed primarily for measurements of the atmosphere and ionosphere of the planet. In order to optimize these observations the spacecraft was placed in a highly eccentric orbit, ranging from a low point of about 150 kilometers above the surface at periapsis, where the atmosphere is dense enough to be analyzed directly, to a high point of more than 66,000 kilometers at apoapsis, where images of large areas of the upper atmosphere and its clouds can be obtained at light, infrared and ultraviolet wavelengths. The plane of the spacecraft's orbit is inclined at an angle of 74 degrees to the equator, so that regions of the planet poleward of latitudes 74 degrees north or 74 degrees south are inaccessible to the radar altimeter. A further limitation arises from loss of signal strength with altitude; measurements cannot be made from altitudes of more than 4,700 kilometers above the surface. Periapsis is at about 17 degrees north latitude, so that the altitude limit does not reduce coverage in the northern hemisphere. In the southern hemisphere, however, the limit is reached at a latitude of 63 degrees. Between these two parallels lies 93 percent of the surface, which becomes accessible to observation as the planet rotates slowly under the plane of the spacecraft's orbit. The spacecraft has an orbital period of 24 hours; therefore between each successive periapsis passage Venus rotates 1.5 degrees. After 243 days a complete rotation of the planet presents all longitudes to altimeter observation.

Inspection of the altimeter data from the Venus orbiter reveals a striking difference between the overall figure of Venus and the figure of the earth. As a result of the earth's substantial rate of rotation its radius at the Equator is some 21 kilometers larger than the radius at the poles. On Venus, where the rotation rate is lower by a factor of 243, there should be a negligible difference between the equatorial and the polar radii if the surface is homogeneous and has come to gravitational equilibrium. This expectation is confirmed. Eighty percent of the mapped surface falls within a height interval of two kilometers and 60 percent falls within an interval of one kilometer. Venus has several "continents" that rise two kilometers or more above the mean surface altitude (equivalent to a radius of 6,051.4 kilometers), but they constitute only about 5 percent of the total area observed. On the earth about 35 percent of the surface lies within the outer boundary of the continental shelves and 65 percent is truly oceanic. The continental regions on the earth are not in general higher than those on Venus. A large fraction of the earth's ocean bottoms, however, lie between five and six kilometers below sea level.

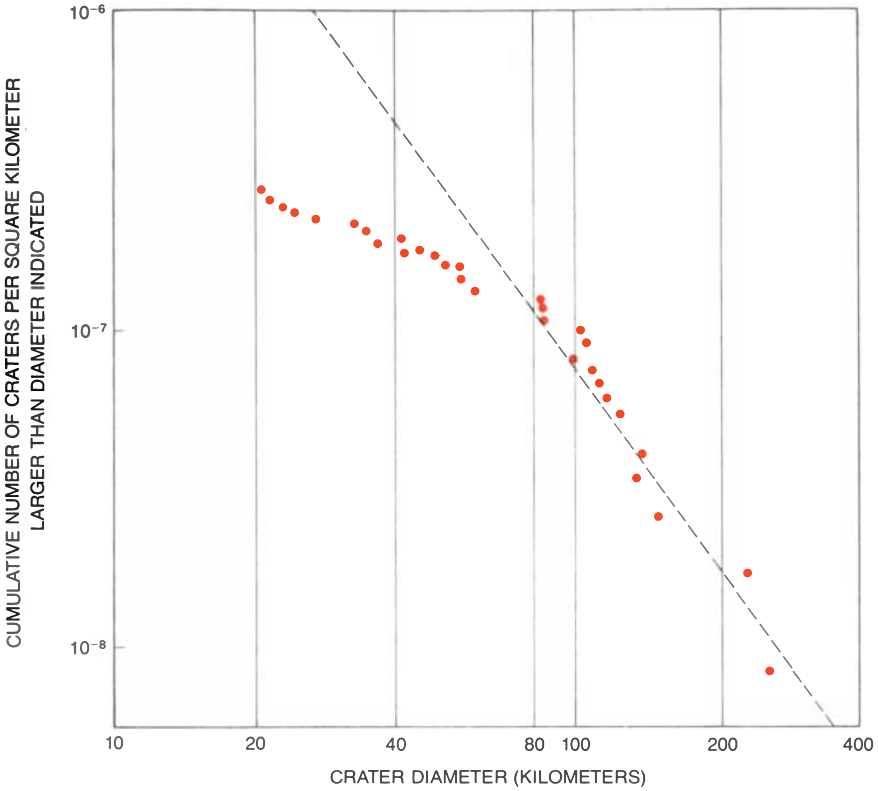
When the Venus orbiting-altimeter map is compared with the roughness im-



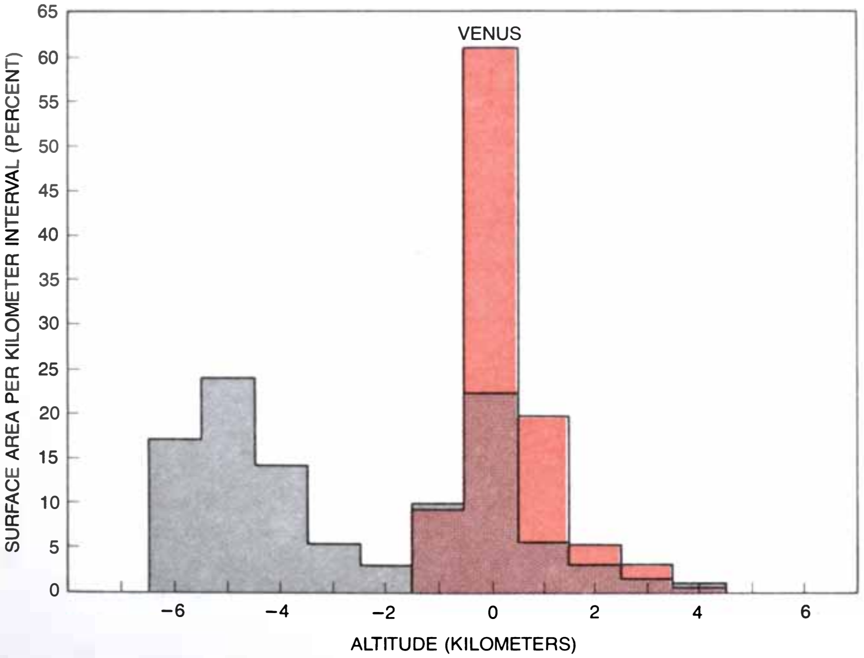
ALPHA REGION is shown with a resolution of about eight kilometers in this image made from the earth. The long parallel markings running from the northeast to the southwest resemble the faulted basin ranges that are found in Nevada and adjacent areas of the southwestern U.S. The ring-shaped feature has been named Eve. Roughly 200 kilometers across, it is probably an ancient impact crater. It has been proposed that the bright central spot serve as the zero meridian for the planet's longitude system. It lies 32 degrees south of the equator.



THREE RING-SHAPED FEATURES lie about 1,500 kilometers to the west of Alpha. The largest is about 100 kilometers across; the resolution is about five kilometers. Because the radial extent of rim roughness and the relief profile are unlike comparable details around impact craters on other planets and the moon, it is uncertain whether rings are really impact craters.



CUMULATIVE DISTRIBUTION OF RING-SHAPED FEATURES on Venus suggests that if they were created by meteorite impact, they conform to a theoretical model (*slanting line*) for the number of impact craters that would have been made within the past 600 million to a billion years. The model is derived from counts of craters on the moon, Mercury and Mars. The agreement is good for craterlike features that are larger than 80 kilometers in diameter. Objects that would give rise to craters smaller than 20 kilometers would tend to burn up in the dense atmosphere. This does not explain apparent dearth of craters smaller than 80 kilometers.



COMPARISON OF RELIEF on Venus (*color*) and the earth (*black*) demonstrates the marked contrast between the two planets. The distribution of surface height is plotted in one-kilometer intervals as a function of surface area. For Venus height is measured from a sphere with the average planetary radius of 6,051.4 kilometers. For the earth the reference is sea level. The dual nature of the earth is clear: it is 65 percent oceanic and 35 percent continental. The 65 percent outside the continental shelf is on the average about five kilometers below sea level. In contrast some 60 percent of the surface of Venus falls within half a kilometer of the average radius.

age made from the earth, a striking fact emerges: at radar wavelengths the highest regions tend also to be the roughest. Thus Maxwell, by far the brightest (that is, the roughest) large feature in the scattering image made from the earth, is seen also to be the highest, towering above the rest of the planet at altitudes of as much as 11 kilometers above the planetary mean. The Lakshmi plateau to the west of Maxwell is an exception to the rule. Although it is elevated from two and a half to three kilometers above the mean, it displays one of the smoothest large surfaces on the planet. The plateau is fringed on the north and west by fairly high mountain chains. The entire elevated continent has been named Ishtar (after the Babylonian goddess of love). The other large continental structure, called Aphrodite (after Ishtar's Greek counterpart), is along and just south of the equator, between longitudes 70 and 140 degrees east. Although Aphrodite is not as high as Ishtar, it covers nearly twice the area, a fact obscured by distortion associated with the Mercator projection.

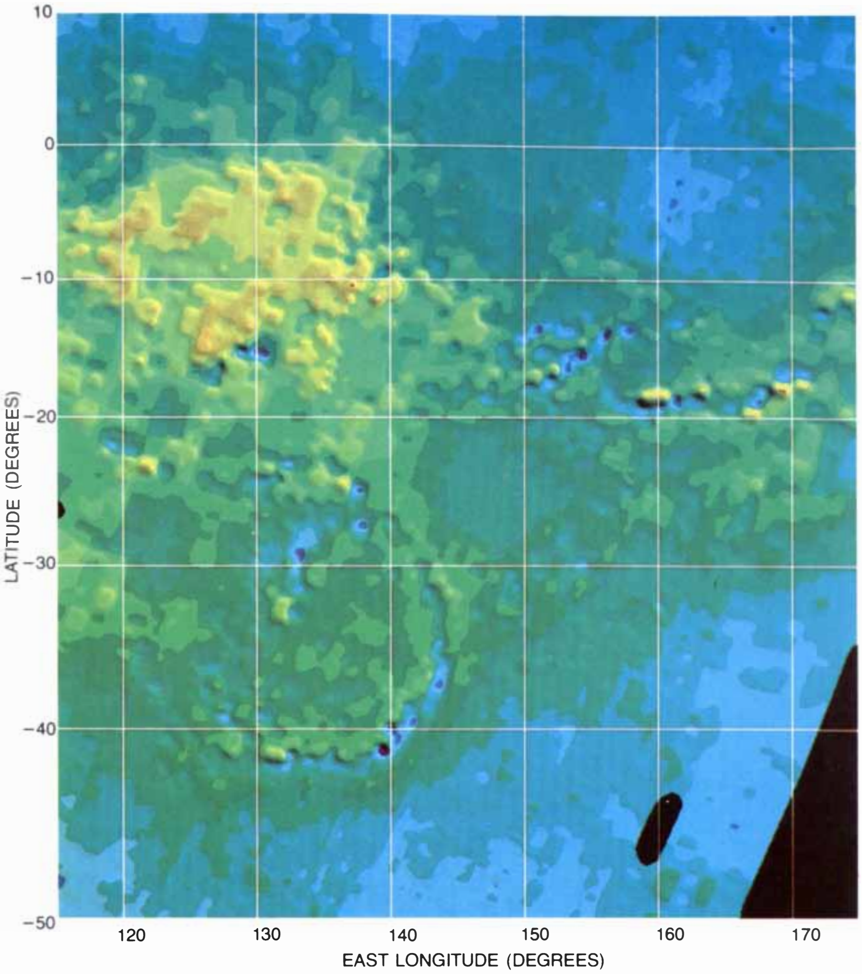
Since Venus has continents of a sort, it is natural to wonder if, like the continents on the earth, they represent regions that are in gravitational equilibrium with their surroundings. This state, known as isostatic equilibrium, requires that topographic relief be supported by buoyancy arising from a reduced density, as an iceberg floats in water. Thus continents on the earth, which are in isostatic equilibrium, rise above the surrounding ocean basins to an extent that depends primarily on the continents' density and thickness. The degree of isostatic equilibrium on Venus can be tested by studying small perturbations in the motions of the orbiter as it passes over the large elevated structures. William L. Sjogren of the Jet Propulsion Laboratory, who has examined such perturbations in the gravitational fields over Ishtar and Aphrodite, has concluded that the regions have largely settled into a state of minimum gravitational energy.

If gravitational equilibration accounts for the large-scale relief observed on Venus, one is almost obliged to assume that substantial differences in the density of the planet's crust have been brought about by processes of differentiation. On the earth differentiation has resulted from large-scale melting of the planet's interior. Additional evidence for comparable melting on Venus is furnished by the planet's dense atmosphere of carbon dioxide with a substantial admixture of argon. Such an atmosphere argues for the thorough outgassing of a hot interior. Still further evidence for chemical differentiation on Venus is the significant amount of radioactivity measured at the planet's surface by the Russian Venera probes.

To the east of Ishtar and Aphrodite the relief is complex. The region to the east and southeast of Aphrodite is particularly chaotic; it is here that patterns suggestive of tectonic activity are most evident. A roughly circular feature 1,800 kilometers across, centered at 35 degrees south latitude and 135 degrees east longitude, may be the faint remnant of a gigantic ancient impact crater [*see illustration at right*].

In the region just north of 20 degrees south latitude and between 150 and 175 degrees east longitude is a remarkable feature that offers the strongest evidence so far for tectonic (and hence internal dynamic) activity on Venus. The feature is a long, moderately straight valley that has a sharp vertical relief approaching four kilometers. In places it shows a lateral offset, strongly reminiscent of the faults in terrestrial rift valleys.

Turning now to another aspect of the surface of Venus as it has emerged from radar observations, we have sought to correlate the time-delay spreading of the near-vertical-incidence radar echo observed by the spacecraft's altimeter with off-vertical measurements of the backscattered energy made from the earth. The former provides information about the average inclination of reflecting facets with dimensions of a meter or more. Mean values for the slope of the facets were estimated from the spacecraft's radar observations at the same time and at the same resolution as the analysis for altitude. When the results are displayed in a gray-scale pattern, they yield a map generally similar, where the maps overlap, to the centimeter-scale roughness patterns apparent in observations made from the earth [*see illustration on pages 60 and 61*]. The similarity presumably indicates that surface roughness has components ranging all the way from dimensions of a few centimeters to dimensions of many meters. A significant departure from this correlation can be seen to the northeast of Maxwell, where the centimeter-size components (the image obtained from the earth) and meter-size components (the image obtained from the spacecraft) are distributed quite differently.

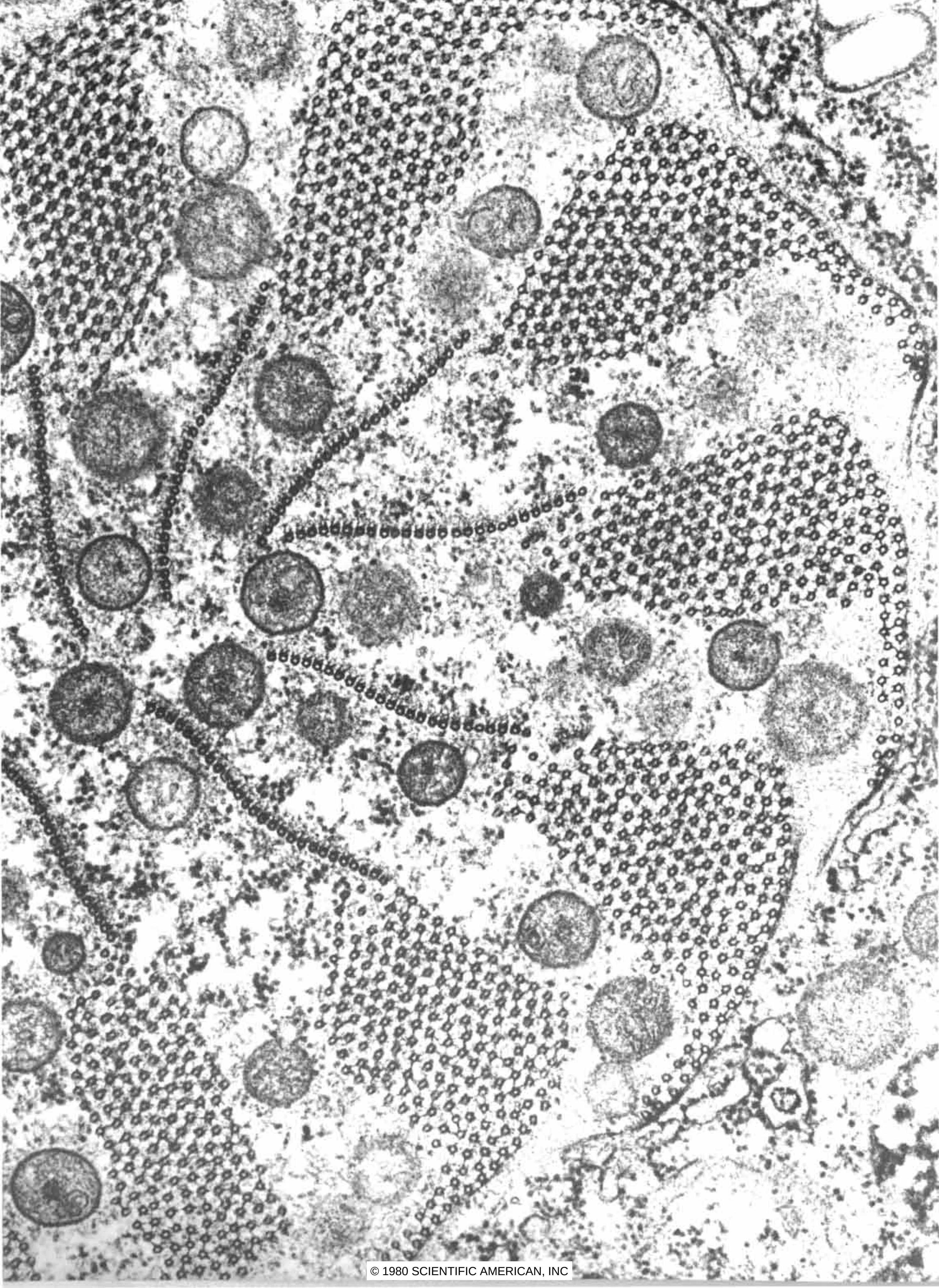


REGION EAST OF APHRODITE, based on orbiter altimetry, is depicted here with the same color contour key and shading technique used in the global map on pages 58 and 59. The region is particularly chaotic. At the right center there is a series of fairly narrow valleys flanked by elongated hills. The most likely cause of such features is tectonic motion in the crust or under it. Centered at 35 degrees south latitude and 135 degrees east longitude there appears to be a circular feature 1,800 kilometers across. It is possibly remnant of a gigantic impact crater.

From a synthesis of all the data now available there begins to emerge a picture of a planet nearly the size of the earth whose surface has been modified by all the processes that have shaped the earth's surface except erosion by rain. The tectonic motion of large crustal plates appears not to have played the dominant role in altering the surface that tectonic motion has on the earth; certainly the distribution (and probably the amount) of light continental material is far different on Venus from what it is on the earth. If the ring-shaped features prove to be the signature of ancient impacts, one must infer that much of the surface of Venus is about a billion years old. Tentatively we conclude that the planet has evolved geologically much as the earth has but not to the same degree. On the other hand, Venus has not preserved as much of its early history as the moon and Mercury have.

Questions of course remain. What are the relative roles of the three major processes—meteorite impact, volcanism and tectonics—that appear to have modified the surface of Venus? Does Venus have a central core of liquid iron-nickel as the earth does? Is there evidence on the surface of Venus for convective motion in the underlying mantle? Are volcanoes still spewing volatile substances into the atmosphere? Relatively simple radar observations have parted the veil of clouds and have given us our first comprehensive glimpse of the surface. The resolution that has been achieved so far, however, is too coarse to answer many questions in a satisfactory way. For any better understanding images with a resolution of hundreds of meters or less, such as *Mariner 9* first made of Mars at the wavelengths of light, are needed.

NASA now has under consideration, for launching later in this decade, a spacecraft that may carry an advanced form of synthetic-aperture radar in a low circular orbit around Venus. Called the Venus Orbiting Imaging Radar (VOIR), this advanced radar system would map the entire surface of the planet at a resolution of about half a kilometer, comparable to the resolution obtained by *Mariner 9* at light wavelengths. At that resolution *Mariner 9* was able to unambiguously establish that there were both volcanism and tectonic activity on Mars, to define geologic units on the surface of the planet and to indicate their relative ages. In short, *Mariner 9* was able to provide a credible geologic history of Mars. Now that the technology for studying the surface of a planet by radar has matured, one can look forward to a similarly successful effort to understand the geologic history of Venus.



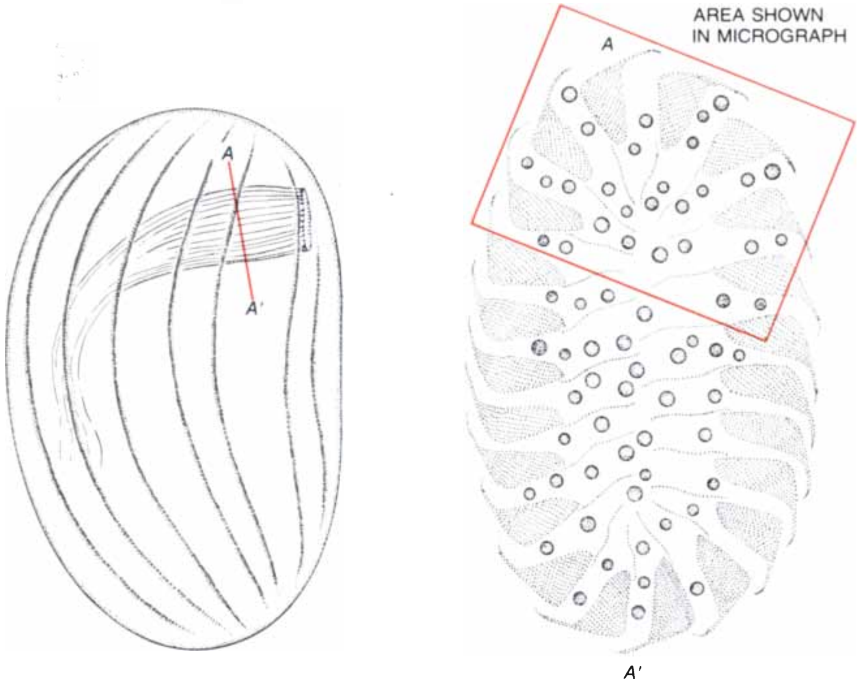
Microtubules

They are structural organelles that are found in all nucleated cells. Assembled like scaffolding from protein subunits, they participate in cell division, cell movement and the maintenance of cell shape

by Pierre Dustin

One of the fascinating aspects of biology is the continual rediscovery of evidence for the unity of all living cells, from the ubiquity of DNA as the genetic material to the presence, in unicellular organisms and the cells of advanced plants and animals, of the same intricate structures performing essentially the same functions. Among these structures are the cellular organelles known as microtubules: long, slender tubes that function, sometimes as fairly rigid rods and sometimes as rather flexuous ropes, to maintain and change the shape of the cell or its component parts, to move material through the cell and to separate the duplicated sets of chromosomes in the course of cell division. Microtubules are present in every eukaryotic (nucleated) cell in one form or another, and usually in many forms. Many of those forms had been observed and described as much as a century ago, but recognition of their common structure and composition—of the microtubule as such—has come only in the past two decades.

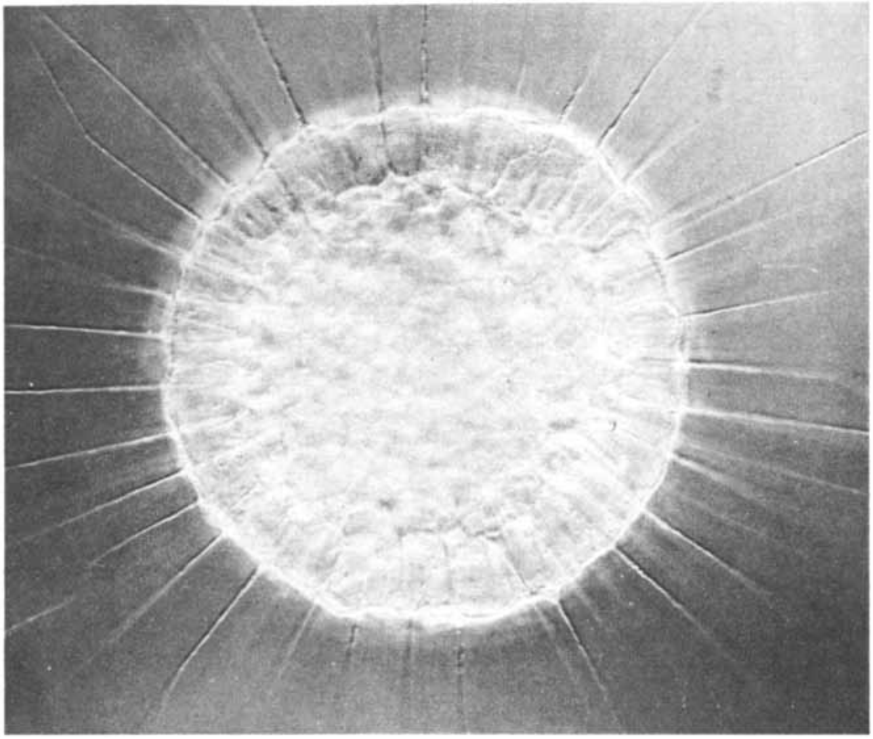
The investigative pathway to microtubules began, strangely enough, with gout. That painful disease results from a high level of uric acid in the blood. Microcrystals of urate are engulfed by white blood cells, and the release of irritating enzymes from granules in the cells causes the sharp pain of an acute attack of gout. The most effective drug for mitigating the pain is (for reasons that are still unclear) the drug colchicine, a toxic alkaloid from the meadow saffron (*Colchicum autumnale*), a plant known for centuries as a specific for joint pains. Colchicine itself was purified in 1883. Its known toxicity led an obscure investigator in Sicily named B. Pernice to study its effect in dogs, and he reported in 1889 that the drug caused striking changes in the germinative zones (regions where cells normally keep proliferating) of the intestine: nearly all the cells seemed to be in the process of division. Pernice's report was not noted at the time, and it was rediscovered only in 1949.



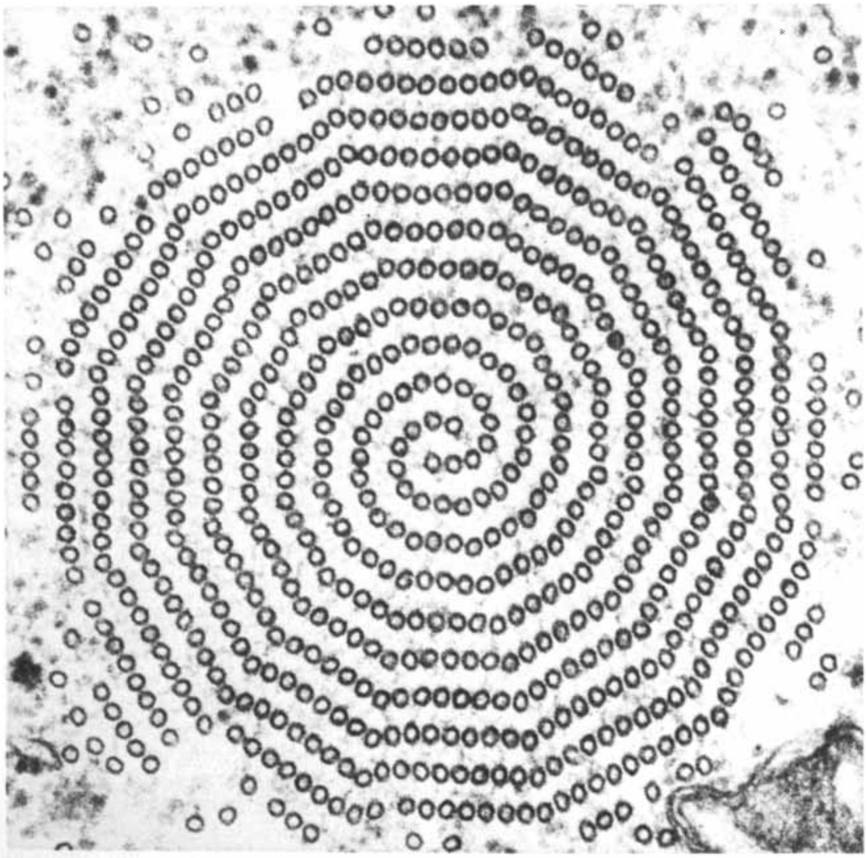
ARRAY OF MICROTUBULES forming the framework of the pharyngeal basket of a protozoan, the ciliate *Pseudomicrothorax dubius*, is seen in cross section enlarged about 75,000 diameters in an electron micrograph (*opposite page*) made by Klaus Hausmann of the University of Heidelberg. The pharyngeal basket (*drawing at left above*) is a tubelike structure that opens to ingest prey such as algae. A full cross section of the closed basket (*right*) shows an elliptical structure framed by roughly triangular bundles of microtubules (22 in this case), with the same number of linear elements converging in the interior. The framing bundles are arrays of microtubules, which are linked together in a hexagonal pattern; the linear elements are sheets composed of about 25 microtubules. Interspersed round structures are mitochondria.

Early in this century, however, there were several reports that colchicine seemed to stimulate cell division, and they led to modern colchicine research. It began in 1933 at the University of Brussels in the laboratory of my father, Albert P. Dustin, who had been studying the regulation of cell growth and division for many years. A young medical student, Franz Lits, suggested that colchicine's specific effect on cell division should be studied. Lits found that injecting mice with colchicine seemed to result in a large increase in mitosis, or cell division, in all germinative tissues.

In the next few years the apparent increase was explained. Cell division is not stimulated by colchicine. Actually it is halted: the drug arrests cell division at a particular stage, prometaphase, by destroying the fibrillar apparatus (called the spindle because of its shape) that moves the two sets of chromosomes apart in preparation for making two cells out of one. The observer sees many mitotic figures not because mitosis has been stimulated but because there is an accumulation of cells blocked in mid-mitosis. In 1937 the same effect was noted in plant cells, and colchicine became an important tool for producing plants with multiple sets of chromosomes and thus for giving rise to fertile hybrid plants. By 1955, when the Amer-



AXOPODS of the heliozoan *Actinosphaerium*, thin extensions that radiate from the cell like the rays of the sun, trap prey and move it to the cell body. The protozoan is enlarged 200 diameters in this photomicrograph made by Manfred Schliwa of the University of Frankfurt.



AXONEME, the core of a single axopod, is seen in cross section enlarged 90,000 diameters in an electron micrograph made by L. E. Roth of the University of Tennessee; it consists of an array of microtubules assembled in a double spiral. The pattern has 12-fold symmetry; in each pie-shaped segment the number of microtubules increases by one in successive rows.

ican botanist O. J. Eigsti and I published a monograph on colchicine, it was clear that the alkaloid was a very specific inhibitor of cell division. We assumed that it became attached to some particular component of the spindle fibers.

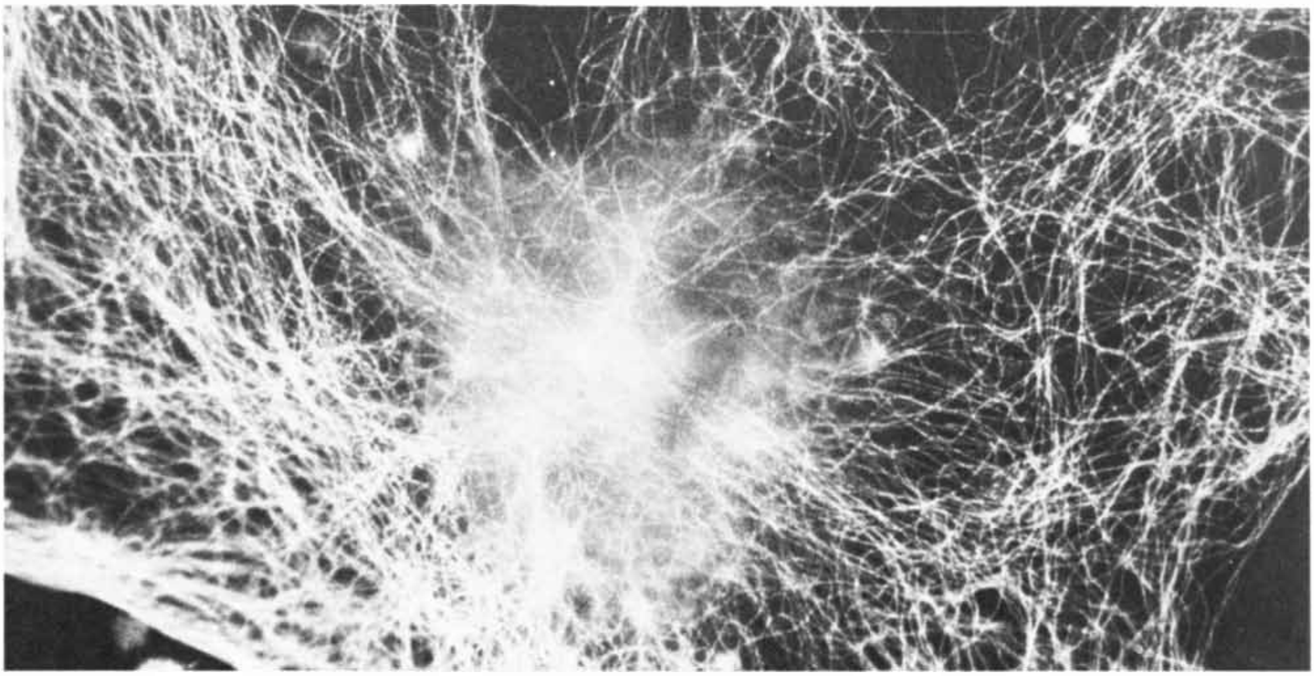
In the 1960's a group headed by Edwin W. Taylor of the University of Chicago studied the action of colchicine by labeling it with tritium, the radioactive isotope of hydrogen. Taylor reported in 1965 that labeled colchicine bound irreversibly to human cells in tissue culture and, in low concentrations, arrested mitosis without having other metabolic effects; he suggested that the drug bound to a structural component of the spindle. In 1967 Gary G. Borisy and Taylor isolated the colchicine-binding protein and found it was most abundant not in dividing cells but in nerve cells in the brain, which do not divide; wherever it was present, they pointed out, there were the structures known as microtubules.

The microtubules had been named in 1963 by Myron C. Ledbetter and Keith R. Porter, who were then working at Harvard University, and by David B. Slautterback of the University of Wisconsin Medical School. By the time Porter summarized what was known about microtubules in 1966 they had been recognized, on the basis of apparently identical structure and ultrastructure, in higher and lower plants and animals, in nerve cells as well as dividing cells and most clearly in two appendages that effect movement: the hairlike cilia of many kinds of cells and the taillike flagella of motile cells such as spermatozoa. Borisy and Taylor suggested that the colchicine-binding site was a subunit of the microtubule, which was thus shown to be chemically as well as structurally similar in many different cells.

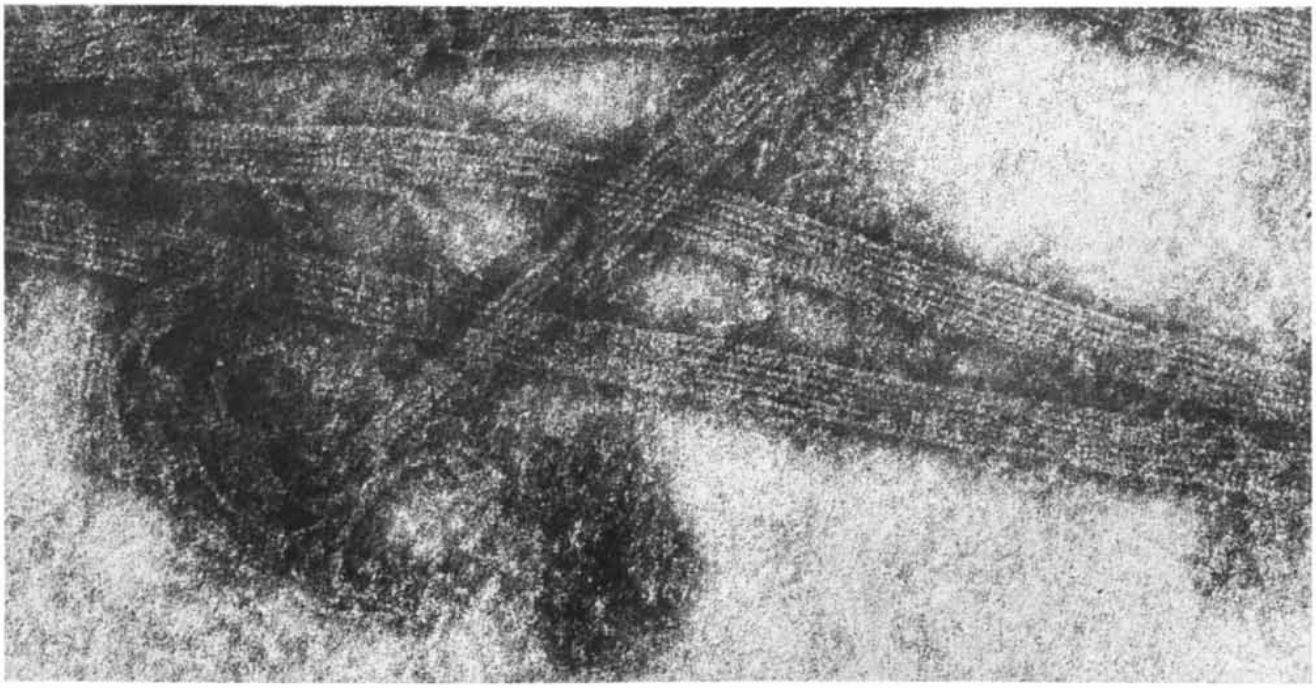
In the years that followed investigators in many laboratories studied the multiple functions of microtubules in a variety of cell types. In my laboratory at the Université Libre de Bruxelles, Étienne de Harven, who is now at the Sloan-Kettering Institute for Cancer Research, and the late Wilhelm Bernhard showed that the spindle fibers are tubular in shape and that the centriole, the structure from which those fibers extend, is itself a complex association of microtubules. Other workers in the laboratory showed that microtubules have an essential role in the secretion of hormones by the thyroid gland and the pancreas. More recently Jacqueline Flament-Durand and I have studied the effect of colchicine on the transport of secretory granules through the fibers of nerve cells. The ubiquity of microtubules in eukaryotic cells and their importance for a wide variety of functions have been abundantly demonstrated.

Whatever their particular function, whether in plants or in animals, microtubules are essentially the same: long tubular structures with an outside diameter of about 24 nanometers (a nanometer is a millionth of a millimeter) and a central lumen, or bore, about 15 nanometers in diameter. Their length is indeterminate but is almost always much greater than their width; it is often many micrometers (thousandths of a millimeter). Microtubules extend along the axons of nerve cells, which in large animals can be several meters long, but the organelles themselves are apparently not continuous over anything like that length; recent observations of several serial sections of the nerves of a nematode worm by Martin L. Chalfie and J. Nichol Thomson of the Medical Research Council Laboratory of Molecular Biology in Cambridge show that the microtubules range in length from 10 to 25 micrometers.

When cross sections of microtubules are examined with the electron microscope, they look like circles. At very



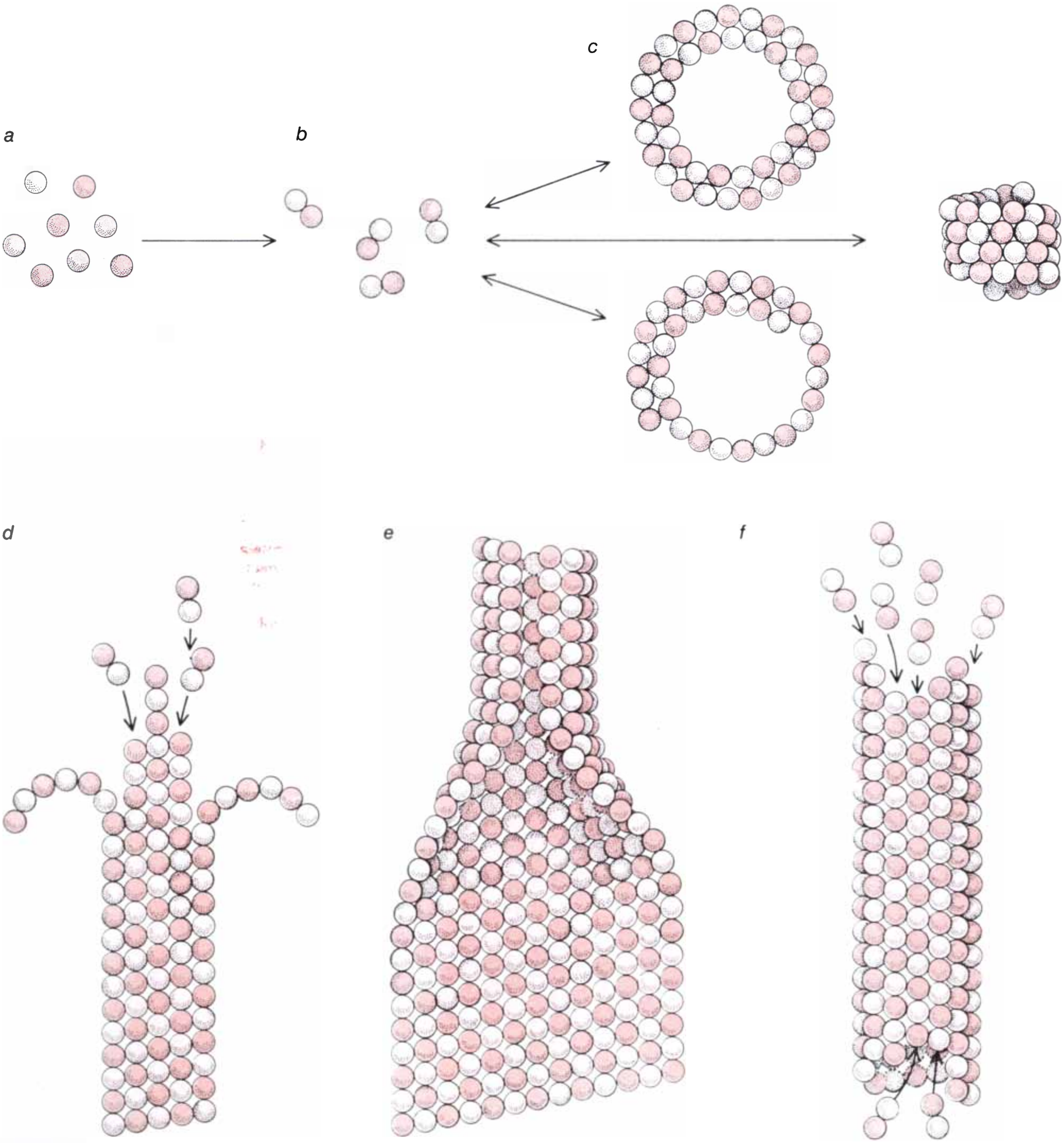
NETWORK OF MICROTUBULES crisscrossing a fibroblast (connective-tissue cell) is visualized by immunofluorescent staining and is enlarged about 1,500 diameters in a photomicrograph made by Klaus Weber and Mary Osborn of the Max Planck Institute for Biophysical Chemistry in Göttingen. The cell was exposed to a rabbit antibody against tubulin, the protein of which microtubules are constituted; the rabbit antibody bound to the microtubules. Next the rabbit antibody was stained in turn by a goat antibody directed against rabbit immunoglobulin, to which a fluorescent dye had been linked, and the cell was then photographed under ultraviolet illumination.



ISOLATED MICROTUBULES from blood platelets are negatively stained and enlarged about 250,000 diameters in an electron micrograph made by Olav Behnke and Tor Zelander of the University of Copenhagen. Each flattened microtubule displays six parallel protofilaments, beaded because they are composed of tubulin subunits and tending to separate and curl at the ends, as is seen at the bottom left.

high magnifications it is apparent that the circle is composed in turn of a number of roughly circular subunits. As Porter had observed in 1966, there are almost always 13 of these subunits; sometimes there are a few more or less. Longitudinal views of flattened microtubules show that they are composed of strands called protofilaments (usually 13 of them), each one a linear assembly of subunits.

The subunits are dimers, or double molecules, composed of two very similar proteins: the alpha and beta tubulins. Each is a globular molecule—probably a prolate spheroid or an ellipsoid—with a molecular weight of about 55,000 daltons. Of the roughly 500 amino acids comprising each of these molecules about a fifth have been determined, and the sequences are remarkably similar, suggesting that the two molecules derive from a single primordial protein. The alpha and beta tubulins not only



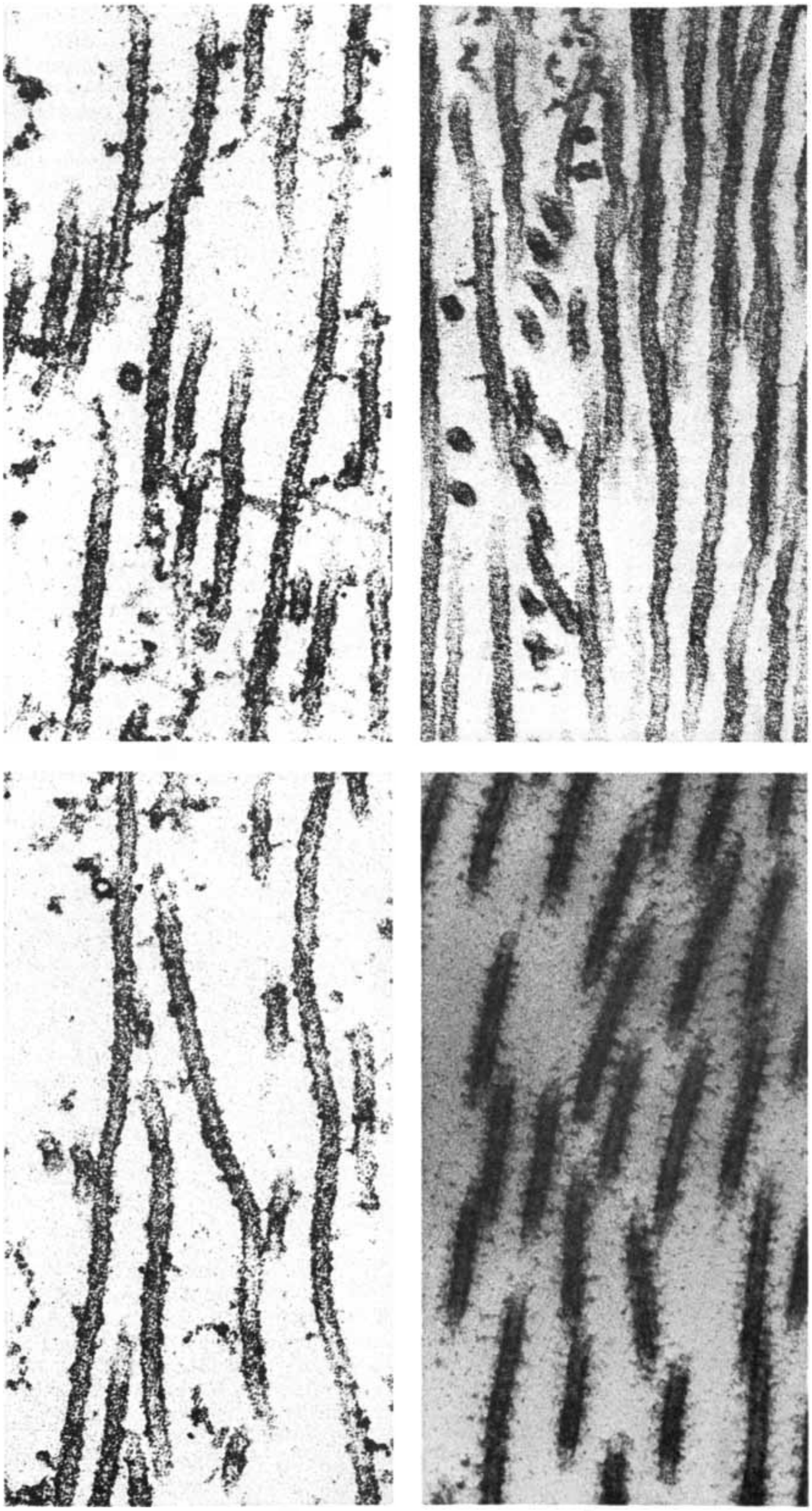
ASSEMBLY OF MICROTUBULES in the laboratory begins with two protein molecules, alpha tubulin and beta tubulin (*a*), which are globular molecules (probably more ovoid than these highly schematic spheres). The tubulins form dimers, or double molecules (*b*). If the dimers are present in a high enough concentration, they associate to form various intermediate structures, including double rings, spirals and stacked rings (*c*); the equilibrium is biased in favor of either the isolated dimers or the intermediate structures, depending on the conditions. The next steps are not well established. It seems that the rings or spirals open up to form strands, called protofilaments, of linearly associated dimers, which assemble side by side in a sheet (*d*); sometimes the ends of protofilaments curve. When a sheet is wide enough, it forms a tube, perhaps by curling up (*e*). Once a short tube has formed (*f*) it is lengthened by the addition of dimers preferentially at one end.

are very similar to each other but also are nearly identical in all the classes of organisms in which they have been studied, which suggests that the tubulins have existed as such ever since the first eukaryotic cells appeared on the earth about a billion years ago.

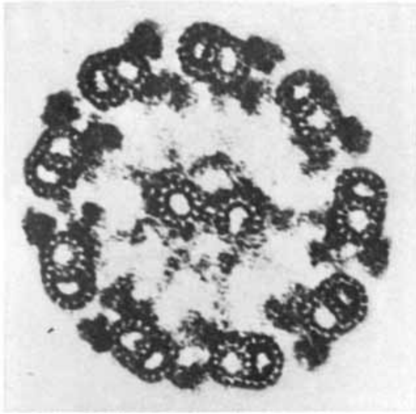
The assembly of tubulin subunits into microtubules is now partially understood, largely as the result of Richard C. Weisenberg's demonstration at Temple University in 1972 of the self-assembly of microtubules in the test tube. He found that if tubulin purified from brain tissue was incubated at a certain concentration, at a certain *p*H (acidity) and in the absence of calcium ions, the preparation would self-assemble to form long tubular structures that looked much like the microtubules seen in cells. Subsequent studies have shown that an alpha and a beta tubulin molecule first become associated to form a dimer shaped like a somewhat squashed figure eight. Each dimer has one specific binding site for colchicine and another for vinblastine, a drug that (like colchicine) poisons microtubules and so prevents cell division. (Vinblastine is effective in the chemotherapy of cancer, unlike colchicine, which is too toxic.) The dimer also has specific binding sites for the nucleotides guanosine diphosphate and triphosphate, which may provide energy for the assembly process.

The sequence of events that links dimers to form a microtubule is still not clearly established; it probably varies with particular conditions, both in the test tube and in the living cell. There is apparently an initiation period, lasting for several minutes, during which a laboratory preparation shows the dimers linked end to end to form rings, double rings, spirals or stacked rings. Next one often sees a number of protofilaments lying side by side to form a sheet. The fact that *C*-shaped (rather than circular) cross sections are sometimes seen in electron micrographs of microtubules suggests that the sheet may curl up to form a tube. In any case a short tubule is characteristically the first microtubulelike structure one sees, with the protofilaments arrayed alongside one another in a helical structure, each turn of the helix being composed of 13 subunits. The tube becomes elongated as additional dimers take their place in the assembly preferentially, but not exclusively, at one end.

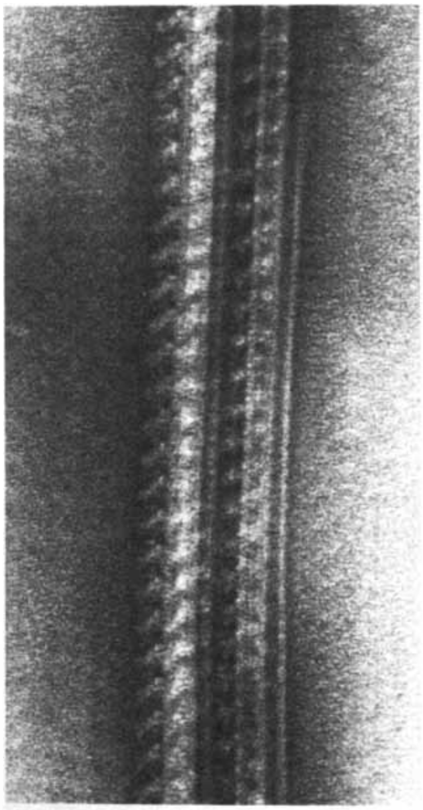
Each of the dimers must have several different links, both longitudinal and lateral, to other dimers. Certain links may be sites that bind colchicine, since a complex of tubulin and colchicine does not self-assemble into tubules. The role of calcium is important, with very small changes in its concentration affecting the assembly process. Some recent results suggest that the calcium-dependent regulatory protein called calmodulin



TUBULIN-DIMER SUBUNITS were assembled under various conditions by Roger D. Sloboda and Joel L. Rosenbaum at Yale University (*top, bottom left*) and by Helen Kim, Lester I. Binder and Rosenbaum (*bottom right*) to produce these microtubules, all enlarged about 100,000 diameters in the electron micrographs. Microtubules assembled in the presence of microtubule-associated proteins (MAP's) show the MAP's as a fuzzy coating (*top left*). Assembled from purified tubulin without MAP's, the microtubules are smooth-walled and pack more densely (*top right*). When such smooth microtubules are resuspended with MAP's, the coating is restored (*bottom left*). Microtubules assembled from tubulin and one associated protein, MAP 2, show projections spaced about 30 nanometers apart (*bottom right*). The print was made by offsetting two duplicate negatives just enough to reinforce projections' periodicity.



CROSS SECTION OF A CILIUM of a sea urchin is stained with tannic acid and enlarged 225,000 diameters in an electron micrograph made by Keigi Fujiwara of the Harvard Medical School and Lewis G. Tilney of the University of Pennsylvania. Two central microtubules are surrounded by nine doublets, each composed of a complete microtubule (whose 13 subunits are visible) and an incomplete one. Several links connect the structures, in particular two arms of the protein dynein extending from each complete microtubule to the next doublet, and nine "radial spokes."



ADJACENT DOUBLETS from a cilium of the protozoan *Tetrahymena* are negatively stained and seen in longitudinal section enlarged about 190,000 diameters in an electron micrograph made by Fred D. Warner and David R. Mitchell of Syracuse University. Cilia were dissociated in a medium containing adenosine triphosphate (ATP). In this "active" state the dynein arms by means of which two doublets slide in relation to each other are seen as periodic oblique extensions.

controls the assembly and disassembly of microtubules in dividing cells.

Microtubules in turn aggregate to form a number of more complex bodies, including cilia and flagella, basal bodies and centrioles (whose functions I shall discuss below). Basal bodies and centrioles are identical in structure. They are made up of nine sets of triplets, each triplet consisting of one complete microtubule and two *C*-shaped ones. Basal bodies (the templates on which cilia are formed) and centrioles (which are found, in many cells, at the center of the pole bodies from which the spindle fibers originate) belong to a group of structures known as microtubule-organizing centers that appear to be prerequisite for the growth of microtubules. They are not always as structurally discrete as centrioles and basal bodies; in many instances they are seen simply as dense bodies in the cytoplasm of cells or along the cell membrane. A great deal of current research is aimed at understanding the biochemistry and the function of these organizing centers.

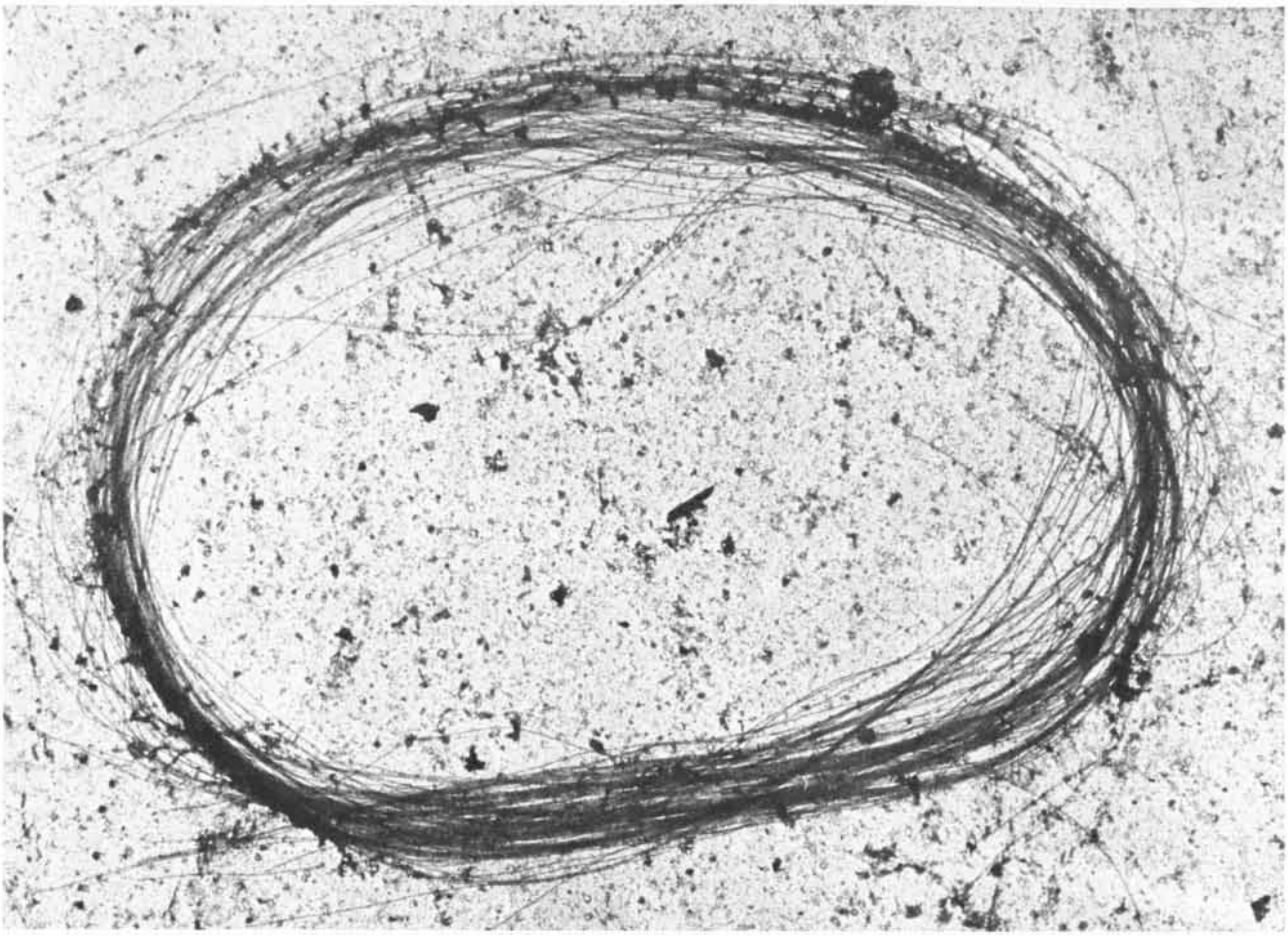
The study of tubulin assembly led to the discovery of the microtubule-associated proteins, or MAP's: several large proteins, with a molecular weight of about 200,000, and a smaller one, the tau protein. The MAP's are not required for the assembly of tubulin dimers into microtubules, but they seem to facilitate the process, since microtubules take form faster, and at a considerably lower tubulin concentration, when the MAP's are present. The MAP's also seem to protect microtubules from agents (such as colchicine) and under conditions (such as cold and high fluid pressures) that tend to dissociate them. The MAP's project from the surface of microtubules, and at least one of them, MAP 2, has recently been shown to be fixed to the surface at regular intervals. Such projecting arms might participate in some kind of ratcheting mechanism whereby the microtubules function to maintain cell shape and also to effect cell movement.

Microtubules have often been said to provide a "skeleton" for the cell. If they do, it is a very unstable skeleton indeed: microtubules can be disassembled within minutes, after which their tubulin subunits are often reassembled to form entirely new kinds of structures. There are several other proteinaceous fibrils in the cytoplasm of cells, including microfilaments (made largely of the contractile protein actin) and several kinds of "intermediate" filaments; they are thinner than microtubules and much stabler. It seems likely that an interaction among these various filaments and the microtubules maintains and changes the shape of most cells. The particular role of the microtubules is not so much that of a skeleton as it is one of scaffolding: a rapidly assembled and disassembled framework that has its effect not through rigidity but through the ability to change shape. The relation between cell shape and microtubules is apparent in certain formed elements of the blood, in many unicellular organisms and in the higher plants.

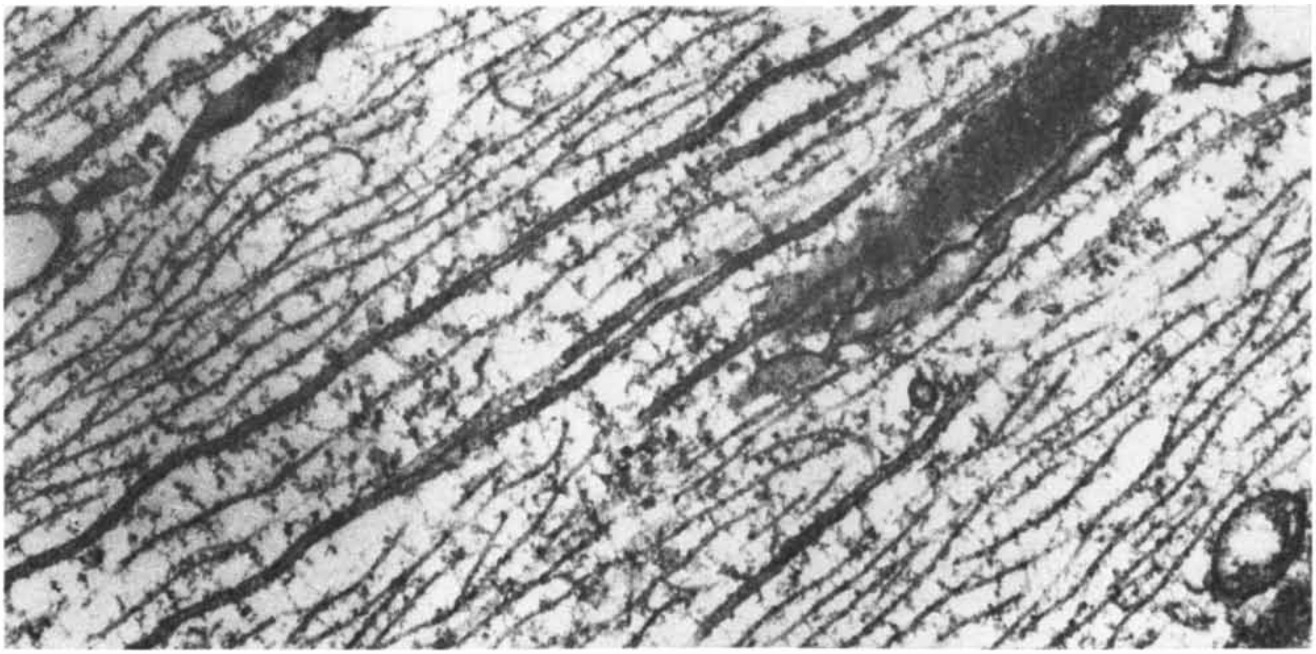
The erythrocytes, or red blood cells, of all vertebrates other than mammals have nuclei and are biconvex and oval in shape. Long before the discovery of microtubules it was known that in these nucleated erythrocytes a marginal band of protein encircles the elliptical perimeter of the cell just under the cell membrane. It is a bundle of microtubules. Since free microtubules tend to be straight, those of the bundle must be linked somehow to confer the elliptical shape and rigidity. A similar structure is seen in the blood platelets of mammals, which are without nuclei and indeed are not really cells, being fragments of large multinucleated precursor cells in the bone marrow. The platelets, which halt bleeding and are essential for blood clotting, are flat disks. Their shape is maintained by the marginal band; the platelets change to a more or less spherical form when the band is disrupted by low temperature or by colchicine. On the other hand, in mammalian red cells, which are biconcave disks without a nucleus, there are no microtubules (although they are present in the erythrocytes' nucleated precursor cells). There is an exception among mammalian erythrocytes: the red cells of the Camelidae (camels and llamas) are oval, although without nuclei, and they have a marginal microtubule bundle that is apparently indispensable for giving the cells their oval shape but not for maintaining it, since the bundle can be destroyed without the loss of cell shape.

The shape and perhaps the functioning of many complex structures in unicellular animals (protozoans) depend on microtubules. Among these structures are the radiating axopods of heliozoans, cytoplasmic extensions in which prey is entrapped and carried toward the cell body. The axoneme, the core of the axopod, is a sheaf of microtubules with protein cross-links, often assembled to form remarkable patterns. A cross section of the axopod of *Actinosphaerium*, for example, shows a double helical arrangement of hundreds of tubules with an overall 12-fold symmetry. Other patterns have been described, all of which imply the existence of protein links between microtubules. The microtubules are labile, sometimes disintegrating in a few minutes and then being reconstituted in less than an hour from a pool of cytoplasmic tubulin. When the structure is specifically disrupted by colchicine, it is soon regenerated; how the cell directs the assembly process is still a mystery.

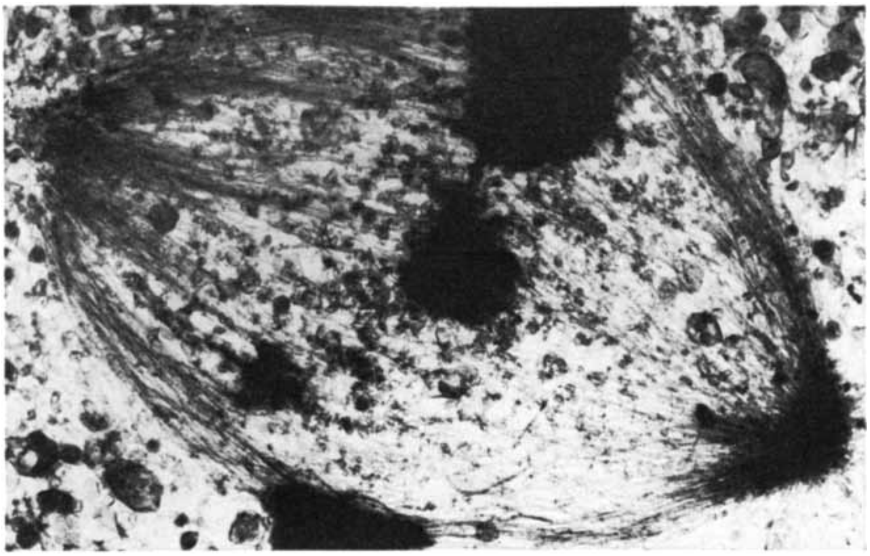
Exquisitely complex patterns of microtubules are also seen in the pharyngeal basket (a food-ingesting organelle)



MARGINAL BUNDLE of microtubules is all that remains (except for cell debris) of a red blood cell of the newt *Triturus cristatus* after treatment with a bile acid. Such a bundle, characteristic of the ovoid red cells of vertebrates other than mammals, helps to maintain the cell's elliptical shape, probably in association with proteins that link the microtubules together and curve them. The structure is enlarged about 4,500 diameters in this electron micrograph, which was made by Bruno Bertolini and Gianni Monaco of the University of Rome.



AXOPLASM (protoplasm of a nerve-cell axon) is enlarged 75,000 diameters in an electron micrograph, made by the author, of the interior of a human axon. The prominent long, tubular structures (two of which cross from lower left to upper right) are microtubules. The numerous thinner fibrils are neurofilaments; the larger, irregular bodies are membranes of the endoplasmic reticulum. Projections from the microtubules' surface (probably MAP's) may be connected to neurofilaments and to material that is transported along the axon.



MITOTIC SPINDLE of a cultured mammalian cell is seen at the metaphase stage of cell division in a high-voltage electron micrograph made by J. Richard McIntosh of the University of Colorado at Boulder and his colleagues. Microtubules extend from the pole bodies to the as yet undivided chromosomes (*dark masses at center*) and from one pole to the other, forming the barrel-shaped spindle typical in vertebrate cells. The enlargement is about 11,000 diameters.

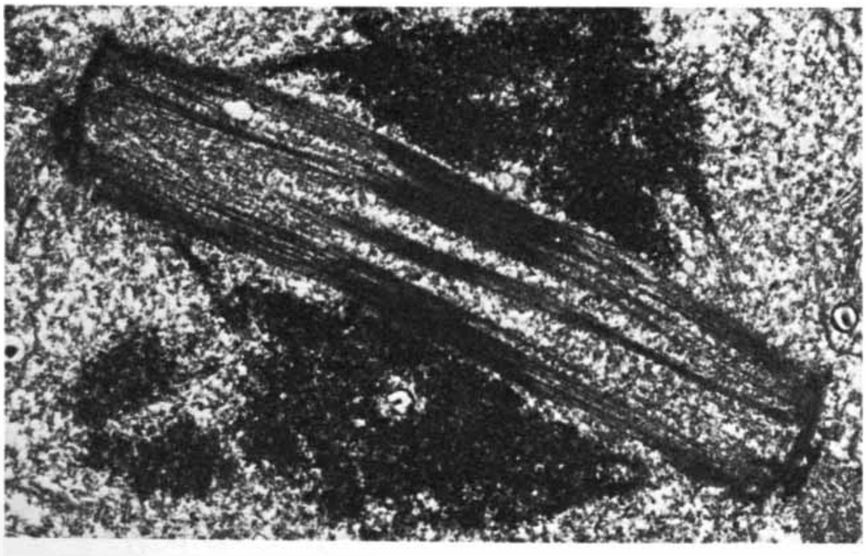
of ciliates and in several kinds of tentacles, as well as in the cilia and flagella of protozoans. In all of these the microtubules clearly have a role as supporting structures: as rods that give shape to extensions of the cell or to intracellular organelles. In addition their ability to dissociate and reassociate and the fact that they are closely linked with contractile proteins allow them to undergo a considerable amount of deformation and thereby to take part in cell movement and in the movement of particles within the cell.

The effect of microtubules on cell shape is also apparent in plant cells. When some early experiments on the action of colchicine were done at Brussels by Laszlo Havas in 1937, the inhibition of root-tip growth by colchicine was found to lead to peculiar swellings of the rootlets that were called *C* tumors. Later research showed that microtubules have to do with the formation of the rigid fibrous wall of plant cells, controlling the orientation of the wall's cellulose fibers. The plane along which a plant cell will divide is indicated early by an equatorial band of microtubules just under the membrane. When the division is asymmetric (as it is in the formation of the porelike stomata of leaves), the asymmetry is foreshadowed by the location of the microtubules. Recent work by Brian E. S. Gunning of the Australian National University and by Adrienne R. Hardham of Carleton University in Ottawa shows that the location of the equatorial band is determined by genetic information. The microtubules therefore provide a visible link between the activity of genes and the shaping of the many different cell types required for the formation of roots and leaves.

The integrity of microtubules is required for movement by cells (such as white blood cells) that move essentially by repeatedly changing their shape, elongating and retracting their cytoplasm along an axis oriented in the direction of motion. Microtubules seem to be responsible in particular for oriented movement toward an objective. (It is therefore possible that colchicine mitigates the pain of gout by reducing the ability of white blood cells to locate and engulf urate crystals.)

It is in cilia and flagella that microtubules operate most spectacularly to achieve motion. In both of these motile structures an extension of the cell membrane encloses an axoneme composed of nine microtubule doublets (one complete tubule with an incomplete tubule nested alongside it) symmetrically arrayed around a central pair of microtubules. The doublets and the central pair are interconnected by several different protein links. The motion results from the action of the protein dynein, which forms arms that project from the surface of the tubules and cause the doublets to slide in relation to one another. Shear resistance offered by links between doublets converts the sliding motion into bending: the waving of cilia and the beating of flagella.

The conveyance of ingested particles toward the cell body along the axopods of protozoans is one example of another kind of movement associated with microtubules: transport within the cell. This has been most thoroughly studied in axoplasm, the cytoplasm of nerve-cell axons, within which there are two kinds of movement. One is a slow (perhaps two millimeters per day) migration, called axoplasmic flow, of various components synthesized in the cell body, including microtubules. The other, much faster (some 400 millimeters per day), is axonal transport. It is arrested when microtubule function is disrupted by an agent such as colchicine, as we have shown by observing the movement of large neurosecretory granules in axons extending from the hypothalamus in the brain to the pituitary gland. Colchicine inhibits the transport of the granules, but the microtubules in the axons appear not to be destroyed. The reason



PRIMITIVE FORM of cell division takes place in the diatom *Pinnularia major*. The axis of the division is established by two interdigitating sets of microtubules, which extend toward each other from two pole bodies that look like concave plaques; the two sets of microtubules overlap at the center. The chromosomes (*dark granular masses*) are somehow pulled toward each pole; just how they are linked to the microtubules is not known. The electron micrograph was made by Jeremy D. Pickett-Heaps of the University of Colorado at Boulder and his colleagues.

may be that the drug interferes with the attachment of a contractile protein such as actin to the surface of the microtubule. One current model for the mechanism of axonal transport assumes that the microtubules serve as tracks along which particles are drawn by filaments made of some contractile protein [see "The Transport of Substances in Nerve Cells," by James H. Schwartz; SCIENTIFIC AMERICAN, April].

Microtubule poisons such as colchicine also inhibit movement within secretory cells and in the pigment cells called melanophores. In both kinds of cells granules (containing hormone or enzyme molecules in secretory cells and the pigment melanin in melanophores) are transported toward the cell surface, to be secreted from the cell or to darken the cell as the case may be. Again the microtubules appear to act as guides, with the actual source of energy perhaps being provided by contractile proteins attached to them.

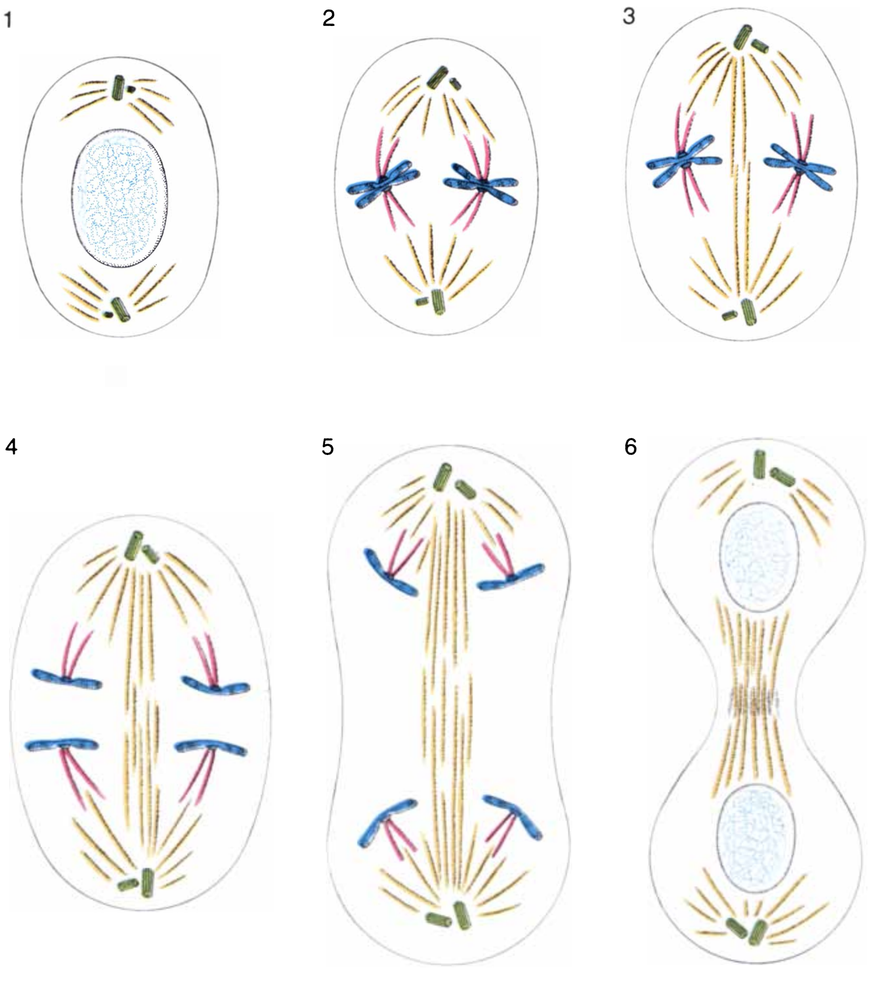
As the earliest observation of the effects of colchicine indicated, microtubules are indispensable for mitosis. Their disruption puts a prompt halt to the complex minuet of the chromosomes that precedes cell division. Clearly the spindle fibers are essentially microtubules, which are assembled at the proper stage of the cell cycle from a pool of subunits in the cell. Even in a particular cell type, however, there are several groups of spindle fibers, each of which may be associated with different contractile proteins. Moreover, in different organisms both the process of cell division and the nature of the structures that mediate it can be quite different. In spite of many years of investigation mitosis and the role in it of microtubules are far from being thoroughly understood.

What one can say is that in most cells two different groups of microtubules are required for chromosome movement. One group grows out from a specialized region of each chromosome, the kinetochore, to a pole body (which in primitive plants and in animal cells includes a centriole) at each end of the spindle; the other set extends from pole to pole. The fibers attached to the kinetochores play a role first in grouping the chromosomes at the cell equator during the initial stages of mitosis. The subsequent movement of one set of chromosomes toward each pole is accomplished either by the shortening of the microtubules attached to them or by a sliding action between the chromosomal microtubules and the ones extending from pole to pole. In many cells the nucleus itself is meanwhile elongating significantly as the pole-to-pole fibers lengthen, a process that contributes to separating the chromosome sets.

Microtubules do not contract; they become shorter only as the result of the dissociation of tubulin subunits at one end or at both ends. It is hard to imagine that such a passive process as the disassembly of a structure attached to the chromosomes can move them, even if their motion is very slow and requires very little energy. It seems likely instead that a sliding mechanism is at work, powered perhaps by proteins of the actomyosin group, which are responsible for muscle contraction; such proteins have been demonstrated in the spindle by a variety of techniques. Disassembly of microtubules is probably also taking place: calmodulin (which seems to control assembly and disassembly) has been shown to be present in the spindle of some cells.

In addition to the spindle-fiber microtubules I have mentioned, another microtubular structure often appears in the last stages of cell division. After two daughter nuclei have formed and just before the two new cells separate, a threadlike bridge is the only connection between them. It consists of two sets of microtubules, interdigitated at their extremities, which are embedded in a dense matrix of unknown composition. It may be that these microtubules represent the ends of the two groups of polar spindle fibers, which have slid (or have actively ratcheted their way) past each other and by this stage overlap only at their tips.

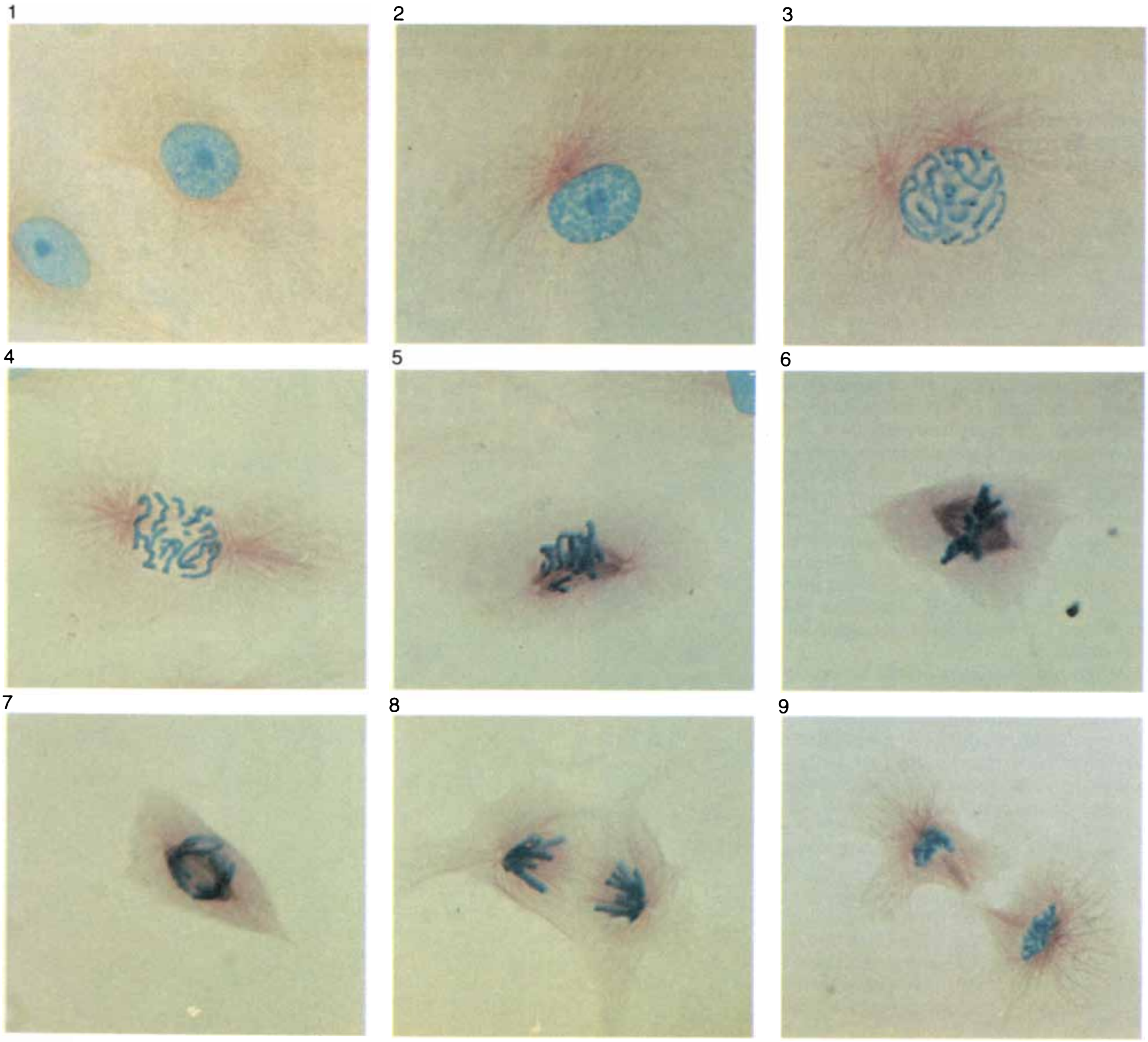
To summarize what is known of mitosis, changes in the length of microtubules seem both to elongate the cell and to pull the two sets of chromosomes apart. The force that is required for these movements, for the narrowing of the waist of the dividing cell and for the



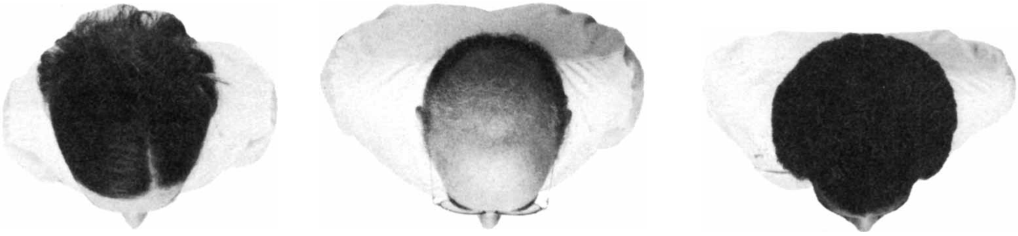
CELL DIVISION is diagrammed schematically in a cell that has centrioles. At the beginning, with the chromosomes as yet uncondensed and bounded by the nuclear membrane, polar microtubules extend from the region around the centrioles, from each of which a daughter centriole is beginning to bud (*1*). As the polar microtubules elongate, other microtubules grow out from the kinetochores of the condensed but as yet undivided chromosomes (*2, 3*). Then the chromosomes begin to separate (*4*), the kinetochorial microtubules shortening and the polar ones elongating. The centrioles (now two at each pole) appear to pull the chromosomes as the kinetochorial microtubules become shorter; the polar microtubules may still be elongating (*5*). When the chromosomal cycle is completed and two daughter nuclei have formed (*6*), a bundle of microtubules persists at waist of dividing cell, which is constricted by actin fibers (not shown).

final pinching off of the bridge connecting the two daughter cells is probably provided by microfilaments or other fibrils consisting of proteins such as actin and myosin.

As ubiquitous structures with varied functions microtubules have been the subject of intensive investigation by workers interested in many different aspects of cell biology. Current attention is focused largely in three areas. What is the precise nature of the microtubule-associated proteins, how are they associated with the tubulin subunits and what are their functions? What various structures serve as microtubule-organizing centers, how do they develop and how do they give rise to microtubules? What explains the seeming polarity of microtubules, notably their tendency to assemble subunits at one end and lose them at the other end? In addition the genetics of microtubules and their associated proteins is being examined in such simple eukaryotic cells as yeasts; the genes for tubulin synthesis have been identified and their control is under investigation. At the other end of the phylogenetic tree human pathology may provide information on microtubule function. A condition called Kartagener's syndrome involves abnormalities of the dynein or other protein links of cilia, and some pathological fibrillary structures in the nerve cells of aging or psychotic patients may be related to microtubules. Finally there is the problem of how such control factors as calcium contribute to shaping complex three-dimensional structures that are as different from one another as mitotic spindles, centrioles, the axoneme of cilia and flagella and the marginal bundle of red blood cells.



MICROTUBULES AND CHROMOSOMES are stained differently in a series of photomicrographs made by Jan De Mey and Marc De Brabander of Janssen Pharmaceutica in Belgium; the microtubules (*brown*) are stained by colloidal gold coupled to an antitubulin antibody, the chromosomes by toluidine blue. At interphase, before cell division begins, there is a fine network of microtubules throughout the cytoplasm (*1*); the chromosomes are uncondensed and the nucleolus is distinct. In early prophase (*2*) an aster (rays surrounding what will be a pole body) is visible. During prophase (*3, 4*) two asters become visible and migrate to opposite poles of the cell as the chromosomes condense. In prometaphase (*5*) the spindle fibers take shape; in metaphase (*6*) the chromosomes have lined up at the equator of the cell and are attached to spindle fibers leading to opposite pole bodies. In anaphase (*7*) the chromosomes begin to separate. The cell elongates in late anaphase (*8*) and the two sets of chromosomes move apart. In telophase (*9*) two daughter cells are about to be formed.



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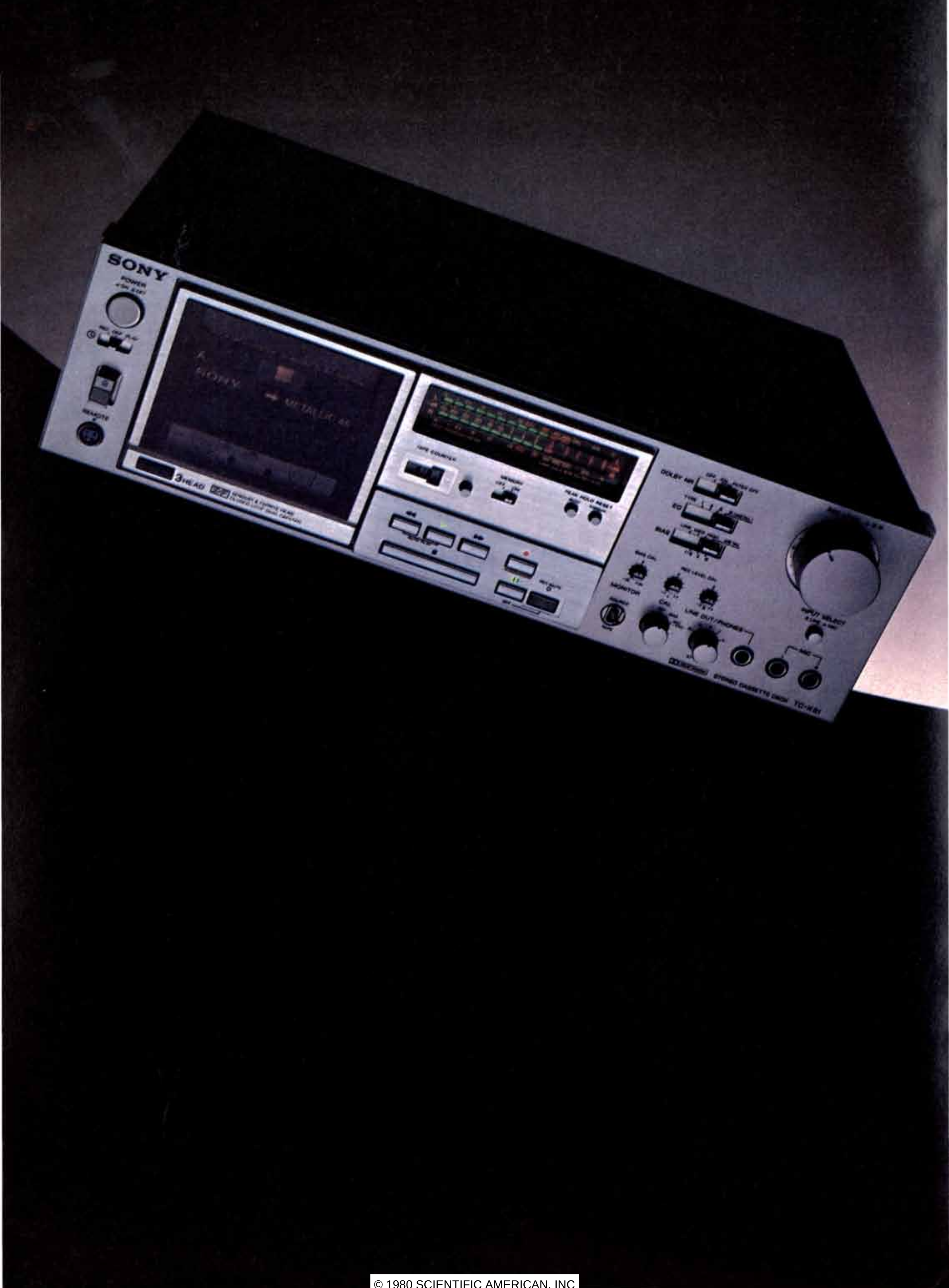
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SCIENCE AND THE CITIZEN

Risk Assessment

A study of the domestic safety record of 18 U.S. airlines and the international safety record of 40 U.S. and foreign carriers has shown that the fatality risk of air travel has dropped by more than half in the past 15 years. Flights within the U.S. are about four times safer than international flights on the largest airlines. The larger of the international carriers in turn have safety records that are about four times better than those of the smaller carriers. The study finds little evidence, however, that long flights are inherently more hazardous than short ones. Within the U.S., for example, flights of less than 200 miles accounted for 39 percent of all flights and 38 percent of all fatal accidents.

The differences in safety records among U.S. domestic airlines appear to represent chance fluctuations. Among international carriers the best safety records were achieved by airlines that are large or, with a few exceptions, are operated by the most technologically advanced countries. The study, which appears in a recent issue of *Management Science,* was conducted by Arnold Barnett of the Massachusetts Institute of Technology and two of his students, Michael Abraham and Victor Schimmel.

The authors address themselves to the following question: "Given that one has decided to fly from *A* to *B,* is there any reason related to safety to prefer one airline flying the route to another?" For the case where *A* and *B* are both in the U.S. the authors analyze the safety record of the 18 major interstate airlines for the 20-year period 1957–76. For the case where *A* and *B* are in different countries, the authors review the safety record for a 16-year period (1960–75) of 40 world airlines that carry the overwhelming majority of international travelers. The international list includes two U.S. carriers, Pan American and TWA; it excludes the Russian airline Aeroflot because comprehensive accident records are not available.

Within the U.S. in the 20-year period studied there were 54 fatal commercial-airline accidents in which 2,394 people were killed, roughly 10 percent of them crew members. The report argues at some length against the inclusion of such variables as differences in airports and in the design of aircraft when assessing safety records. The authors do believe, however, that the airlines are subject to luck, either good or bad. In addition to the unwitting purchase of flawed equipment, bad luck would also include "drastic and unforeseen weather changes that destroy an airplane, involvement in midair collisions that an airline neither caused nor could have avoided and, arguably, certain incidents of sabotage. It is extremely hard to tell when, if ever, an airline is really blameless for an accident that befalls it. But such luck-related accidents should, by definition, be distributed randomly among the airlines."

In order to test the hypothesis that fatal crashes are indeed distributed among airlines more or less by chance the authors divided up the total number of crashes for the periods under study and assigned to each airline a fraction proportional to the airline's statistical accident exposure. The exposure was based on the number of flights and the industry-wide accident rates for successive five-year periods.

For their analysis the authors introduce the concept of the "cumulative fatality quotient," a formulation that converts actual crashes with variable numbers of survivors into a hypothetical number of full-crash equivalents, or FCE's. A full crash is a crash no one survives; if half of the occupants survive, it is considered a half crash. In most crashes there are no survivors. Hence the 54 crashes actually experienced by the 18 domestic airlines in the 20-year period work out, after allowing for a 15.7 percent survival rate, to 45.5 full-crash equivalents.

The 45.5 FCE's were allocated among the 18 airlines according to their statistical exposure. An airline that is average in every respect should have experienced 2.53 FCE's (45.5 divided by 18). North Central, the most nearly average airline, was assigned 2.51 FCE's. United Airlines, the biggest U.S. carrier, was assigned 6.4; Hughes Airwest, the smallest, was assigned 1.17.

The full-crash equivalents, thus distributed on an equal-probability basis, were compared with the actual number of FCE's experienced by each airline. North Central and Hughes, for example, did slightly better than expected with 1.82 FCE's and 1 FCE respectively. United did slightly worse than expected with 7.42 FCE's. In none of these cases, however, is the difference from expectation statistically significant.

Two airlines, Southern and Western, had no fatal crashes. Only one airline, Northwest, had more than twice as many FCE's as expected: 4 against an expected 1.64. By chance alone one and a half airlines should have exceeded fatality expectations by more than a factor of two. Similarly, instead of two airlines with a perfect record, chance would predict 2.7 in that category. "Thus chance alone," says the report, "would usually lead to greater disparities in safety records than actually arose."

The case of Northwest is instructive. Although it had the poorest record over the full 20-year period, it has been accident-free since 1963. If the study had covered a 15-year period beginning in 1964, Northwest would have moved from the bottom of the list to the top. Southern, on the other hand, one of the two airlines with a perfect record between 1957 and 1976, was the only domestic carrier to have a major accident in 1977. "Such abrupt reversals," say the authors, "are more consistent with differences caused by chance than with differences with genuine roots."

The improvement in domestic air safety becomes evident when the odds of a passenger's being killed on a given flight are computed for successive five-year periods from 1957 through 1976. The odds improved from one in 988,000 to one in 1,087,000, then reached one in 2,064,000 and in the most recent period were one in 2,599,000.

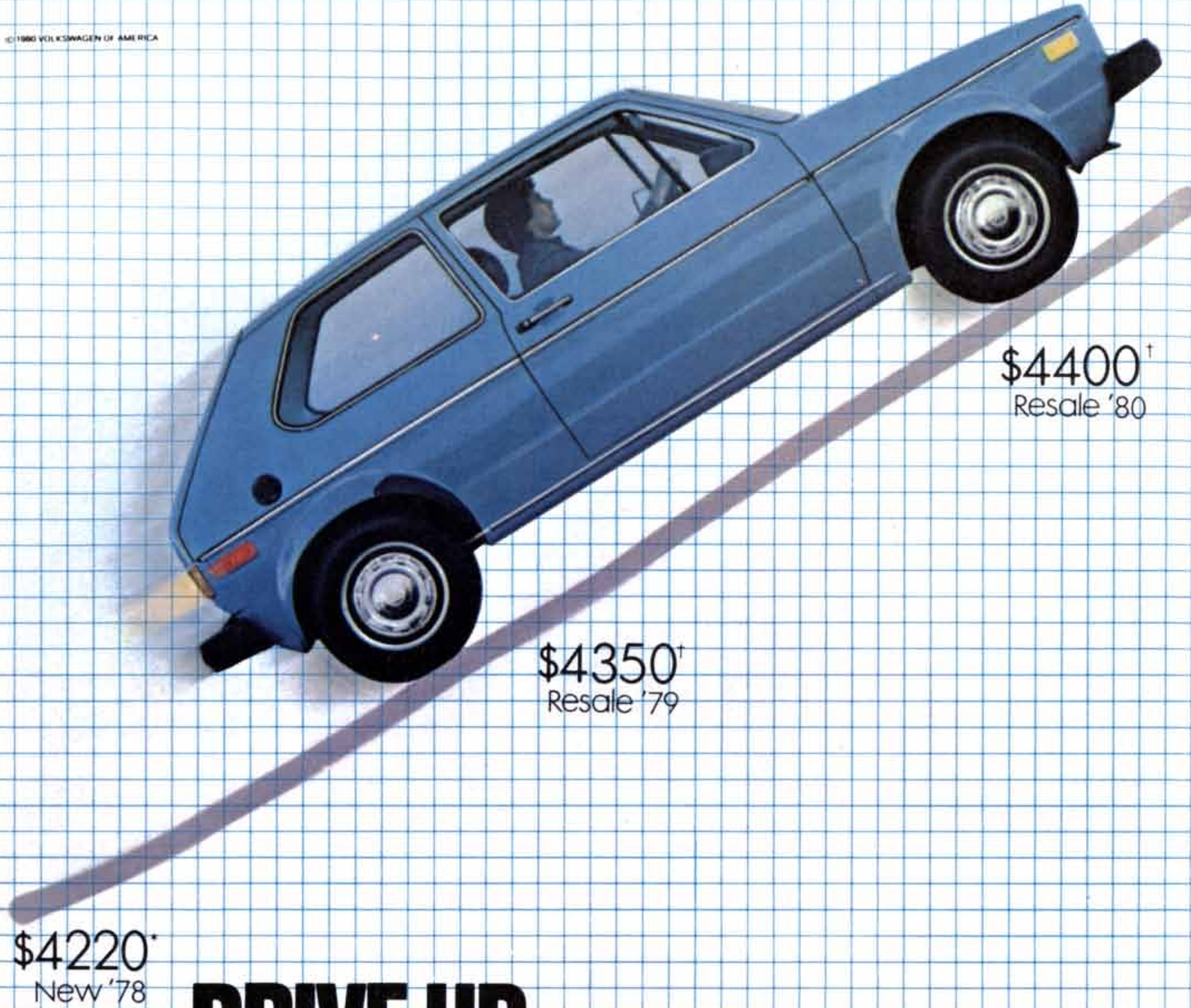
Among the 40 international carriers studied, the report finds what seem to be genuine differences in safety. The odds of being killed on an international flight improved from one in 163,000 in 1960–64 to one in 366,000 in 1965–70 but then slipped slightly to one in 340,000 in the five-year period ending in 1975.

When the same comparison is made between expected and actual FCE's, it is found that 15 of the 40 carriers had fatality rates at least twice the rate expected if all airlines had been equally safe. By chance alone only 7.2 should have had such poor records. This means that the observed dispersion in accident records is highly significant statistically and indicates genuine differences in safety. The largest of the 15 airlines at the bottom of the list was Argentinas; allocated .59 FCE on an equal-probability basis, it actually had 2 FCE's. The poorest performance was turned in by the Hungarian airline, Malev, one of the smallest studied. Instead of an expected .17 FCE it had 3.88 FCE's, or 23 times the fatality rate expected if its safety record had matched the group average.

Eight carriers had perfect records: Air Canada, Ethiopian Airlines, Finnair, Iranair, Olympic (Greece), Philippine Airlines, Quantas (Australia) and TAP (Portugal). Three other carriers had records almost as good: El Al, of Israel (.41 FCE expected and .02 actual), Lufthansa, of West Germany (3.50 expected, .38 actual) and the Scandinavian airline SAS (4.35 expected, 1.33 actual).

Predispositions

It is now generally accepted that most human cancers arise from exposure to some natural or manmade environmental agent. Cigarette smoke includes such agents. Yet many heavy smokers do not get lung cancer and many nonsmokers do; there are individual differ-



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ences in susceptibility. A number of factors determine the risk of cancer. First there is exposure to a potential carcinogen: chemical (cigarette smoke, say, or vinyl chloride), physical (asbestos, ultraviolet radiation) or viral. Then there may be exposure to a cocarcinogen that enhances the effect of a carcinogen synergistically, not merely additively. (Alcohol thus increases the risk of esophageal cancer due to smoking.) Finally, to account for the different susceptibilities of particular families and individuals to particular carcinogens, it is clear that there must be predisposing host factors, some present at birth and some acquired. Individual differences in susceptibility, the predisposing factors that have been identified and the possibility of preventing cancer in highly susceptible individuals were discussed by National Cancer Institute investigators at a staff conference recently reported in *Annals of Internal Medicine.*

John J. Mulvihill discussed clinical observations bearing on "ecogenetics," his term (by analogy with pharmacogenetics, the study of genetic differences in response to drugs) for the study of genetic variation in response to an environmental agent. In a number of cases family studies show that a predisposing trait is controlled by a single gene. One such trait is familial polyposis of the colon, which increases the risk of cancer of the colon to such an extent that prophylactic surgery (partial or complete removal of the colon) is recommended before age 20. The polyposis gene is a more potent carcinogenic factor than widely noted geographic differences in diet, although it is diet that presumably supplies the actual environmental carcinogens.

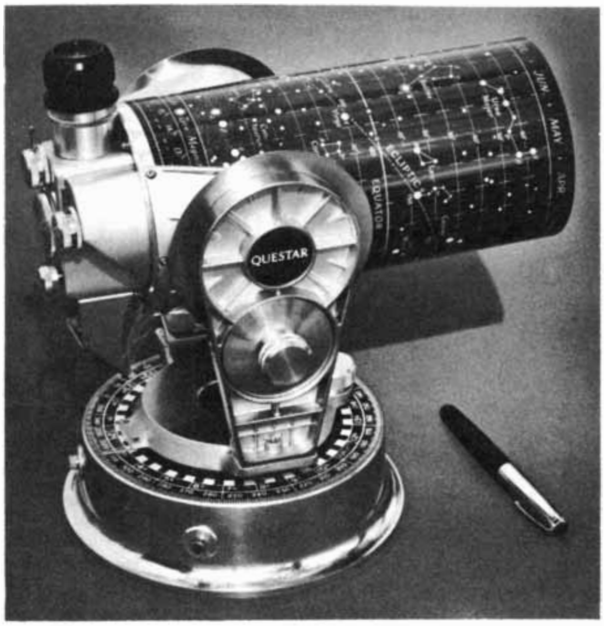
Mulvihill pointed out six conditions in which affected individuals are unusually sensitive to ultraviolet or ionizing radiation. In one case the precise defect is known: patients with xeroderma pigmentosum develop skin cancer on exposure to sunlight (and their cells have been shown in laboratory tests to be unusually sensitive to ultraviolet radiation) because they lack a particular enzyme required to repair damage to DNA, which is usually the first step in carcinogenesis. Other ecogenetic cancers represent an interaction of a mutant gene with a drug, with another chemical agent or with a virus.

A number of predisposing factors have been traced to specific chromosomal abnormalities, mostly present at birth in the case of solid tumors and mostly acquired in the case of lymphoma and leukemia. Congenital genetic abnormalities are constitutional, present in every cell of an affected person; acquired abnormalities are seen only in cells associated with the cancer. A small deletion in chromosome No. 13 that is constitutional in patients with bilateral retinoblastoma, a familial cancer of the retina that affects both eyes, is also found in the tumor cells in nonfamilial, unilateral retinoblastoma.

In addition to single-gene and chromosomal traits the concept of multifactorial inheritance—an interaction of many genes—is invoked to explain a general tendency for many common adult cancers to aggregate in families. First-degree relatives of a person with cancer of the lung, stomach, colon, breast or uterus have a risk about three times as high as that of the general population of developing the same cancer. Clinicians should be alert to the possibility that a common cancer can occasionally be familial or the result of a rare genetic disorder, Mulvihill said, with a view to early detection in relatives of patients and possibly to prevention through avoidance of carcinogenic exposures and even through prophylactic surgery.

Studies of carcinogenesis in experimental animals can provide data bearing on individual differences in human susceptibility, according to Snorri S. Thorgeirsson. Environmental chemicals are apparently the major causes of cancer, he said. Most of the implicated chemicals are actually "procarcinogens," however, and become carcinogenic only after metabolic activation; the same metabolic processes that ordinarily detoxify foreign chemicals (such as drugs) for excretion from the body can create highly reactive metabolites that interact with DNA and initiate carcinogenic cell transformation. Just as there are very wide individual differences in the rate of drug metabolism, Thorgeirsson reported, so qualitative and quantitative differences in metabolic activation "can in many instances explain species differences, as well as individual variations, in response to chemical carcinogens." He cited results of experiments associating the presence or absence of particular enzyme activities in different animals with the carcinogenicity of the procarcinogens whose activation requires those enzymes. He found, moreover, that the genes for enzymes involved in the activation of two different procarcinogens (benzo[*a*]pyrene, found in tobacco smoke, and the liver carcinogen 2-acetylaminofluorene) segregate together in the mouse, that is, the genes are apparently close together on the same chromosome.

Curtis C. Harris pointed out that activation of a procarcinogen is to some extent countered by metabolic deactivation, so that the ratio of activation to deactivation in an individual may in part determine the person's susceptibility to a particular procarcinogen. He reported on experiments with human and animal tissues aimed at assessing mechanisms of carcinogenesis, variations in susceptibility, the validity of extrapolation from animal data to human responses and potential methods of chem-



ical intervention in the carcinogenic process. For example, his group has studied the metabolism of benzo[*a*]pyrene in tissue specimens from the human bronchus, colon and esophagus. Both the steps of the metabolic pathway and the nature of the activated adduct that binds to DNA are identical with those observed in experimental animals in which benzo[*a*]pyrene is carcinogenic, strengthening confidence in extrapolation from animals to humans.

Harris measured the extent to which activated adducts bind to DNA in various tissues; he found 50- to 100-fold differences among different individuals. Then he cultivated human tissue with hamster "detector" cells in the presence of a procarcinogen (which could not be activated by the hamster cells) and assessed the animal cells for the frequency of mutation, which is usually a step toward the transformation of a cell. When activation was provided by human bronchus cells, he found both wide individual variation in activation and a significant correlation between DNA-adduct binding levels on the one hand and the frequency of hamster-cell mutations on the other. Harris suggested, in summarizing the discussions, that further research along the lines discussed at the conference might eventually make it possible to prevent cancer by interfering with the metabolism of procarcinogens, either to inhibit their activation or to enhance deactivation steps.

Faster than Light

Over the past 10 years astronomers have discovered that four compact extragalactic radio sources appear to be expanding with velocities between two and 20 times the speed of light. Three of the sources are quasars, the brightest and most distant objects in the universe, and the fourth source, 3C 120, is a galaxy. At radio wavelengths each source can be resolved into at least two diverging components: a small bright spot and a diffuse "pipe" whose length is three or four times its width. Embedded in the pipe are small bright areas. Observations made at intervals of months or years show that the components are moving apart. When the observed velocities of angular separation are combined with estimates of the distance to the objects, they seem to imply that the relative velocities are greater than the speed of light.

The principle that nothing physical (such as mass, energy or information) can move faster than light is a consequence of the special theory of relativity. The four radio sources surely do not violate this principle; their apparent superluminal motion must be only an illusion. The question that remains to be settled is: Exactly what gives rise to the illusion?

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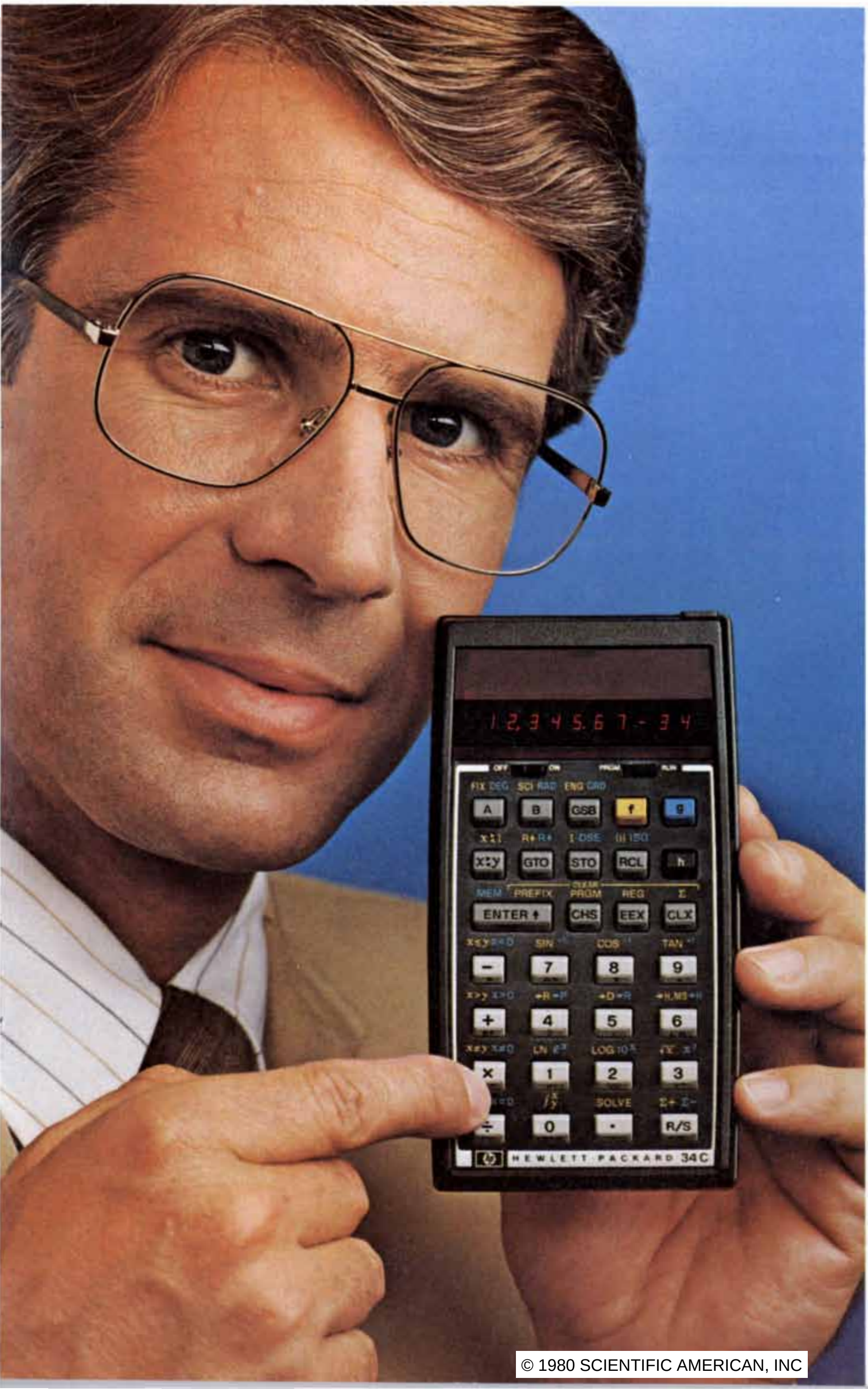

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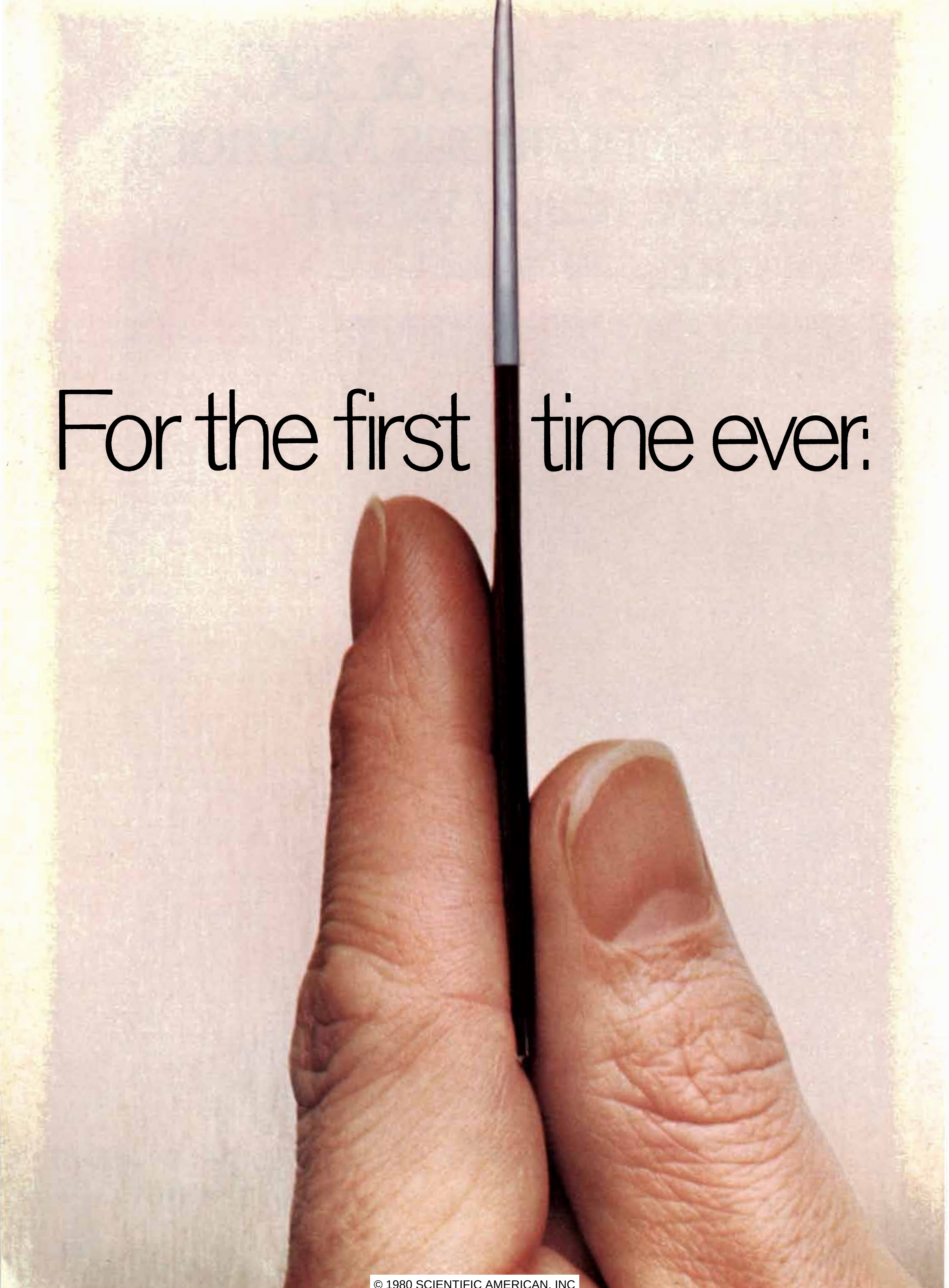
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minal phenomenon is the flashlight effect, in which the projection of a beam of light on some distant surface is seen to move faster than the speed of light. For example, imagine an ultrapowerful flashlight whose collimated beam illuminates a circular patch of a distant cloud. With a flick of the wrist the illuminated spot would travel across the sky at speeds exceeding the speed of light. This motion does not violate the theory of relativity because no physical object is moving faster than the velocity of light. The photons, or particles of light, that make up the spot are not the same photons from moment to moment.

A flashlight effect is the basis of one of six models that have been developed to account for the apparent superluminal expansion of the compact radio sources. The models are discussed by Alan P. Marscher of the University of California at San Diego and John S. Scott of the University of Arizona in a recent issue of *Publications of the Astronomical Society of the Pacific.*

In the flashlight-effect model a rotating beam of photons or other particles emitted by the radio source strikes a distant dust cloud, where a bright spot appears because of the energetic interactions of the incident particles with the dust. As the beam rotates, the bright spot can move across the sky faster than the speed of light.

The weakness of the flashlight model has to do with how the speed of the bright spot should change with time. The model predicts that, except for extremely unlikely arrangements of the beam and the cloud, the spot should decelerate. The prediction is in conflict with observations of the compact source 3C 345, whose velocity has remained constant for at least six years. A similar model, called the light-echo proposal, involves a beam of emitted particles that strikes a series of clouds with different orientations. The model fails because it does not predict the observed tube structure of the radio sources.

Another explanation attributes the apparent superluminal expansion to an overestimation of the distance to the sources. The distance is deduced from the red shift of the received radiation: the extent to which the wavelengths have been increased because of the recessional motion of the emitter. A fundamental assumption of modern cosmology holds that the faster an object is receding, the farther away it is. The red shifts of the superluminal sources are quite large. According to the usual interpretation of red shifts, the sources are receding at speeds approaching the speed of light and they lie at an enormous distance from the solar system.

Some theorists have objected that quasars cannot be moving as fast as their red shifts imply and so they suggest that the red shifts of quasars are not the result of recessional motion. Whether or not this suggestion turns out to be right has little bearing on the mechanism of the superluminal sources since one of them is not a quasar but a galaxy. For a galaxy there is little doubt the red shift is an accurate measure of recessional velocity and of distance. Hence the apparent superluminal expansion of 3C 120 cannot be explained through an overestimation of its distance.

A model that was popular initially pointed out that flares erupting at random in a compact radio source could simulate superluminal expansion. From the earth the flares might appear not as many independent events but as one source of radiation in rapid motion. The model was soon rejected because the observed expansion is too systematic to be explained by random flares.

Still another model suggests that a massive distributed body lying between the compact radio source and the solar system could act as a gravitational lens, deflecting the emitted radiation to give the illusion of superluminal expansion. Such a gravitational lens is now the favored explanation of the peculiar appearance of another quasar, where the rate of expansion is not at issue. For the compact radio sources under consideration here, however, the gravitational-lens model has a serious problem: 3C 120 is sufficiently close to the solar system (500 million light-years) for any body capable of acting as a gravitational lens to be detected. No such body appears in any photograph of 3C 120.

The most promising model of the superluminal sources is based on the proposal that the central parts of the sources may actually be moving with speeds approaching the speed of light but not of course exceeding it. Martin J. Rees of the University of Cambridge has shown that such relativistic velocities can create an illusion of superluminal motion for a distant observer. The illusion results from the relativistic phenomenon of time dilation: The time between two events in a system that is moving at relativistic speed is less in the frame of reference of a stationary observer than it is in the frame of reference of the moving system itself. To put it another way, if there were a clock on the compact radio source, an observer on the earth would see the clock ticking much faster than an observer on the source. As a result phenomena in the source would seem to an observer on the earth to be taking place at a much faster pace than they actually are. Thus the expansion that appears from the earth to be superluminal would be relativistic but still subluminal when measured by the slower clocks of the source itself.

Although the relativistic model is now the most widely accepted one, there are various ways of modifying the other models to overcome their drawbacks. The one point on which all astronomers seem to agree is that the illusion of superluminal motion is a common one in bright, compact radio sources. Of 10 sources studied in detail, four (and possibly a fifth) exhibit apparent superluminal expansion. Therefore theorists expect that roughly half of all such sources will appear to expand with speeds greater than the speed of light.

Short Viruses

A virus is an obligatory parasite: it can survive only by seizing control of the reproductive machinery of a living cell. Certain defective viruses are doubly parasitic. Having lost a part of their genome in a genetic accident, they require for their reproduction not only a cell but also proteins manufactured under the direction of the normal virus.

Can such a "shortened" virus compete with the longer, normal one and thereby limit the severity of a disease? A decade ago Alice S. Huang of the Harvard Medical School and David Baltimore of the Massachusetts Institute of Technology first made that speculation. Later John J. Holland and his colleagues at the University of California at San Diego tested it on mice. They found that the virulence of vesicular-stomatitis virus, which causes a fatal brain infection, did in some cases diminish if the brain of the experimental animal also received an injection of the shorter version of the virus.

Nigel Dimmock and his colleagues at the University of Warwick now report a still more positive finding. The virulence of Semliki Forest virus, which also causes a fatal brain infection in mice, abates in as many as 90 percent of the cases in which the animal inhales the shorter version of the virus along with the longer, virulent version. (The viruses reach the brain by way of the olfactory nerves.) A different line of research, conducted by Huang and her colleagues at Children's Hospital Medical Center in Boston, suggests an unsuspected complexity in the way the long and the short viruses compete.

The shortened versions of a virus are called DI, or defective-interfering, viruses. The name is a concatenation of their two important attributes. They are thought to arise in nature when the enzyme that engineers the replication of a virus in a cell of the host animal is prematurely detached from the virus it is transcribing. What replicates under this circumstance can be as little as the site to which the enzyme initially binds on the nucleic acid of the virus. Since the resulting DI virus lacks a complete genome, it cannot reproduce itself in the usual manner. Instead it can capture a replicating enzyme that was manufactured when a longer, fully functional virus commandeered a ribosome in the cell of the host and turned the ribosome to the production of viral protein.

The simplest hypothesis about what happens next is that the replication of the shortened virus by the enzyme is faster than the replication of a longer, normal virus; consequently many more of the short ones can be made in a given interval. The shortened viruses therefore tend to monopolize the replicating enzymes. In this way they might stifle the increase of the longer, virulent viruses and reduce the severity of the disease.

Dimmock undertook his investigation "with the one important aim of finding out, unequivocally, whether or not DI viruses could be used therapeutically." Writing in the British publication *Spectrum,* he notes a "daunting problem" that emerged. The mouse must inhale a DI virus of precisely the same strain as the virulent one. Moreover, it must inhale the two simultaneously. A delay of only a few hours is fatal. The question of whether DI viruses might be medicine for human disease is therefore not yet answered.

Huang and her collaborators, meanwhile, have determined the sequence of the nucleotides that encode genetic information in both the normal and the DI versions of vesicular-stomatitis virus. On the simplest hypothesis the second is merely a truncated version of the first, but actually it is not. The genetic material in the normal virus is a single strand of RNA about 12,000 nucleotides long. With the exception of three mismatches the 18 nucleotides at one end of the strand are complementary to the 18 at the other end. In other words, the two ends of the strand are sequences that can bind to each other, the mismatches notwithstanding, to make a length of double-strand RNA.

The DI versions of the virus are from 3,000 to 6,000 nucleotides long. In part they duplicate a sequence in the longer virus. At the ends of a DI strand, however, the three mismatches have somehow been corrected: the sequence of 18 nucleotides at one end of the strand is precisely the complement of the sequence at the other end. In addition the complementarity extends beyond the last 18; it tends to account for at least 46 nucleotides at each end of the strand, and sometimes for as many as 60. Some of the DI viruses include repeated copies of these sequences. The success of a DI virus in competition with the longer version may therefore involve more than mere brevity and speed of replication. For example, the differences in its structure may make it better at binding the replicating enzyme.

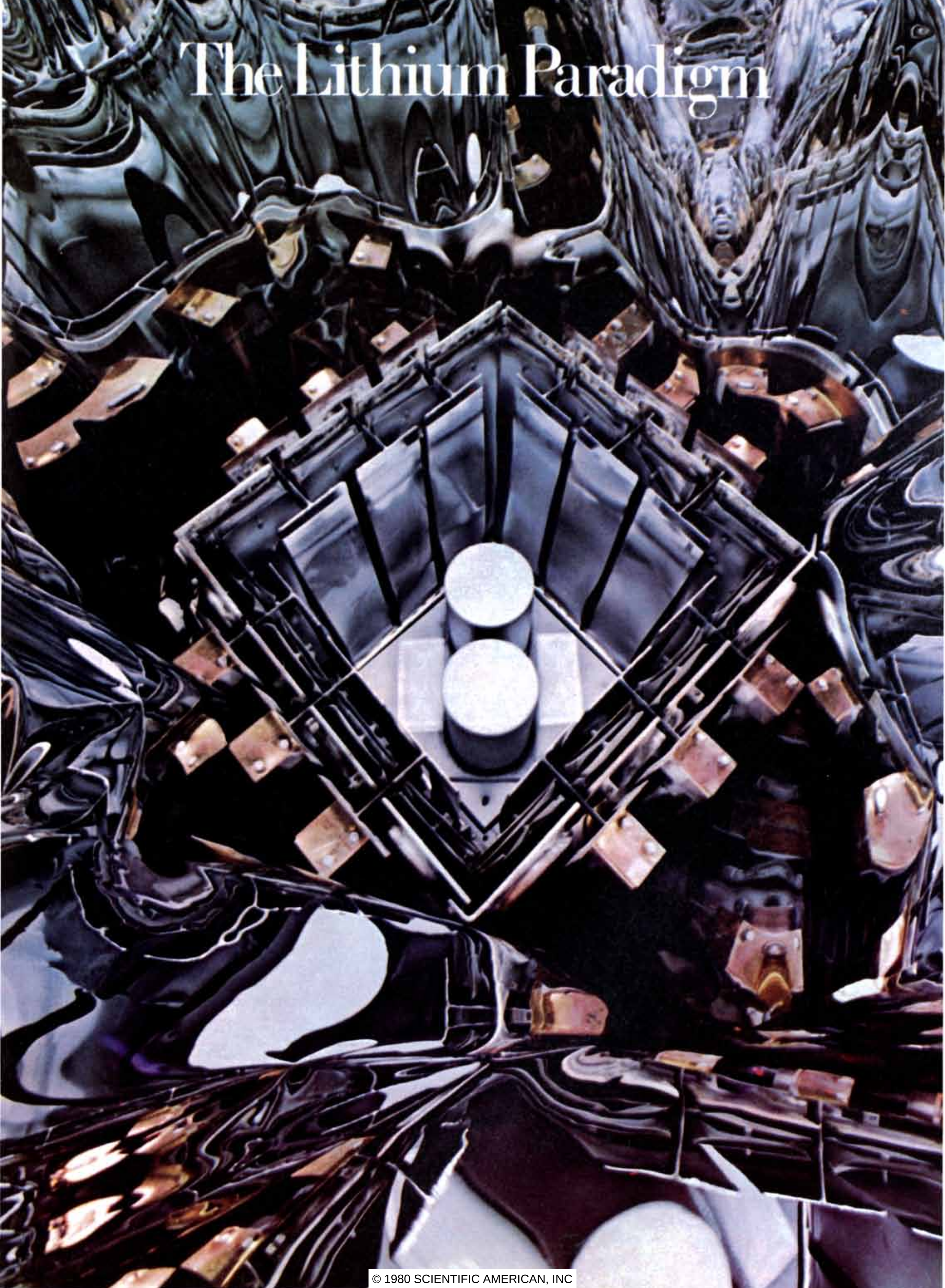
The Iridium Connection

One of the great mysteries in the history of life on the earth is the apparently simultaneous extinction, at the end of the Cretaceous period and the beginning of the Tertiary period some 65 million years ago, of as many as three-fourths of the species extant at the time. Among the groups of organisms that disappeared were the dinosaurs, the giant marine reptiles, the flying reptiles, certain marine invertebrates and virtually all the calcareous deep-sea plankton, the organisms whose skeletons of calcium carbonate form deposits of limestone. Many hypotheses have been put forward to explain the Cretaceous-Tertiary boundary event, as it is called by paleontologists, but so far none has accounted satisfactorily for all the available evidence.

In recent years interest has centered mainly on catastrophic mechanisms of extinction, because of the abrupt disappearance of all traces of the fossilized skeletal remains of certain calcareous plankton at the Cretaceous-Tertiary boundary in sedimentary rock formations in various parts of the world. Among the leading catastrophic hypotheses at present are those that attribute the extinction to extraterrestrial causes, such as a nearby supernova explosion or the impact of a massive meteorite or a comet. Interest in such hypotheses was aroused several years ago by the discovery of anomalously high concentrations of the trace element iridium in a thin layer of brown clay identified with the Cretaceous-Tertiary boundary at a limestone outcropping near the town of Gubbio in central Italy. The iridium excess was discovered by the physicist Luis W. Alvarez, his geologist son Walter Alvarez and their co-workers at the University of California at Berkeley. The trace-element measurements of the Gubbio rocks were made at the Lawrence Berkeley Laboratory by the extremely precise technique of neutron-activation analysis.

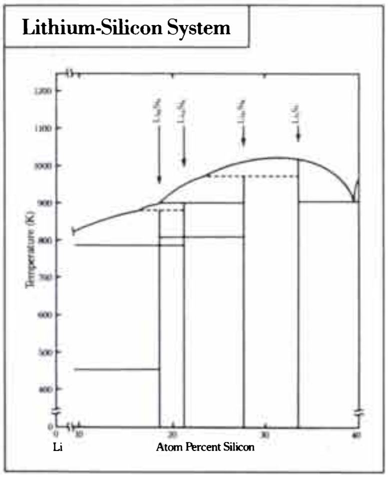
Iridium, like the other metals in the platinum group (which also includes osmium and rhodium), is normally very rare in the rocks of the earth's crust. What little iridium there was in the material that coalesced to form the earth is thought to have been selectively concentrated in the core during the planet's differentiation. The meteorites called chondrites typically have 1,000 times more iridium than crustal rocks do, and the composition of the chondrites is generally taken as indicative of the average concentration of iridium in the solar system. The presence of an anomalously high concentration of iridium in a layer of sedimentary rock could therefore indicate a sudden influx of extraterrestrial material.

The findings of the Alvarez group at Gubbio have encouraged other workers to look for similar evidence elsewhere. In a recent issue of *Nature* two European geologists, J. Smit and J. Hertogen, report the results of their investigation of an unusually complete and thick sequence of calcareous pelagic sediments exposed at Caravaca in southeastern Spain. Their analysis reveals that the extinction of the planktonic fossils at


The Lithium Paradigm

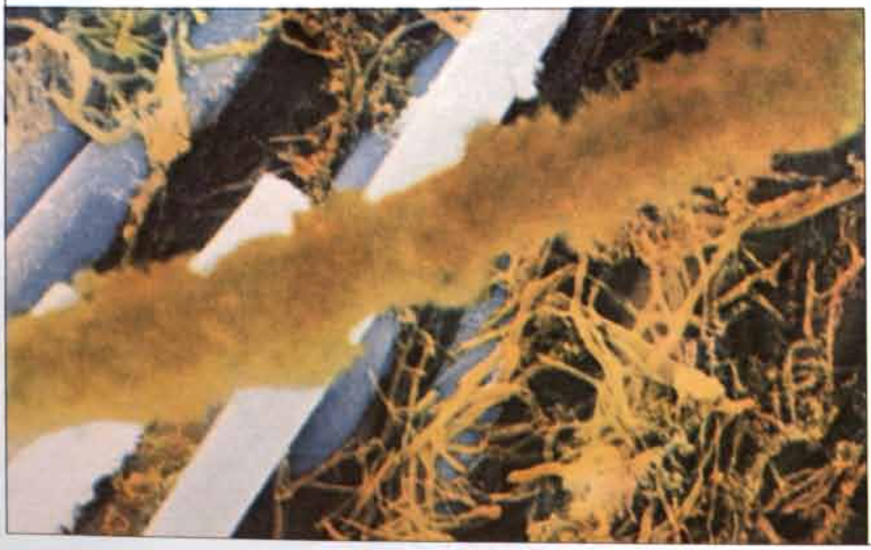
The Lithium Paradigm

The practicality of a mass-produced electric car depends upon the development of a long-life, low-cost, rechargeable battery. Recent discoveries at the General Motors Research Laboratories have encouraged scientists seeking to harness the abundant but elusive energy available in lithium—a highly desirable battery component.



Partial phase diagram of the lithium-silicon system. Lithium activity changes by two orders of magnitude in the concentration range shown.

Color-enhanced scanning electron micrograph showing the results of lithium attack on boron nitride.



HIGH ELECTROPOSITIVity and low equivalent weight make lithium an ideal battery reactant, capable of supplying the specific energy needed to operate an electric vehicle. The source of the abundant energy available in lithium, however, is exactly what makes it almost impossible to manage. The challenge is to prepare alloys and find materials stable enough to contain the aggressiveness of lithium without greatly suppressing its activity.

New knowledge of the thermodynamic properties of lithium-containing materials has been revealed by fundamental studies conducted at the General Motors Research Laboratories. Investigations, carried out by Dr. Ram Sharma and his colleagues, aim at developing a basic comprehensive understanding of selected "exotic" systems. Their work is directly related to the search for an advanced molten salt battery cell.

Specific energies greater than 180 W·h/kg, about five times that of the lead-acid battery, have been demonstrated by electrochemical cells utilizing LiCl-KCl electrolyte and electrodes of metal sulfide and lithium alloy. But operating temperatures of 723 K and the aggressive nature of the chemical reactants pose serious new challenges to cell construction materials. Of particular concern is the lithium attack upon separators and seal components. Most inorganic insulators, including the refractory oxides and nitrides, are destroyed or rendered conductive by this attack. Boron nitride, one of the more resistant materials, has been the subject of Dr. Sharma's recent, successful efforts to establish conditions under which attack may be avoided.

Dr. Sharma began by exploring the thermodynamics of the lithium-silicon system. Silicon reduces the activity of lithium without substantially increasing its weight, and produces a manageable solid at 723 K.

Constant-current potentiometry experiments were carried out in an inert atmosphere. The electrochemical cell consisted of a Li-Si alloy positive electrode, a eutectic mixture of LiCl-KCl electrolyte, and two Li-Al alloy electrodes—one negative and one reference electrode.

A series of anodic and cathodic cycles at very low current densities indicated three well-defined voltage plateaus below 80 atom percent lithium composition. This behavior was confirmed by experiments in which pure silicon was used in place of Li-Si alloy as the starting material.

The results were used to modify the Li-Si phase diagram, which indicated only two such plateaus. The revised phase diagram shows four compounds: Li_2Si, $Li_{21}Si_8$, $Li_{15}Si_4$ and $Li_{22}Si_5$. The exact composition of $Li_{21}Si_8$ had not previously been known.

Dr. Sharma confirmed the existence of the new compound by x-ray diffraction analysis. He determined its melting point to be 976 ± 8 K by differential thermal analysis. He produced a scanning electron micrograph that clearly indicates a single phase for the compound. He was also able to determine the maximum nonstoichiometric ranges of the lithium-silicon compounds from charge passed during the transitions between voltage plateaus.

KNOWLEDGE OF THE lithium activity present in the system's various compounds allowed Dr. Sharma to evaluate the stability of boron nitride with Li-Si alloys of differing composition.

A controlled potential was imposed on a boron nitride cloth sample in an electrochemical cell. By monitoring the current in the cell at different potentials, Dr. Sharma established the point at which lithium activity produces reaction.

Boron nitride was found to react with $Li_{15}Si_4$ only when in the presence of $Li_{22}Si_5$. The new compound, $Li_{21}Si_8$, did not exhibit sufficient lithium activity to attack boron nitride.

Reaction occurred according to the following equation:

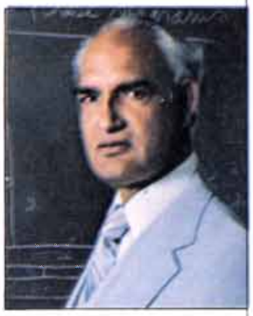
$$BN + (3+x)\,Li = Li_xB + Li_3N$$

The lithium nitride that formed during reaction dissolved in the molten salt electrolyte, but the lithium boride remained on the surface and became electronically conductive, causing high self-discharge in the cell.

"The establishment of the region of stability of boron nitride makes it possible to recommend appropriate charging limits," according to Dr. Sharma.

"Restricting the amount of charge in keeping with the recommended limits will control lithium activity, preventing the formation of highly-conductive compounds and adding durability to an electrochemical system which already displays high specific energy. Ultimately, that brings the prospect of high-performance electric vehicles closer to reality."

THE MAN BEHIND THE WORK



Dr. Ram Sharma is a Senior Research Scientist in the Department of Electrochemistry at the General Motors Research Laboratories.

Dr. Sharma was educated in India and England. He graduated from Banaras Hindu University with an M. Sc. in physical chemistry. He received a Ph. D. in physical chemistry and chemical metallurgy from London University's Imperial College of Science and Technology.

Before joining General Motors in 1970, Dr. Sharma conducted research at the Argonne National Laboratory, the Institute of Direct Energy Conversion at the University of Pennsylvania, the Nuffield Research Group in England and the National Metallurgical Laboratory in India.

GM General Motors

People building transportation to serve people the Cretaceous-Tertiary boundary "was abrupt, without any previous warning in the sedimentary record, and that the moment of extinction was coupled with anomalous trace-element enrichments, especially of iridium and osmium." The rarity of these two elements in the earth's crust, they add, "indicates that an extraterrestrial source, such as the impact of a large meteorite, may have provided the required amounts of iridium and osmium."

In the same issue of *Nature* Kenneth J. Hsü of the Federal Institute of Technology in Zurich advances another interpretation of the data collected at Gubbio and at Caravaca. He suggests that the collision of a comet with the earth might have been responsible for the Cretaceous-Tertiary boundary event. According to Hsü, the evidence indicates that "the extinction . . . of large terrestrial animals was caused by atmospheric heating during a cometary impact and that the extinction of calcareous marine plankton was a consequence of poisoning by cyanide released by the fallen comet and of a catastrophic rise in calcite-compensation depth in the oceans after the detoxification of the cyanide."

In the meantime the Alvarezes, with their colleagues Frank Asaro and Helen V. Michel, have extended their findings to other sites. In a review article in *Science* they report that the results of their neutron-activation analyses of deep-sea limestones exposed in Italy, Denmark and New Zealand "show iridium increases of about 30, 160 and 20 times, respectively, above the background level at precisely the time of the Cretaceous-Tertiary extinctions, 65 million years ago."

The most likely explanation of both the extinctions and the iridium observations, according to the Berkeley investigators, is the impact of a large asteroid from the population of asteroids whose orbits cross the earth's orbit. The fall of such an object, they calculate, would inject about 60 times its mass into the atmosphere in the form of pulverized rock. Some of this dust would remain in the stratosphere for years and would be distributed all over the world. The resulting darkness, they write, "would suppress photosynthesis, and the expected biological consequences match quite closely the extinctions observed in the paleontological record."

Estimates of the size of the object thought to be responsible for the Cretaceous-Tertiary boundary event are remarkably consistent. Smit and Hertogen calculate a diameter of between five and 15 kilometers for their hypothetical meteorite. Hsü's comet (which he assumes fell in the ocean) would have to have been about 30 kilometers across. The Alvarez group has made four independent estimates of the diameter of their proposed asteroid; all yield values lying in the range of 10 ± 4 kilometers.

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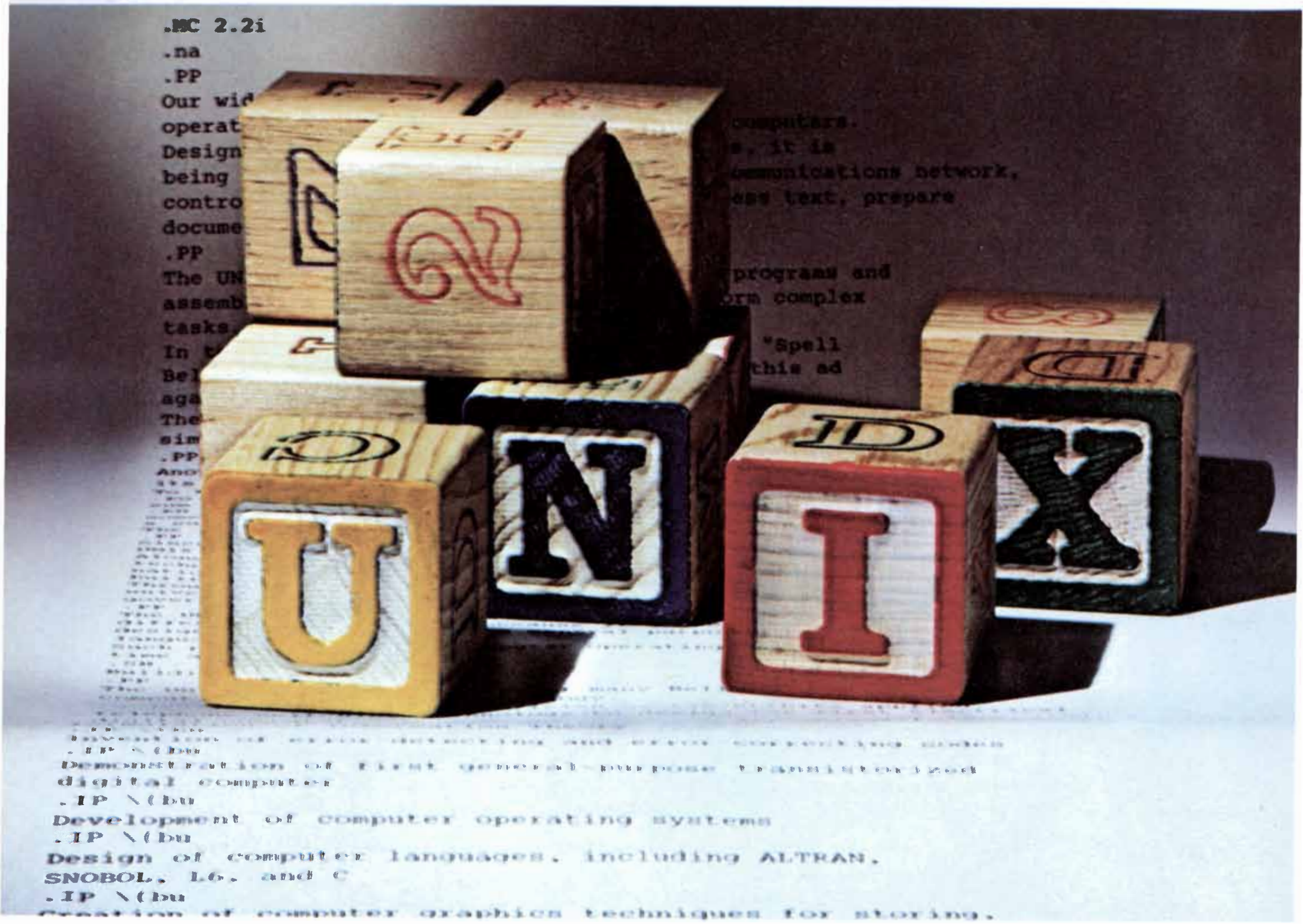

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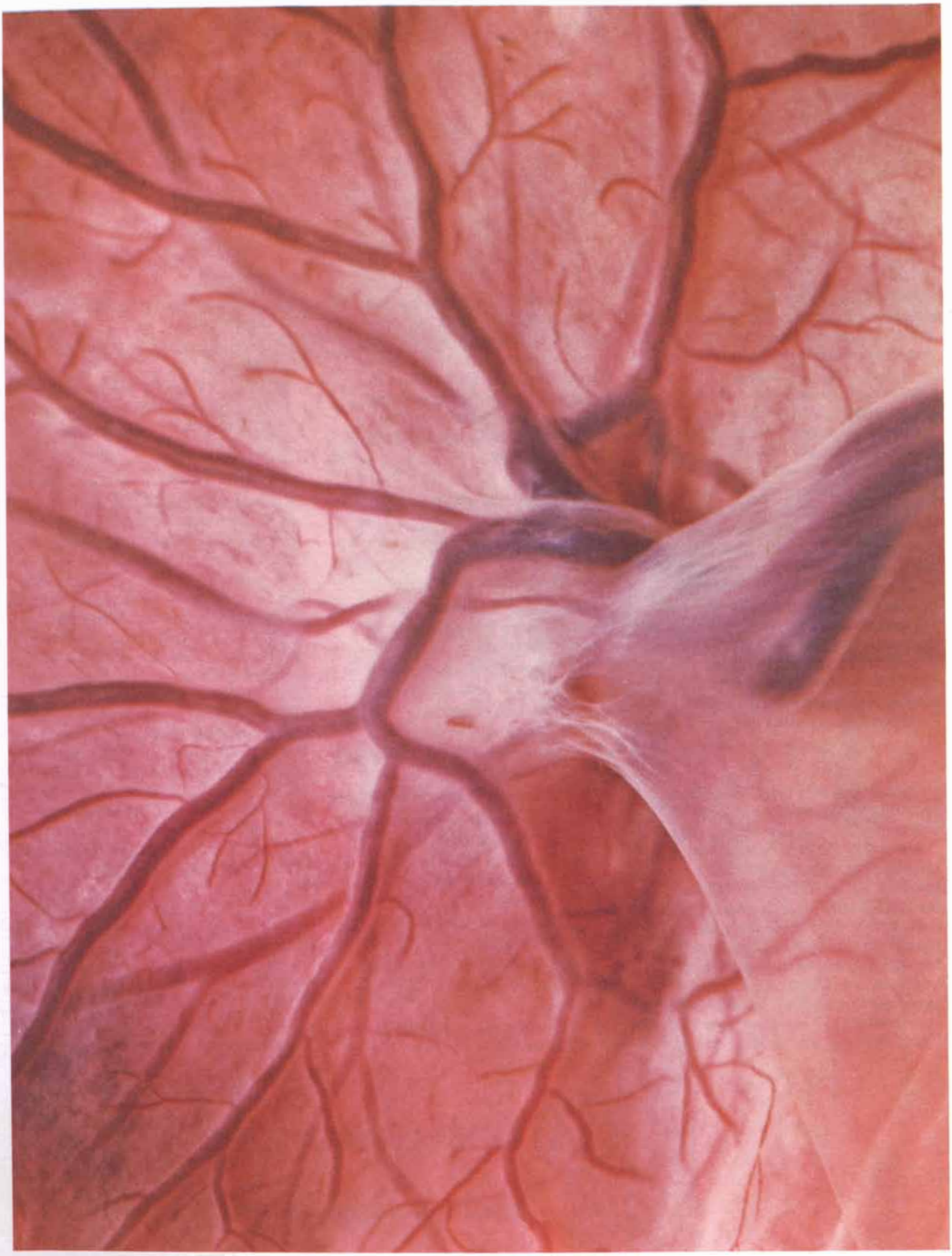


HUMAN PLACENTA is seen from the fetal side in this photograph made by Lennart Nilsson. The umbilical cord is attached at the center; a network of blood vessels radiates to and from the point of attachment. Amniotic membrane encases vessels in cord (*lower right*).

The Placenta

This remarkable organ is the intermediary between two different individuals: the fetus and the mother. After delivery it can also serve as an "experimental animal" for a wide variety of studies

by Peter Beaconsfield, George Birdwood and Rebecca Beaconsfield

The development of a fetus in the womb of its mother is linked anatomically, genetically and metabolically with that of the placenta: the strange temporary organ shaped like a flattened cake that lies nestled against the wall of the mother's uterus. The placenta is often thought to be little more than an attachment for an umbilical cord that like a diver's air hose conveys oxygen to the fetus growing in the amniotic fluid that fills the pregnant uterus. That the importance of this function of the umbilical cord has long been appreciated is indicated by the use our ancestors made of the structure to symbolize healing, even life itself. With its paradoxically red veins spiraling in its white ground substance, the cord is still symbolized today in the barber's pole, handed down from ancient origins by way of the medieval barber surgeons. The Aesculapian staff of life spiraled by a serpent probably has similar origins. Yet little attention, symbolic or otherwise, has been paid to the placenta, without which the cord would have nothing to supply and without which the fetus could not grow.

The umbilical cord delivers far more than oxygen to the fetus, and the placenta does far more than simply anchor the cord. Thickly supplied with fetal blood vessels on one side and washed with maternal blood on the other, the placenta anatomically separates the circulatory systems of the fetus and the mother, so that all exchanges of material in any form must take place across this interface. During its brief life span the placenta is therefore the sole purveyor of all fetal needs and the sole route of disposal for all fetal wastes.

In order to sustain and protect the fetus until it is ready for an independent existence the placental tissue behaves like a graft transplanted into the uterus of the mother: gaining acceptance, growing, invading and metabolizing. The placenta is unique as an organ in that it differentiates and grows from embryonic tissue to reach maturity (and may even decline into senescence) in a period of only weeks or months, depending on the species. Moreover, the placenta can continue to flourish in the uterus after the fetus has died or has been removed, and it can be implanted into other maternal tissues to nurture a fetus sometimes even to term without the protection of a uterus. In short, the placenta exhibits a biological primacy that reflects its indispensable role in the perpetuation of species.

There is still a great deal to learn about how the placenta works, but in recent years it has become clear that rather than serving as a passive filter the placenta is both active and selective in its transfer of substances essential to the development of the fetus. Having a distinct metabolic identity, the placenta is able to modify molecules of maternal, fetal and external origin. It is a biological microcosm, a multiple organ system, carrying out a uniquely comprehensive range of alimentary, pulmonary, renal, hepatic and endocrine services for and in collaboration with the fetus during the various stages of its intrauterine development. In addition the placenta is able to regulate many of the body functions of the mother as well by synthesizing an entire range of control hormones: chemical messengers indistinguishable from those manufactured by the pituitary.

In all these areas the placenta must give priority to its own needs as a prerequisite to satisfying those of the fetus and yet, unlike more primitive parasites that shortsightedly sap their host, the placenta must carry out its wide range of metabolic activities without jeopardizing the health of the mother. Both the structure and the function of the placenta are dictated by the complementary necessities of promoting growth on the one hand and maintaining an equilibrium between the fetal and maternal systems on the other. In the complex array of physiological activities that are undertaken to meet these needs several processes are of particular scientific interest. They include the control of cell differentiation and replication in the course of the placenta's tumorlike growth and invasion of the maternal uterine tissue, the hormonal system by which the placenta governs countless aspects of pregnancy in itself as well as in the mother and the fetus (a continual relaying of chemical messages that culminates in the initiation of labor), the immunological processes that protect the placenta and the fetus from rejection and yet allow the newborn infant to be equipped with protective antibodies, and the maturing of the placenta.

In what follows we shall discuss each of these areas of placental function in turn. In addition we shall point out some of the ways in which this organ's uniquely wide range of activities seems to make it a particularly suitable model for investigating such diverse subjects as the genetic code, normal growth, cancer, organ transplantation, the effects of drugs and even aging. To begin with, however, we shall consider the way the placenta and the fetus develop.

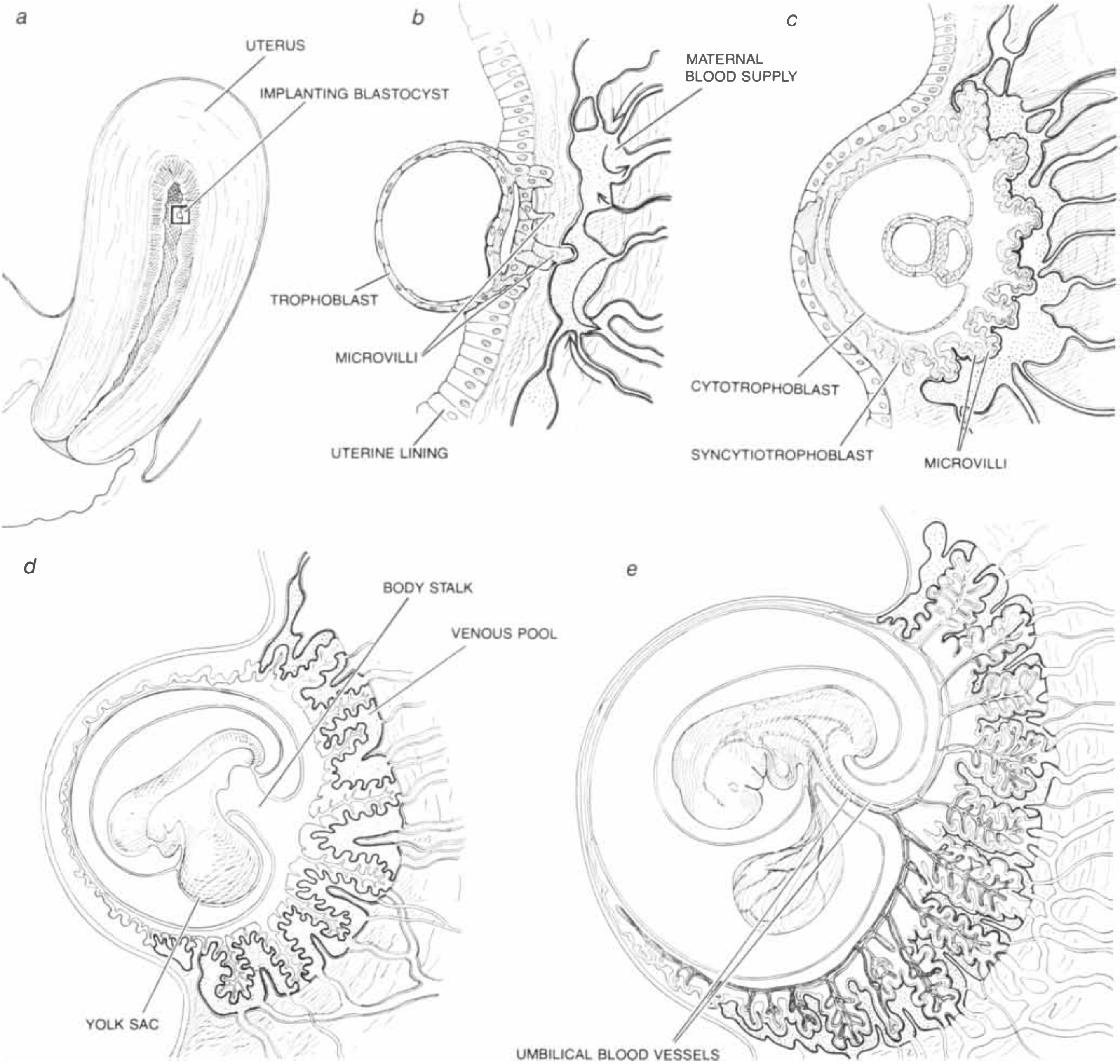
Beginnings

It is rarely appreciated that the placenta and the fetus both arise from the same single cell: the fertilized ovum. Hence the placenta and the umbilical cord and the blood flowing in them are of fetal, or more precisely embryonic, origin. This means that the fertilized egg has to be genetically programmed to make provision for its own present and future needs. Indeed, until the egg completes the journey from the upper end of the fallopian tube of the mother, where it is usually fertilized, to the uterus and becomes implanted in the uterine wall, it gets surprisingly little help from the mother. How, then, does the placenta develop its own distinctive structure and function? Broadly speaking, it does so by virtue of the same genetic instructions that govern the development of the fetus.

Soon after the egg is penetrated by a

sperm the two unite to form the single-celled zygote that contains genetic information from both parents. Within hours the zygote, obeying its own first instructions, begins to divide: the single cell becomes two cells, the two cells become four and so on. The fertilized egg is beginning to grow, but at this point the mother is not yet pregnant, that is, no special maternal arrangements are being made for the support of the egg. To be able to divide, the fertilized egg needs only to be in a progestational fluid environment.

Progesterone, one of the two main types of female steroid sex hormone, also acts to transform the endometrium, or the lining of the uterus, into a vascular, spongy surface suitable for nurturing the fertilized egg. Thus the phase of heightened progesterone production that follows ovulation in each menstrual cycle not only facilitates cell division in the embryo as it passes down the mother's fallopian tube but also serves to prepare the uterus for its implantation. As has been widely noted, these conditions can be reproduced without much difficulty in the laboratory to create "test-tube babies," or more precisely test-tube



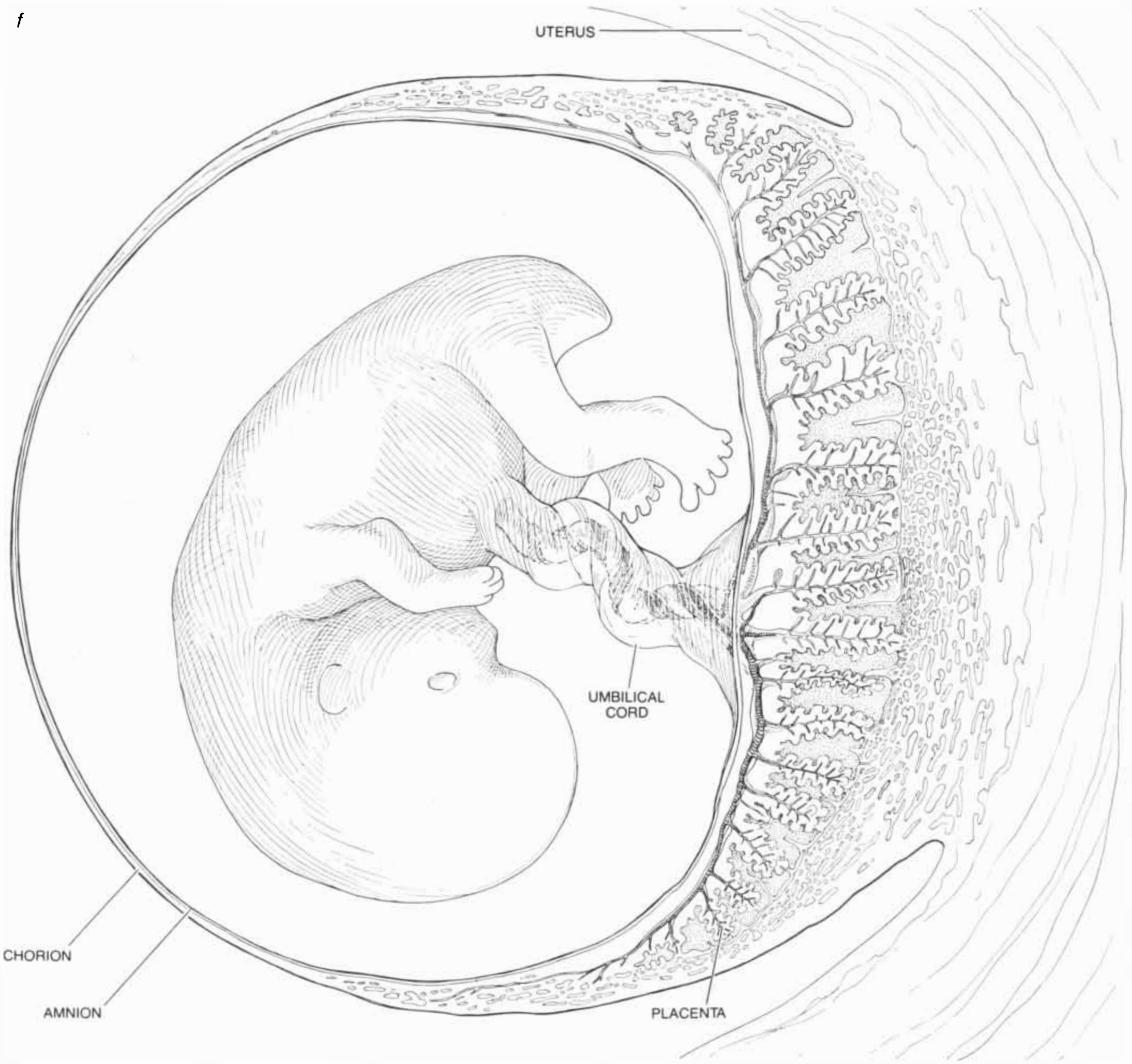
DEVELOPMENT OF THE HUMAN PLACENTA is portrayed in the sequence of drawings on these two pages. The sequence starts with the implantation of the blastocyst in the wall of the uterus (*a*). When the part of the blastocyst containing the inner cell mass first makes contact with the endometrium, or uterine lining, the trophoblast (the cell layer that will develop into the placenta) begins to form the small, fingerlike projections called microvilli, which extend into the endometrial lining (*b*). As the invasion proceeds the trophoblast differentiates into two layers, the outer syncytiotrophoblast, which leads the advance into the endometrium, and the cytotrophoblast, which forms a complex system of projections that eventually push through the syncytiotrophoblast into the pools of maternal blood that

embryos, that can survive in culture for a few days before they must be inserted into a properly prepared uterus.

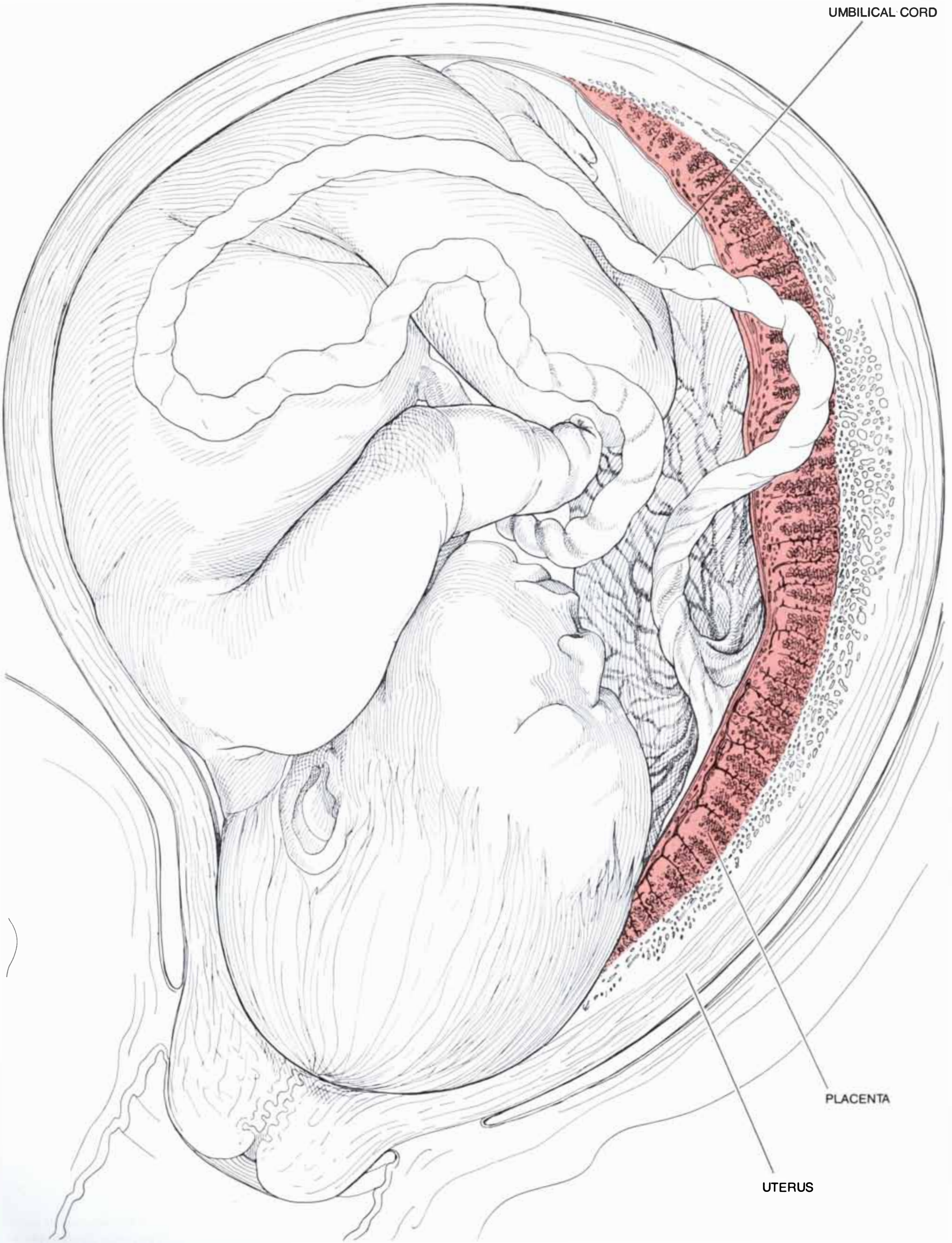
Given a suitable environment, then, embryonic cells divide purely as a result of fertilization and zygote formation. In no living organism, plant or animal, do any other cells besides cancer cells divide on their own initiative in this way, without the stimulus of a tissue's demand for replacement or regeneration. The impetus for division comes from the replication of DNA in the zygote, which is closely followed by the synthesis of RNA. The enzymes required for this first nucleic acid synthesis must be present in the egg before fertilization, but once cell division has begun and certainly by the two-cell stage virtually all the mechanisms needed for cell metabolism and replication are already present in the zygote.

Similarly, the protein synthesized in the first few hours after fertilization depends on the maternal RNA present in the oocyte (the precursor of the egg), but with the formation of the embryo's own RNA at this early stage the synthesis of true embryonic protein soon begins. Indeed, with the first few cell divisions

f



collect in the path of the invading cells; before long the blastocyst becomes completely buried in the endometrial tissue (*c*). During the invasion phase the trophoblast and the developing fetus continue to be connected by the body stalk, a structure that at a later stage of development will become the umbilical cord (*d*). At about the fifth week of pregnancy the branched projections of the cytotrophoblast are penetrated by fetal blood vessels originating in the arteries in the umbilical cord (*e*). The cytotrophoblast spreads laterally during this period, finally joining other embryonic membranes to form the outermost shell known as the chorion; the final differentiation of the trophoblast to form the placenta gives rise to inner decidual membranes that actually enclose the amniotic fluid in which the fetus will grow (*f*).



PLACENTA AT TERM is a disklike structure measuring about 20 centimeters across and three centimeters thick in the middle. The maternal surface is divided into many lobes; the fetal surface is vascular but smooth. The average placenta at birth weighs some 500 grams, or roughly a sixth of the weight of the infant it has nurtured. Section in the vicinity of the umbilical cord is shown enlarged on page 100.

the synthesis of all types of embryonic RNA increases rapidly, and as the differentiation of embryonic cells begins, the synthesis of protein accelerates enormously. By the eight-cell stage at the very latest there are more than 1,000 kinds of protein present in the embryo. Thereafter only the quantity, not the variety, of the proteins increases with each successive cell division. All of this is achieved in the fertilized ovum as securely as if it were surrounded by an eggshell, with the biologically unwitting mother providing little more help than if she were simply incubating an egg.

The Blastocyst

The cluster of dividing embryonic cells reaches the uterus about four days after fertilization, and changes have begun to take place that will culminate in the creation of the blastocyst: the nearly hollow ball of cells that is the precursor of the embryo. The individual cells in the cluster have become less clearly defined and less similar in appearance, and distinct inner and outer architectures are beginning to be discernible. As cleavage continues membranous links form between adjacent cells in the outermost layer, creating a protective shell of single cells that resembles a soccer ball. This layer can be regarded as the first stage in the development of the trophoblast, the cell layer that will eventually differentiate into the main structural elements of the placenta. By five days after fertilization, when there are some 120 cells in the human blastocyst, a clump of cells can be distinguished at one end of the fluid-filled cavity formed by the trophoblast. Known as the inner cell mass, this cluster will develop into the fetus.

At this point the developing embryo is still free-floating, still without a placenta and still independent of special maternal arrangements for its nutrition or for the hormonal stimulation of cell division. Once the blastocyst is safely in the uterus, however, it proceeds relatively quickly to make arrangements for its implantation in the uterine wall. This goal is almost certainly accomplished for the most part by the synthesis of estrogen, the second main type of female steroid sex hormone, on the sixth or seventh day after fertilization. The production of this hormone not only facilitates the implantation of the blastocyst by effecting local permeability changes on the endometrial lining of the uterine wall but also triggers the release from the endometrium of a chemical messenger in the form of a prostaglandin, which apparently serves to put the endocrine system of the mother on the alert.

It is the preplacental cells of the trophoblast that perform these functions, initiating pregnancy by ensuring that specific hormonal arrangements for nurturing the embryo will be made by the mother's pituitary gland and her corpus luteum, the temporary hormone-secreting structure that develops in whichever ovary released the egg for possible fertilization. The corpus luteum produces the large quantities of progesterone required in the course of a normal menstrual cycle to prepare the endometrium to support a fertilized egg; in pregnancy the organ is induced to continue manufacturing the hormone past the time of the first expected menstrual period, so that the endometrium will continue to provide a suitable environment for the blastocyst.

The implantation of the blastocyst, or preembryo, in the wall of the uterus is a remarkable process in which the trophoblast comes in intimate association with the maternal endometrium. Although implantation is a continuous process, it is usually described as occurring in three phases: apposition, adhesion and invasion. In the apposition phase of the human blastocyst the inner cell mass comes to lie against the endometrium. The cells of the trophoblast then form small, fingerlike projections called microvilli on their outer surface, and these interdigitate with corresponding microstructures on the endometrium, leaving gaps no wider than 250 angstrom units. In this way close proximity is established between the trophoblast and the endometrial lining of the uterus, stopping just short of intimate contact. Through mutual adhesion the gaps between the two sets of structures are narrowed still further, and then the microvilli on the surface of the trophoblast begin to regress. In the invasion phase that follows, the blastocyst becomes completely buried in the endometrial tissue.

Implantation

In the early stages of invasion the trophoblast begins to differentiate into two cell layers: the outer syncytiotrophoblast and the inner cytotrophoblast. As the syncytiotrophoblast advances into the endometrium it becomes vacuolated, creating a system of small cavities in which maternal blood from the uterine arteries eventually flows. The degeneration of endometrial cells that achieves the opening of these blood vessels is apparently facilitated by the manufacture of cell-destroying substances such as proteases in the advancing trophoblast. At this point the trophoblast and the developing fetus are connected by a structure called the body stalk, which will develop into the umbilical cord.

As the syncytiotrophoblast becomes embedded in the endometrium the inner cytotrophoblast proliferates, forming a complicated system of projections that push through the syncytiotrophoblast into the pools of maternal blood referred to above. These projections, called the primary villi, eventually become branched and vascularized by fetal blood vessels originating from the arteries in the umbilical cord. In this way a large surface area (equal to that of more than half a tennis court) will be provided for interchanges between the fetus and the mother. In addition, during the same period cells of the cytotrophoblast spread laterally and eventually join to form the chorion: a shell completely enclosing the entire conceptus, or all the structures that arise from the fertilized egg.

Human embryonic tissue comes in direct contact with maternal blood when the cells of the trophoblast actually invade the spiral arterioles that lie in the uterine wall, whereas in the development of the placenta in more primitive mammals other structures intervene. This intimate contact is reflected in the description of the human placenta as hemochorial. The proliferation of the cells of the inner cytotrophoblast is accompanied by a rapid expansion of the area of trophoblastic implantation. By the eighth week of human pregnancy the developing placenta has almost stopped growing except at the tips of the villi, which also serve to anchor the organ in the uterine wall.

With the blastocyst implanted in the uterine wall, the placenta is actually created by two processes: the final differentiation of the trophoblast in conjunction with a response in the uterine lining that gives rise to the membranes called decidua. The decidual membranes enclose the amniotic fluid in which the fetus will grow. The more invasive the trophoblast in a particular species is, the greater is the implantation response it elicits. The human trophoblast, which is the most invasive known, elicits the most pronounced uterine decidual response, and as a result the closest possible link is established between the mother and the fetus.

Once implantation has been achieved the blastocyst cells from which the embryo and then the fetus and placenta develop can be said to be parasitic on the mother. No longer independent, they can exist only by taking what they need in the way of oxygen, nutrients, fluid, salts, hormones and the like from the maternal supply and by discharging toxic or merely superfluous waste products into the maternal metabolism.

It is interesting to note that in the trophoblast's invasion of the endometrium it penetrates just so far and then stops, possibly as a result of limits imposed by the host tissue rather than by the trophoblast itself. For example, the trophoblast of the pig barely penetrates the endometrium, but it is far more invasive when it is implanted in an ectopic, or nonuterine, site such as the ureter, which presumably lacks the endometrium's capacity to resist deep invasion. In the macaque monkey the endometrial cells that line the uterus proliferate to create a plaque under the implantation site that may well serve to limit invasion. In the baboon and certain other primates, including man, no such plaque appears, and yet the limitation of trophoblast invasion is universal (except in the rare instances of placental malignancy, where all relevant controls break down). Even the invasive human trophoblast does not penetrate beyond the first muscle layer that underlies the endometrium. It should be added that the entire process of implantation, on which the development of the placenta depends exclusively, has yet to be studied fully in any primate, including man.

At term an average placenta is a disklike structure weighing about 500 grams and having a diameter of about 20 centimeters. As much as three centimeters thick in the middle, it is much thinner at the edges, where it becomes contiguous with the chorion. The villous projections that extend into the sinusoidal spaces over the maternal surface of the placenta divide that surface into fleshy branched lobes. The fetal surface, on the other hand, is highly vascular but smooth: lining membranes cover the fetal arteries and veins that come together at the more or less centrally attached umbilical cord. Human placentas vary in size, shape and weight, but at birth the ratio of the weight of the placenta to the weight of the infant it has nurtured is about one to six.

Control Mechanisms

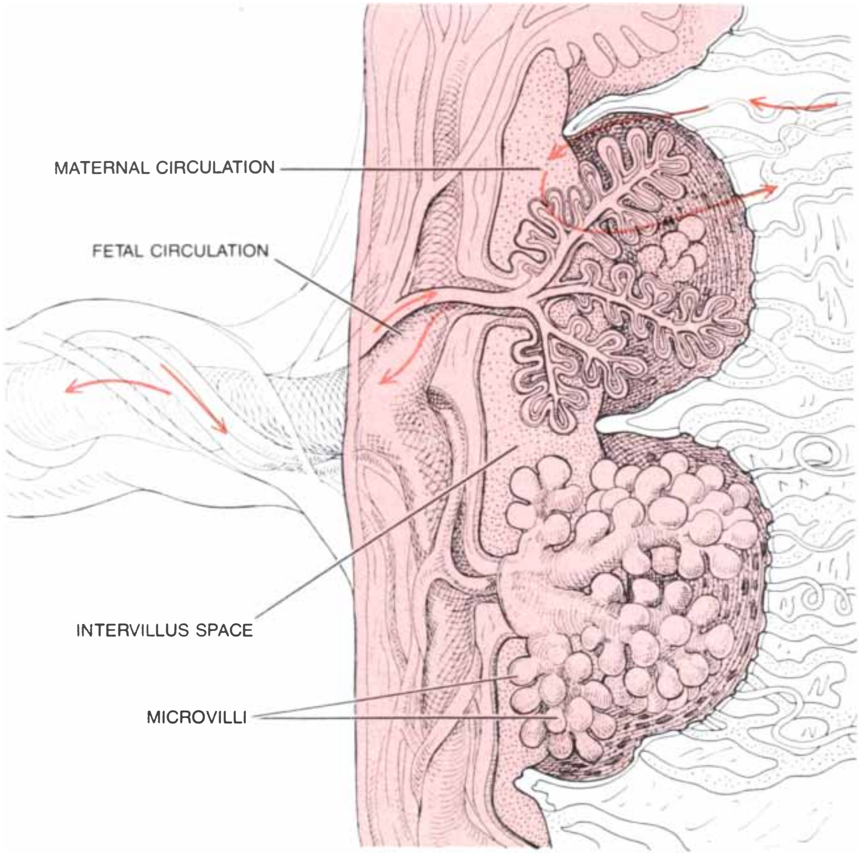
As with Sherlock Holmes's dog that did not bark, it is significant that even the most invasive embryonic tissue fails to provoke inflammatory reactions or immunological rejection in the mother. The developing embryo is immunologically alien, however, and as experience with surgical grafts and transplants has amply demonstrated, when alien tissues meet, such reactions and rejections are almost always observed. To some extent it is the protective layer of trophoblast tissue from which the placenta mainly develops that prevents the rejection of the inner cell mass, but more broadly it appears that maternal rejection of the embryo is forestalled by a sensitive equilibrium, appropriate to each stage of pregnancy, between trophoblastic protection and other control mechanisms.

This is just one aspect of the sophisticated system of controls that governs the growth of a normal embryo and its invasion of maternal tissue. Other mechanisms in the system circumscribe the extent and duration of cell replication and prevent metastasis; they also oversee both the differentiation of primitive cells into the varied types needed to form the placenta and fetus and the positioning and molding of these highly differentiated cells so that they develop into properly formed and appropriately placed organs and tissues. Plainly all these processes depend to a large extent on the precise internal control mechanisms that govern cell replication in the developing tissues themselves.

On the other hand, the detailed genetic instructions that are embodied in the DNA of each individual cell and give rise to normal embryonic development must be selectively activated by the switching on and off of the appropriate genes at the proper times and places. The pattern can be influenced by factors outside the individual cells, including the chemical constitution and temperature of the cellular environment, local interactions of neighboring tissues and the action of hormones and other mediators that direct tissue differentiation and stimulate, inhibit or modify growth. The complexities are immense, and yet of course there can be no question that, tested and retested in the course of evolution, the system works.

Many of the metabolic functions controlled by the placenta are virtually identical with those controlled by other organs. Here we are mainly concerned with those metabolic activities that underlie the special functions of the placenta, the most striking of which is the management of rapid growth. We have mentioned the genetic controls involved in the process, but such growth also requires building blocks—what can be broadly described as structural proteins—and the energy to put them in place. In the placenta these requirements are many times greater than they are in any other organ because the placenta must not only itself grow but also serve as a builder's yard and power plant for a fetus that will rapidly outgrow it several times over.

The metabolism of protein in the placenta is largely governed by the demands of growth. No other organ carries out the synthesis of such a diverse group of proteins for such a wide range of purposes. The vast quantities of structural proteins that will be incorporated into proliferating fetal and placental tissues must be derived from maternal sources, some of them as complete



CLOSEUP VIEW OF A CROSS SECTION of placental tissue in the vicinity of the umbilical cord reveals the fine structure of the interpenetrating tissues responsible for the exchange of blood between the mother and the fetus. In human beings the cells of the microvilli actually invade blood vessels in the uterine wall; hence the human placenta is said to be hemochorial.

protein molecules and some already broken down into their constituent amino acids, either as single units or as short chains. Little of the raw material in the massive flow from the mother, however, is in the precise (and varied) forms required for the different stages of fetal and placental development. Hence in addition to the placenta's prefabrication of specific proteins for its own purposes it must sort through the available supply, matching the quality and quantity of the material available to the current fetal demand. Moreover, the precise synthesis of protein hormones and enzymes, whose role in mediating the genetic control of growth and regulating metabolic processes depends entirely on their molecular structure, is even more demanding.

Ten weeks after fertilization, when the placenta weighs only 50 grams, its total production of protein is calculated at about 1.5 grams per day. At term its production has risen to about 7.5 grams per day. No other organ, including the hardworking liver, synthesizes protein at such a rate and no other organ has such a high rate of metabolism. The placenta utilizes about a third of all the oxygen and glucose supplied to it by the maternal circulation for its own metabolic needs; the exact fraction depends on the respective sizes and activities of the fetus and the placenta at the particular stage of gestation.

Hormone Synthesis

The production of hormones to regulate the activities of pregnancy is one of the most interesting special functions of the placenta. Indeed, to someone reading about the placenta for the first time it may come as a surprise that it is the placenta that bears this responsibility and not the mother or the fetus. The fact is that from the earliest days of pregnancy the cells of the trophoblast and their successors in the placenta manufacture a large variety of hormones. The first to be manufactured in appreciable amounts is the protein hormone chorionic gonadotrophin. Very early in the differentiation of the trophoblast this hormone is found coating the trophoblast's outer cell surfaces, where it is believed to act as an immunologically protective layer, preventing the rejection of the blastocyst and thereby facilitating implantation. As we have already pointed out, the synthesis of the female sex steroid estrogen begins in the free-floating blastocyst, where it too acts to facilitate implantation. The fact that the cells of the small, primitive blastocyst are already equipped to conduct complex steroid manipulations is a measure of the importance of these hormones at this early stage.

It appears that human chorionic gonadotrophin (HCG) exerts some controlling influence over the placental and preplacental hormones, since this hormone stimulates the synthesis of estrogen in the placenta. The small amounts of HCG that reach the fetus may even play a part in the initiation of steroid synthesis in the developing adrenal glands and (in the case of the male) the testes. Moreover, the placenta appears to exercise feedback control over its own production of HCG by means of a hormone similar to the releasing hormones secreted by the pituitary to regulate activity in the other endocrine glands.

As pregnancy proceeds large amounts of progesterone are synthesized in the placenta, principally from maternal cholesterol. In addition to sustaining pregnancy this hormone serves as a raw material for the production of estrogens (mainly estrone, estradiol and estriol), which in turn act on many organs and tissues of both the mother and the fetus. The processes influenced by these hormones include the synthesis of protein and the metabolism of cholesterol, the functioning of specific organs such as the maternal uterus and breast and the regulation of countless aspects of fetal development. Perhaps the most fascinating feature of the synthesis of steroid hormones in the placenta, however, is the way the placenta and the fetus collaborate, which has been examined by Dorothy B. Villee of the Harvard Medical School.

The human placenta lacks the enzymes needed for converting the large amounts of progesterone it makes into certain essential estrogens and other steroids. Villee has found that the synthesis of these hormones from progesterone is carried out in "fetal zone" cells: clusters of transient cells found in the developing adrenal glands of the fetus that lack the enzymes necessary to manufacture progesterone but possess the requisite ones for its conversion. In this way the fetal and placental tissues complement each other. In fact, some of the "fetal" estrogen even returns to the placenta for further manipulation. When the fetus's own endocrine glands become sufficiently mature to begin taking over the manufacture of steroid hormones from the placenta, the fetal-zone cells gradually diminish, and they eventually disappear altogether when they are no longer needed. In the various species that have been investigated the particular functions of the fetal-zone cells and the placenta differ, but in all cases complementary rather than overlapping functions have been discovered. Presumably this sophisticated yet transient collaboration is organized and timed by precise genetic instructions and is regulated by equally precise releasing hormones.

Judging by the great variety of such regulatory protein hormones synthesized in the placenta, including two (chorionic gonadotrophin and placental lactogen) found only in pregnancy, the control exercised by the placenta during pregnancy cannot be much less comprehensive than that maintained by the pituitary throughout life. By means of these hormones the placenta not only carries out the functions of the fetus's pituitary until that organ is ready to perform on its own but also conducts the entire endocrine orchestra of pregnancy, which performs largely in the placenta itself. Actually the protein hormones act on other hormones, mainly steroid ones, to regulate virtually all these activities. To continue with the orchestra analogy, if DNA provides both the full orchestral score and precise instructions for the instruments on which it should be played, the protein hormones elaborated by the placenta and by the pituitary coordinate the performance, usually relying on steroid hormones as mediators.

Immunological Protection

Among the physiological processes in pregnancy that call for particularly precise coordination are those concerned with protecting the embryo from immunological rejection by maternal tissue. One of the many mechanisms that seem to play a part in this task is the nonspecific suppression of lymphocytes, the cells that would normally mediate the rejection of a graft. In the laboratory, at least, the activity of lymphocytes can be suppressed by a variety of substances manufactured in the course of a normal pregnancy, including the protein hormones chorionic gonadotrophin, placental lactogen and prolactin, the steroid hormones cortisone, progesterone and the estrogens and a variety of other proteins and glycoproteins.

As we have noted, the embryo may also be physically protected by the large, tightly packed decidual cells that enclose it soon after the implantation of the blastocyst. This protective barrier cuts off the drainage of lymphocytes to maternal tissues. Moreover, the maternal blood vessels do not invade the trophoblast or the placenta and so a second avenue typically leading to the rejection of grafts is blocked. In the early stages of the development of the trophoblast further protection is afforded by the absence of the expression of antigens: the substances that stimulate the production of antibodies specific to them and give rise to graft rejection. In other words, although the embryonic tissue is foreign, it manages to conceal the fact, at least for a while.

On the other hand, there is evidence that antigens corresponding to a variety of tissues are present in trophoblast tissue. W. D. Billington of the Medical School of the University of Bristol has pointed out that antibodies deliberately produced to attack these antigens could be of great clinical value, say for inducing abortion or for the immunotherapy of placental cancers such as choriocarcinoma. It is possible that in the course of pregnancy such antibodies are formed in maternal tissues but that like other rejection mechanisms they are then held in check by a delicate interplay of protective forces. As Billington puts it: "The unique immunological properties of the trophoblast and the diverse maternal immunoregulatory processes apparently contrive together ... to avert the anticipated rejection reactions resulting from feto-maternal tissue incompatibility." He believes the various elements in this complex immunological equilibrium must have arisen at different times in the course of evolution. Guy Voisin and his colleagues at the Center of Immuno-Pathology of the National Institute of Health and Medical Research in Paris have taken the argument further, suggesting that "tumors may be regarded as pathological tissues that have 'understood' and utilized some of the placenta's tricks" to prevent their own rejection by host tissues.

Another highly specific immunological function of the placenta is to supply the fetus at the end of pregnancy with maternal antibodies of the type known as immunoglobulins. These antibodies summarize the mother's experience of and resistance to various infections and provide the newborn infant with a ready-made prophylaxis against infection until its own immune system can begin to function. Antibody molecules are far too large to diffuse across the placenta and would lose their activity if they were broken down, so that they must be conveyed by active, or energy-requiring, systems of transport. These transport systems are highly selective, conveying some larger antibody molecules at the expense of smaller ones, presumably in accord with the needs of the fetus.

One particularly striking feature of the active transport of antibodies is that the antibodies are transported through tissue that normally protects the embryo from immunological attack and breaks down protein molecules as large as antibodies. A. D. Wild of the University of Southampton has observed that highly specialized transport systems that are in effect independent of the tissue through which they convey substances might be exploited as a means of "targeting" therapeutic drugs for particular organs or tissues. By the same token it might be possible to block those systems in the placenta. It would be desirable, for example, to keep maternal *Rh* antibodies from reaching the fetus and attacking its red blood cells.

Aging in the Placenta

Obstetricians have long been aware of what appear to be aging changes in some human placentas toward the end of pregnancy. In fact, after full term the development of calcium deposits and fibrotic infarcts, areas of dead tissue resulting from the hardening and occlusion of placental arteries, does make some placentas hard and shrunken—apparently old. Can these changes really be attributed to aging? To put it another way, is the placenta genetically programmed to do its nine-month stint and little more?

These questions are remarkably difficult to answer. An obstetrician seeing an apparently aging placenta in conjunction with a small infant may assume that the placenta was inadequate to support its fetus, which therefore suffered from "placental insufficiency." On the other hand, it is possible that the genetic program governing the growth of the fetus and the placenta simply dictated that both should be smaller than usual. After all, a fetus that is destined to be a small infant needs only a small placenta. More generally, although anyone can recognize the effects of aging at a glance, so far neither the specific features of this phenomenon nor its causes have been fully identified. Hence there are no firm criteria for assessing the placental changes that resemble aging. Indeed, the calcified deposits that seem to be such incontrovertible evidence of aging are often found at birth in the placenta of infants that are clearly not suffering from any placental deficiency, and there is also evidence to suggest that the development of such deposits is actually reversible.

Moreover, it is far from certain that such changes necessarily impair the function of the placenta. Willi Hijmans of the Institute for Experimental Gerontology at Rijswijk in the Netherlands has suggested that the placenta matures but does not age. If that is the case and the placenta is indeed an organ that matures and then remains in optimal condition until it finally stops functioning, it would provide an ideal model for gerontological investigations. On the other hand, it is interesting to note that as the placenta grows older its synthesis of phospholipids increases; similar effects have been observed in the arterioles of aging men and of women who have taken the birth-control pill over a long period of time.

There are many fields in which the human placenta could serve as an invaluable experimental "animal," endowed as it is with the particular advantage of being human. The most obvious such applications of the placenta are in the area of obstetric research, particularly on congenital abnormalities. For example, for those hereditary diseases that are characterized by defective enzyme systems the placenta represents what we call the largest human biopsy. Moreover, generally speaking the fetus is exposed to the same drugs, food additives and environmental pollutants that the pregnant mother is exposed to. During the first trimester this factor can be of crucial significance because the fetal and placental tissues are still being differentiated and so (as the thalidomide tragedy showed all too clearly) are highly susceptible to damage. With our colleagues at the University of London we are currently studying the way the placenta modifies the chemical structure of drugs (and hence their action) in the hope of someday being able to look directly at the effects of drugs on human tissue.

The Experimental Animal

Because of the placenta's capacity for rapid cell replication it is a particularly suitable vehicle in the testing of substances for toxicity and in the study of drugs that inhibit cell division (for the treatment of cancer). Indeed, it is clear that the placenta is potentially an important tool for evaluating chemical compounds in general. Moreover, the developing placenta is an excellent model for the study of normal and abnormal cell replication, because in its rapid growth, its invasiveness and its mosaic of metabolic activities it does not differ appreciably from a cancerous tumor. The one striking difference between the two is that unlike the tumor the placenta has brakes on its growth. One would like to know where these brakes are and how they come to be applied.

It may turn out to be unfortunate that the apparent simplicity of the bacterium *Escherichia coli* seduced investigators into making it the basic organism for genetic research. If placental cells had been employed for the same purpose, the initial difficulties would have been greater but today the universal model would be human in origin. All the mechanisms and stimuli that affect cell replication can be studied on the placenta with placental cells, whether they are in vivo, in vitro or in tissue culture. Moreover, placental cells are replaced by replication, and so the placenta can be employed to search for the signals of the initiation of normal replication as well as those that herald malignant change. Finally, the placenta can also be utilized for investigating the regulation of genetic expression and the operation of gene repressors. This application might lead to the biggest prize of all: the breaking of the DNA code of cancer.

Chez Renault

Profiles from the Paris Factory/One of a series

"Even a 5-year old child knows that it's easier...more efficient...and more controllable to pull a wagon than to push it. And that's the simple beauty of front-wheel drive."

Hubert Seznec
Director of Product Development
Regie Renault

Historically front-wheel drive has been a passion of the French auto industry; as early as 1899 a Latil pioneered front-wheel drive assembly. Today, Hubert Seznec is so passionately a "front-wheel drive man" that had not his compatriots laid the groundwork, he seems ready and capable of starting a groundswell all his own. No doubt he would be joined in his mission by the many experts around the world who share his belief that front-wheel drive provides some of the best answers to the myriad problems faced by both drivers and car manufacturers today.

A graduate of France's famed Ecole Polytechnique, Seznec has been involved with cars his entire working career. For the past 11 years at Renault, he has directed his staff of over 700 with the tenacity, independence and, yes, passion, that characterizes his Breton antecedents. Not content to be a mere "director," he personally gets involved with the final design and tuning of new cars and with the modifications of existing models. Although Seznec has many other interests outside work—he loves to travel and discover new places—he says, "I'm so bound to my prototypes and, always, the new 'new cars,' I never seem to get away long enough for a good look."

But travel he will if it means an opportunity to expound on front-wheel drive. Five years ago he delivered a definitive paper on front-wheel drive, which he co-authored, to a meeting of the Society of Automotive Engineers in Detroit. At that time he predicted that a preference for front-wheel drive would be a long-lasting trend. Events since then have supported such a view.

Portrait by Marie Cosindas

Tennis, bridge, the movies and cities—are some of Seznec's other passions. "I love cities—the activity, the noise, the things happening all the time—the vitality." Vitality seems to be his keynote whether he's conveying his enthusiasm for a new movie or changing a dry engineering specification sheet to a new kind of reality for today's driver.

Once Seznec starts ticking off the serious advantages that front-wheel drive architecture offers, it's difficult to remain unconverted. "Take the perennial paradox. How do you make a car smaller on the outside—but make it roomier and 'larger' on the inside? Front wheel-drive can do it by eliminating the bulky drive-shaft!" Then there's economy. And efficiency. And road handling—"particularly excellent on bad roads and slippery conditions!" The evidence for front-wheel drive seems to be so irrefutable to Seznec that he seems puzzled by the waywardness that permits any other kind of car even to be considered.

The Seznec family includes a practicing doctor, Mrs. Seznec, whose specialty is problem pediatrics. A soon-to-be-doctor, daughter Anne, is a fifth year medical student; and a neophyte in the business world, daughter Dominique, recently received her *diplome commercial*. Their family life is centered in a high-ceilinged *belle epoque* apartment redolent of the world of Proust and seemingly far from the world of front-wheel drive. Yet just ten minutes away is the car-jammed Champs Élysées where Seznec's daily pre-occupation can be vividly experienced in real life and not just in theory.

"In the world as it is today, I think people will give up all sorts of things before they'll give up their cars. Our aim at Renault is to make cars that are affordable and economical but won't skimp on the creature comforts—so that people won't have to give up on anything. Competition? Of course, we want to beat the others. But for me, the real competition is always with myself. To outsmart the 'me' of yesterday. But as far as front-wheel drive goes—I haven't been able to outsmart 'me' on that one."

We welcome your comments, questions or thoughts about any of the above. Write to Renault U.S.A., Inc., Corporate Group, Englewood Cliffs, N.J. 07632.

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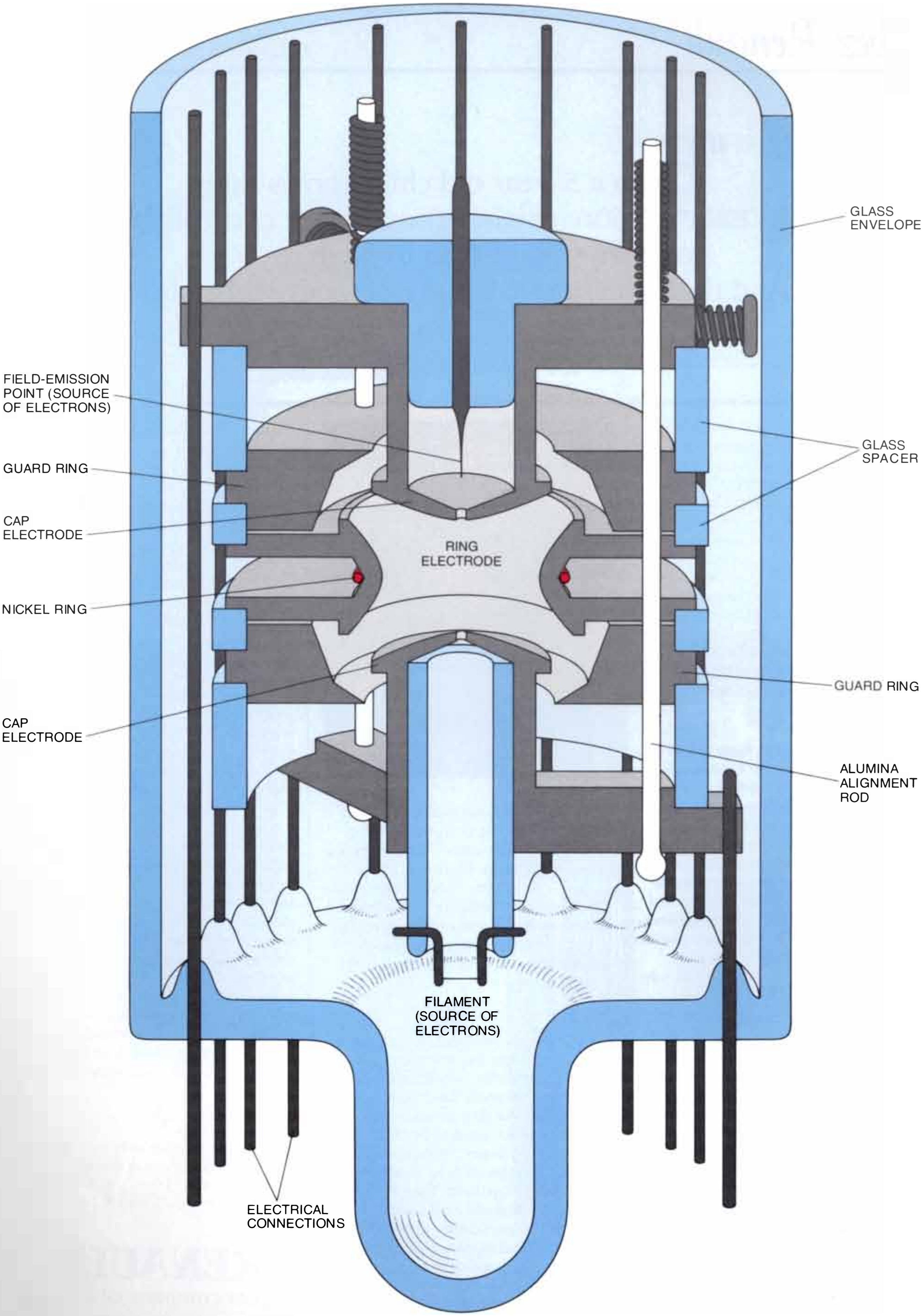
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FILAMENT
(SOURCE OF
ELECTRONS)
ELECTRICAL
CONNECTIONS

The Isolated Electron

From a single electron trapped in an artificial atom of macroscopic size a property of the electron called the g factor can be measured with unexcelled accuracy

by Philip Ekstrom and David Wineland

The electron is a remarkably simple particle of matter. It has mass and an electric charge; it spins (or seems to spin) with a fixed amount of angular momentum, and it has a magnetic moment, so that an external magnetic field exerts a twisting force on it. These four quantities constitute all the known properties of the electron; once their values have been established there is nothing more to be said about the electron.

It can be argued that the electron is even simpler than this tabulation of properties might suggest. The reason is that the four quantities are not all independent; instead any one of them can be derived from the other three. For example, the magnetic moment of the electron is related to its mass, charge and spin by a constant of proportionality called the *g* factor. In the modern theory of electrons the value of the *g* factor can be calculated with great precision, and it can also be measured experimentally. Such measurements are therefore a sensitive test of the theory. Both the calculation and the measurement are difficult, but they have been refined to such an extent that the *g* factor of the electron is now known to greater accuracy than any other physical constant. The values derived from theory and from experiment are in accord to the last decimal place known.

A series of experiments that has been under way for some years at the University of Washington has recently culminated in a new measurement of the *g* factor, which has set a new record for accuracy. The experiments employed a novel technique in which a single electron is confined for weeks at a time in a "trap" formed out of electric and magnetic fields. In effect the electron and the confining apparatus make up an atom with macroscopic dimensions and an extraordinarily massive nucleus. Because the apparatus rests ultimately on the earth the nucleus might even be identified with the earth itself, and so the artificial atom has been given the name geonium, the earth atom. The motion of the single electron in geonium is different from that in an ordinary atom, and it is more accessible to manipulation and measurement. For these reasons it was possible to measure the *g* factor with an uncertainty of less than one part in 10 billion.

When the electron was discovered in 1897 by J. J. Thomson, it was immediately obvious that the particle has mass and electric charge; indeed, Thomson made his discovery by measuring the ratio of mass to charge. It was also assumed, at least implicitly, that the electron has the familiar mechanical properties characteristic of all bulk matter, such as a definite size and shape. A magnetic moment and an intrinsic quantity of spin angular momentum were added to the list of properties some years later during the development of the quantum theory, following a proposal made by Samuel A. Goudsmit and George E. Uhlenbeck. The spin and magnetic moment were required in order to explain certain features observed in the spectrum of light emitted or absorbed by atoms.

With these properties it might seem that the electron could be understood in terms of a simple mechanical model. The electron could be imagined as a material particle with some definite size and shape and with a negative electric charge distributed over its surface. The particle would be required to spin about an axis, much as the earth does, with a specified and unvarying quantity of angular momentum.

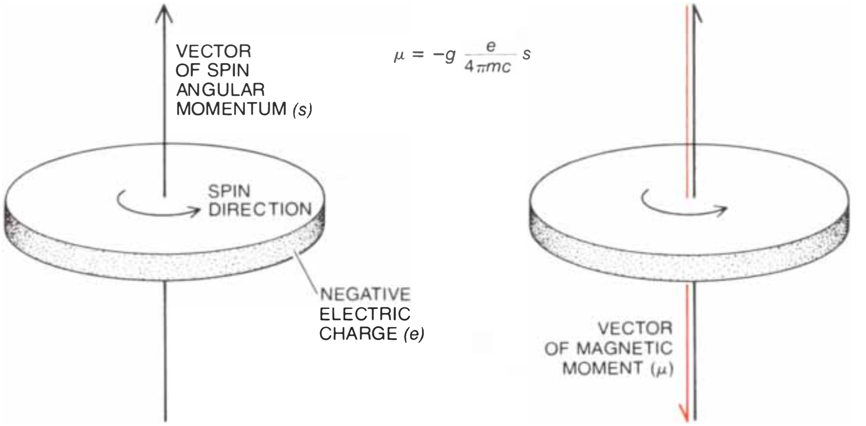
In this model the magnetic moment of the electron has a straightforward explanation. The rotation of a body with a charge on its surface necessarily entails a circulation of electric charge, or in other words an electric current. The circulating current gives rise to a magnetic field in the electron just as it does in the windings of an electromagnet. Both the spin angular momentum and the magnetic moment can be represented by vectors, or arrows, lined up along the spin axis. By convention (and because the charge of the electron is negative) the vectors representing the spin and the magnetic moment point in opposite directions.

Continuing to reason in terms of this mechanical model, one would expect the magnetic moment to be proportional to the electric current circulating at the perimeter of the spinning electron. The current should be directly proportional to the total electric charge and to the rotational velocity. The rotational velocity in turn should be directly proportional to the spin angular momentum and inversely proportional to the mass of the electron. The relation among these quantities, along with some numerical factors needed to keep the system of units consistent, can be expressed succinctly in an equation:

$$\mu = -g\frac{e}{4\pi mc}s\,.$$

Here μ (the Greek letter mu) is the magnetic moment of the electron, s is the spin angular momentum, e is the charge, m is the mass and c is the speed of light in a vacuum. The constant of proportionality in the equation is the g factor, a

TRAP FOR AN ELECTRON captures the particle in a special configuration of electric and magnetic fields. The electron occupies the central cavity formed by the two cap electrodes and the ring electrode, which are machined to a mathematically determined shape: they are hyperboloids. Two additional electrodes, the guard rings, compensate for imperfections in the electric field. The entire apparatus, which is about an inch and a half in diameter, is immersed in liquid helium and inserted into the core of a superconducting magnet. The electron is bound by the combination of static electric and magnetic fields in the trap, much as an electron in an atom is bound to the nucleus. Here the part of the nucleus is played by the apparatus, or even by the earth, on which the apparatus rests, and so the atom is called geonium, the earth atom.



PROPERTIES OF THE ELECTRON are electric charge (*e*), mass (*m*), spin angular momentum (*s*) and magnetic moment (μ). A naive mechanical model conceives of the electron as a spinning disk with electric charge distributed on its perimeter. It is the current of circulating charge that gives rise to the magnetic moment, and the moment can therefore be derived from the other three properties. The relation is defined by an equation in which a constant of proportionality called the *g* factor appears. The minus sign in the equation signifies that the moment is opposite to the spin vector. The modern theory of electrons does not allow such a pictorial representation, but the relation of the magnetic moment to the spin still holds, and *g* can be calculated with great precision. In the geonium experiments *g* is measured with equal precision.

dimensionless number. The *g* factor determines how large a magnetic moment will be generated by a given amount of spin, charge and mass. The minus sign that precedes the *g* factor signifies that the magnetic moment is antiparallel to the spin angular momentum.

In this mechanical model the value assigned to *g* depends critically on the shape and size of the electron and on how the electric charge is distributed over its surface. The first experimental values of *g* came from the same spectroscopic observations that suggested the existence of an intrinsic spin angular momentum. Those observations indicated that *g* is approximately equal to 2. Some years later a more refined version of the quantum theory, formulated by P. A. M. Dirac to be consistent with the special theory of relativity, made possible a precise theoretical calculation of *g;* the value predicted was exactly 2, in agreement with the observational evidence available at the time.

Viewing the electron as a rigid, rotating body is somewhat naive; after all, the motion of the particle must be described by the laws of quantum mechanics, where the notions of size and velocity cannot even be defined beyond a certain level of precision. Indeed, the model has grave flaws, some of which were recognized only days after it was first proposed. For example, it turns out that the rotational velocity at the surface of the electron is greater than the speed of light. Another source of difficulty is the size attributed to the electron. The mass or energy of an electrically charged particle depends inversely on its size. One reason this is so can be understood by noting that energy is required in order to pack the repulsive negative charge of the electron into a finite volume. The smaller the volume, the larger the energy needed. According to this scheme, the quite small mass or energy of the electron implies that it should have a rather large size. Experiments in which electrons are scattered by other particles, however, effectively measure the size of the electron, and they indicate that the radius must be exceedingly small. Indeed, all experimental data gathered so far are consistent with the idea that the electron is a point particle, entirely without extension. The arguments presented here then predict that the electron mass is infinite, a manifest absurdity.

Still another reason for doubting the accuracy of the mechanical model, and that of the Dirac theory as well, derives from refined measurements of the *g* factor of the electron. Experimental evidence has shown that *g* is not exactly 2 but rather is greater than 2 by about .1 percent; in other words, its value is roughly 2.002. The Dirac theory could not accommodate such an adjustment.

In the 1940's these problems were resolved by abandoning the mechanical model of the electron and devising a new and more abstract theory, quantum electrodynamics. In quantum electrodynamics the electron is allowed to be a dimensionless point particle and its mass is allowed to be infinite, at least in principle. Surprisingly, there is a mathematical procedure (called renormalization) that cancels this infinity and recovers the observed, finite properties of the electron, including the *g* factor.

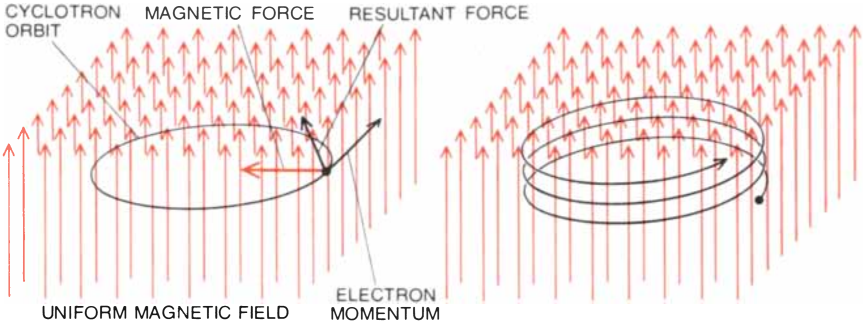
It is far from obvious how a particle with zero radius can have spin angular momentum or a magnetic moment. If quantum electrodynamics offers no consistent mental picture, however, it does provide an explicit procedure for calculating the numerical values of the various properties of the electron. The relation between the electron's magnetic moment and its spin, charge and mass takes the same form it had in the mechanical model, and the constant of proportionality in the equation is the same *g* factor. Moreover, a first approximation still yields a value of $g = 2$. That is only an approximation, however, and an infinite series of progressively smaller corrections can be applied to it. Finding the exact value of *g* by this method is impractical because the entire series of terms would have to be included in the calculation, but any finite precision can be attained by evaluating a finite number of terms.

Beginning in 1950, a series of experimental measurements of the *g* factor was undertaken by H. R. Crane and a number of his colleagues and students at the University of Michigan. What was actually measured was not *g* but the discrepancy between *g* and 2, and so the project came to be known as the *g*-minus-2 experiment. Over the next two decades a succession of increasingly precise values was reported by Crane, Arthur Rich and their collaborators [see "The *g* Factor of the Electron," by H. R. Crane; SCIENTIFIC AMERICAN, January, 1968]. During the same period theorists worked to evaluate progressively more complex terms in the infinite series. The ensuing duel between theory and experiment was punctuated by a few errors and subsequent corrections, but by 1972 the calculated and measured values of *g* agreed to better than eight significant figures. An incidental benefit of this competition was the development of new methods both for theoretical calculations and for experiments. It seemed that each additional decimal place demanded some technical innovation.

In the Michigan experiments a beam of electrons was passed through a magnetic field in an apparatus where the orientation of the electrons' spin axis (or magnetic moment) could be determined both before the passage and after. The applied field had two effects on the electrons: it caused their spin axes to precess and it caused the electrons themselves to describe a circular or helical orbit. If *g* were exactly 2, the frequency of the spin precession and the orbit frequency would be equal. The experiment measured the difference between the frequencies and hence determined $g - 2$.

The accuracy of this method is limited mainly by the statistical nature of an experiment done with many interacting electrons and by deficiencies in the experimenter's knowledge of what happens to an electron during the measurement. Each electron moves through the apparatus at high speed and spends much less than a second in the magnetic field. During that interval its trajectory can be altered by inhomogeneities in the field and by encounters with other electrons in the beam. The Michigan group continues to improve the experiment, seeking to control these uncertainties.

An alternative strategy for improving the measurement of g is to confine a single, slow-moving electron for an extended period in an environment that is simple enough to be analyzed precisely. This is the plan adopted in the geonium experiments done at the University of Washington. The goal of these measurements—a goal that can be approached but never attained—is to isolate an electron from all extraneous influences and make it hold still for examination. The long-term confinement of free electrons was conceived more than 20 years ago by Hans G. Dehmelt of Washington, and the work described here was carried out under his direction. The techniques for preparing and observing an isolated electron were developed mainly by us, although our work was founded on experiments with trapped clouds of electrons done by our predecessors, Fred L. Walls and Talbert S. Stein. We have since left the project, but the single-electron techniques have been refined further by Robert S. Van Dyck, Jr., and Paul B. Schwinberg, who have measured the g factor with great accuracy.



CONFINEMENT OF AN ELECTRON in a uniform magnetic field results from the action of the field on the moving electric charge. The electron is subject to a force directed perpendicular both to the field and to the particle's direction of motion. The continuous application of the force diverts the electron into a circular path, which is called the cyclotron orbit. The size of the orbit increases in discrete steps as the energy and speed of the electron increase. By this mechanism the electron is constrained to revolve in a finite region of the field, but it is not yet fully confined; it can still drift parallel to the field lines, so that its trajectory becomes a helix.

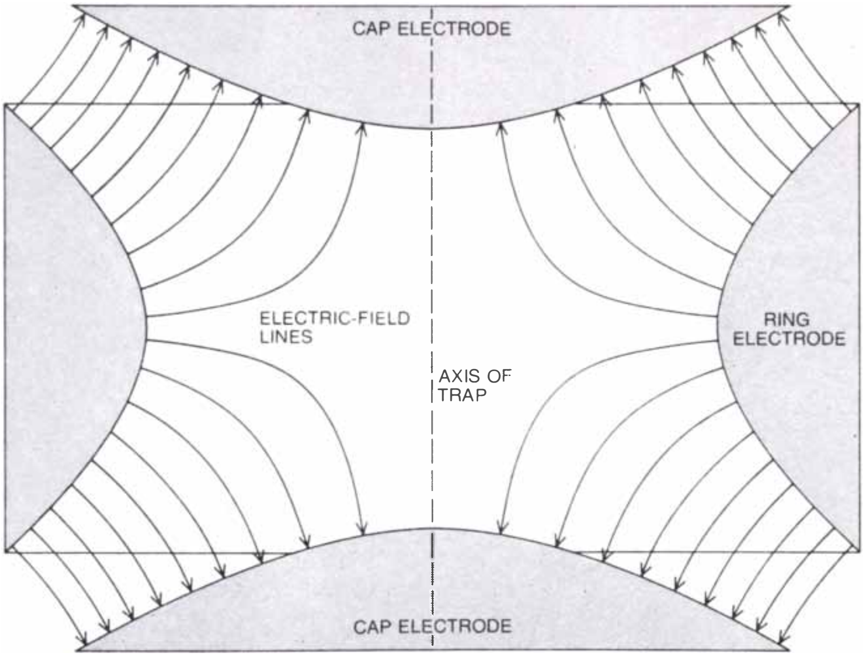
To understand the behavior of the electron in the geonium atom it is helpful first to consider a simpler, idealized system: an electron at rest in a uniform magnetic field. Such a field can be represented by flux lines that are all parallel and evenly spaced. The energy of this stationary electron depends on the orientation of its magnetic moment with respect to the external field. The energy is minimum when the moment and the field are parallel and maximum when they are antiparallel.

It turns out that these two orientations of the electron, which are commonly called "spin down" and "spin up," are the only ones possible. All intermediate orientations, where the magnetic moment would be perpendicular to the field or would cross it obliquely, are forbidden by the rules of quantum mechanics. (To be precise, the rules apply to the orientation of the spin axis and only indirectly to the magnetic moment. Since the two vectors always point in precisely opposite directions, however, the orientation of the electron can be defined with reference to either one of them.)

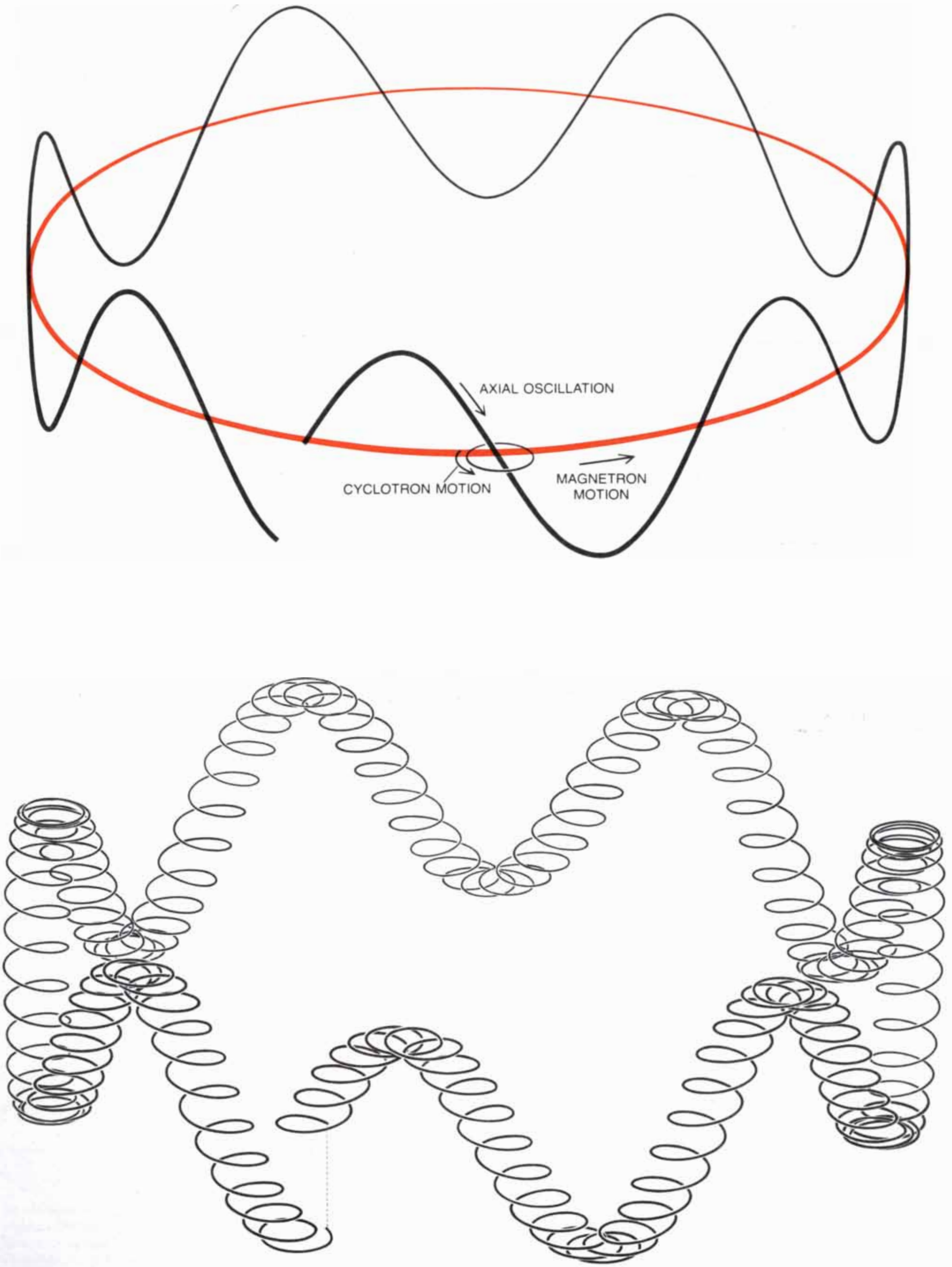
Because an electron has only two possible orientations a stationary electron in a uniform magnetic field has just two distinct energy levels. The difference in energy between the levels is the product of three quantities. One of these quantities is a combination of fundamental constants called the Bohr magneton, which defines the coupling between an applied magnetic field and the magnetic moment of a particle. The Bohr magneton is defined as Planck's constant, h, multiplied by $e/4\pi mc$. The other two quantities that determine the energy levels are the strength of the external field and the g factor. Any measurement of g ultimately calls for a measurement of this energy difference in a context where the strength of the applied field can also be determined. In practical experiments even the need to know the field strength precisely is dispensed with.

An electron at rest is a convenience, but it is a fictitious one; the uncertainty principle of quantum mechanics ensures that no particle as light as the electron can hold still for very long. If the electron must always keep moving, however, a magnetic field can at least confine its motion to a specified region. The confinement results from the interaction of the field with the charge of the particle. If the electron is moving perpendicular to the field, a force arises that pushes the electron perpendicular both to its original direction of motion and to the field. The result is to bend the electron's trajectory into a circle.

As the energy and speed of the electron increase, so does the diameter of the circular orbit. Indeed, the speed and the orbital diameter change in concert in such a way that the time required to



ELECTRIC FIELD generated by the voltages applied to the trap electrodes is superposed on the uniform magnetic field. Because the electron is negatively charged the electric field exerts a force on it that is directed opposite to the field lines. The force has a vertical component, and so an electron that drifts toward either of the cap electrodes is pushed back toward the midplane. In general the electron will overshoot the midplane and so will oscillate parallel to the axis of the trap. The electric field also has a radial component, which forces the electron toward the ring electrode. Radial motion is opposed, however, by the action of the magnetic field, which deflects the electron into a circular orbit called the magnetron orbit. Hence in the combined electric and magnetic fields the electron is fully captive, but its motion is complicated.



THREE MODES OF MOTION of the electron in the trap combine to yield a complex trajectory. The electron revolves rapidly in the cyclotron orbit; at the same time the center of the cyclotron orbit follows the much larger circular path of the magnetron motion; all the while the electron is oscillating along the axis of the trap. Neither the frequencies nor the amplitudes of the various modes are shown to scale. In each magnetron orbit the electron typically completes some 2,000 axial oscillations and 1.4 million cyclotron revolutions.

complete one circuit is almost constant. In other words, the period of the electron's motion is constant (or nearly so) regardless of its speed or energy. The constancy of the orbital period is spoiled only by an effect of special relativity: at high speed the mass of the electron increases and so the period of revolution becomes slightly longer. For low-energy electrons, however, the relativistic correction is small. The orbital motion of an electron in a magnetic field is called the cyclotron motion because it is employed in a cyclotron to accelerate electrons or other charged particles.

At this point quantum mechanics intervenes again to modify the motion of the electron. In classical, or pre-quantum, physics an electron circulating in a magnetic field can take on any arbitrary energy and so can have an orbit of any diameter. In the quantum theory only certain discrete energies and orbital sizes are allowed. There is a smallest-possible orbit, followed by a sequence of larger orbits associated with increasing energies; orbits of intermediate size are forbidden. Each of the allowed orbits is specified by a quantum number, n, which can only assume integer values in the series 0, 1, 2, 3 and so on.

Because the cyclotron orbits are quantized a diagram of the allowed energy levels of the electron takes the form of a ladder. The bottom rung corresponds to the smallest orbit of lowest energy, and each successive rung represents the next-largest orbit and the next-highest energy state. What is most important, the spacing between rungs is almost constant (and it would be exactly constant if relativistic effects could be ignored). The energy difference between rungs is equal to 2 times the Bohr magneton times the strength of the applied magnetic field. These are the same quantities that figure in the energy difference between the down and the up spin states, with one significant change: the g factor is replaced by the exact integer 2. The similarity of the two formulas suggests a procedure for measuring g, or at least for measuring the ratio of g to 2, without knowing to great precision the strength of the magnetic field or the value of the Bohr magneton. All that is necessary is to measure, under the same conditions, the energy spacing between the spin states and the spacing between successive orbital states. Dividing the one energy by the other gives a ratio where the Bohr magneton and the field strength appear in both the numerator and the denominator, so that they cancel.

In practice there is no way to "turn off" the spin while measuring the orbit size, nor can the electron be persuaded to stay still while the energy of its spin orientation is determined. Any real state of the electron has an energy determined both by its orbit and by its spin direction. It is convenient to segregate these combined states into two side-by-side energy ladders. One ladder represents all the states with the spin up and the other ladder includes all those with the spin down. Within each ladder the rungs correspond to successively larger orbits, and the rungs are labeled with the principal quantum number, n. The spacing between any two rungs is the same on both ladders, but one entire ladder is displaced with respect to the other by an amount equal to the energy needed to flip, or reverse, the spin. Since this energy is roughly equal to the rung spacing, one ladder begins about a rung higher than the other.

Three kinds of transition between states are possible in this system. Suppose the electron initially has its lowest-possible energy: its spin is down, so that its magnetic moment is parallel to the field, and its cyclotron orbit is the smallest one allowed, with n equal to 0. The electron therefore occupies the bottom rung of the lower energy ladder. A first transition would leave the spin orientation fixed but would enlarge the orbit to the next allowed size; this transition corresponds to climbing one rung of the same energy ladder, to the $n = 1$ state. The energy required to effect the change is equal to the spacing between rungs and hence is given by 2 times the Bohr magneton times the field strength.

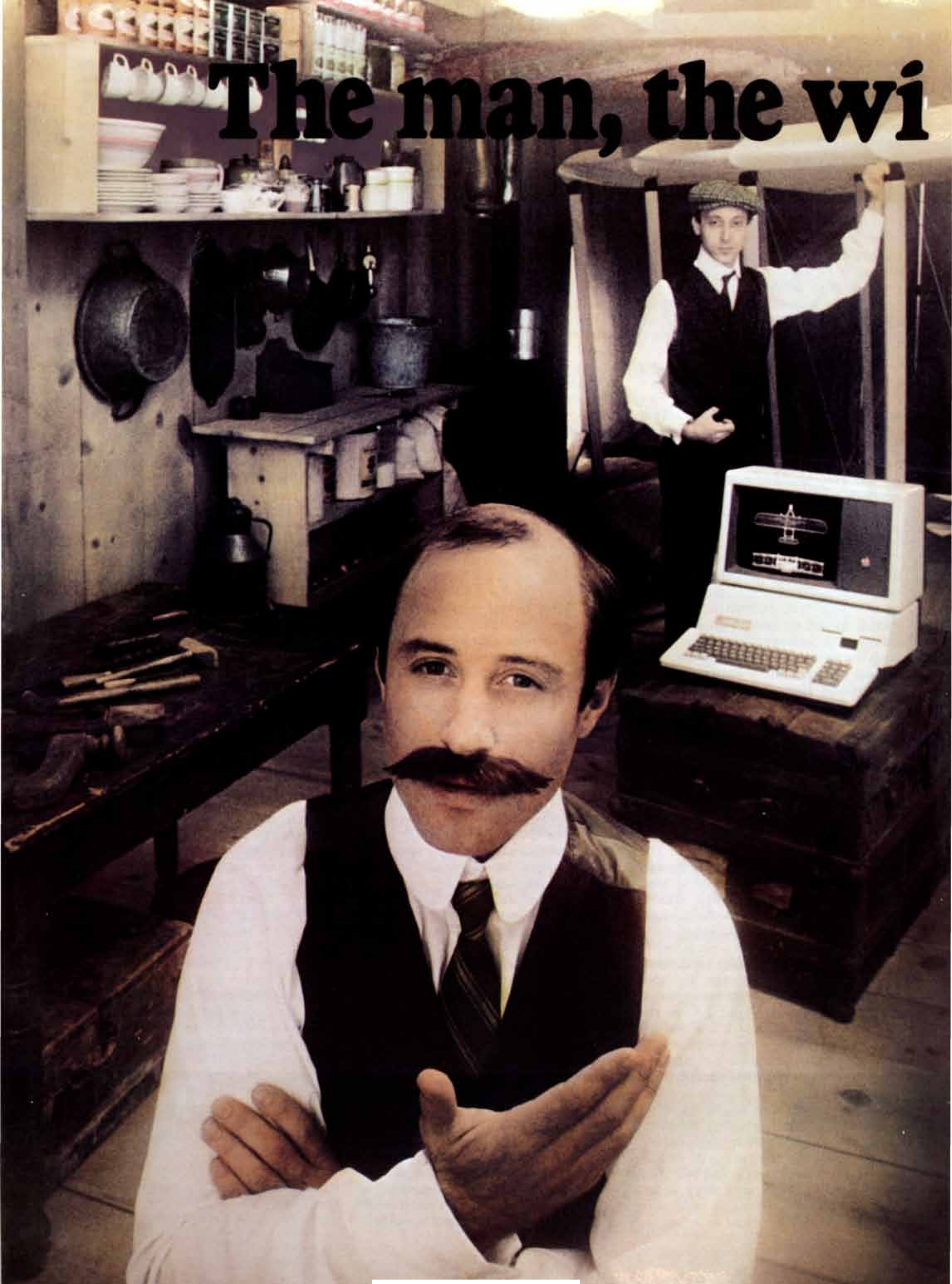
This level having been reached, another transition might flip the spin of the electron without altering the orbit, so that the electron would move from the $n = 1$ level of the spin-down ladder to the corresponding $n = 1$ level of the spin-up ladder. The energy required in this case is g times the Bohr magneton times the field strength. The third possibility is for the orbit to change size by one unit and for the spin to flip simultaneously. For example, the electron might step from the $n = 1$ rung of the spin-down ladder directly to the $n = 0$ rung of the spin-up ladder. These levels almost coincide; the energy required to flip the spin to the antiparallel orientation is almost made up by the energy liberated when the orbit shrinks by one unit. Only the small difference in energy between these quantities need be supplied. It is equal to $(g - 2)$ times the Bohr magneton times the field strength.

The energy required for these changes of state is conveniently expressed in terms of the frequency of electromagnetic radiation that induces the transition. Any frequency can be converted into energy units by multiplying by Planck's constant, but for our purposes it is not even necessary to make the conversion. The frequency itself can be allowed to stand for the energy. The frequency needed to flip the spin is proportional to g, the constant that determines the difference in energy between spin states. In the same way the frequency of radiation that changes the cyclotron orbit size by one unit is proportional to 2, the constant that determines the spacing between rungs on a single energy ladder. For typical values of the applied magnetic field both of these frequencies are in the microwave region of the electromagnetic spectrum. The difference between them, which is called the anomaly frequency, induces the double transition where the spin and the orbital diameter change simultaneously. The anomaly frequency is therefore proportional to $g - 2$. Since g exceeds 2 by only about .1 percent, the anomaly frequency is smaller than the cyclotron-transition frequency by a factor of about 1,000.

The procedure for measuring the g factor can now be given in terms of radiation frequencies. Two quantities must be determined: the cyclotron-transition frequency and the anomaly frequency. The actual values of both frequencies depend on the strength of the magnetic field and on the value adopted for the Bohr magneton, and so they cannot be predicted beyond the accuracy with which these quantities are known. In the ratio of the two frequencies, however, both of these factors cancel and the only significant quantities remaining are the proportionality constants that define the level spacings in the ladder diagram. For the anomaly frequency that constant is $g - 2$ and for the cyclotron-transition frequency it is exactly 2. Hence the ratio of the two frequencies equals $(g - 2)/2$. Multiplying by 2 and adding 2 gives the value of g itself.

This method of finding the g factor may seem needlessly roundabout. Why not just measure the spin-flip transition frequency, which is directly proportional to g, and have the desired value in a single step? One part of the answer lies in the substantial advantage to be found in working with a dimensionless ratio. Suppose the spin-flip frequency were measured to an accuracy of eight decimal places. To find the g factor that frequency must then be multiplied by the Bohr magneton, by the strength of the applied magnetic field and by Planck's constant. The eight decimal places would remain significant only if all these factors were known to at least the same accuracy. Taking the ratio of two frequencies eliminates all the extraneous quantities, so that the precision of the frequency measurement alone determines the accuracy of the result.

There is another argument in support of the indirect method. Because g is known to be very close to 2, deriving the value of g from a measurement of $g - 2$ yields a large divident in accuracy. If $(g - 2)/2$ is known to eight significant figures, then multiplying by 2 and adding 2 yields a value of g accurate to 11 significant figures. This seeming paradox of accuracy obtained at no cost can be resolved in a number of ways. One explanation is that the anomaly frequency is 1,000 times smaller than the


The man, the wi

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spin-flip frequency, so that a measurement with a given fractional accuracy yields a much smaller uncertainty in terms of cycles per second. Another approach is to point out that in any measurement of the anomaly frequency the cyclotron-orbit level spacing of exactly 2 is subtracted by the physical system itself and not by the experimenter; as a result only the small discrepancy from 2 need be measured. The situation of the experimenter is somewhat like that of a surveyor asked to lay out a course of 1,001 meters. The distance could be measured meter by meter, but high accuracy could be achieved more easily with a chain known to be exactly one kilometer long. That distance could then be subtracted from the total and only one meter would have to be measured with high precision.

The procedure adopted at the University of Washington for measuring the g factor can be summarized as follows. First an electron is captured in a uniform magnetic field and then its motion in the field is analyzed in order to determine two quantities: the frequency of applied radiation that changes the orbit size and the frequency that induces a simultaneous change in orbit size and spin orientation. From the ratio of these frequencies g can be found through trivial arithmetical operations. This synopsis does indeed set forth the principles of the experiment, but it is rather like the famous recipe for elephant stew that begins, "Take one medium elephant. . . ." Most of the work has been left out, and much of the adventure.

One deficiency of the experiment as it has been described so far is that the electron is not trapped by the magnetic field alone. In a uniform magnetic field the electron cannot migrate across the field lines, but there is nothing to prevent it from drifting parallel to the field and thereby escaping. Something is needed to seal the ends of the trap; what we chose at the University of Washington was an electric field superposed on the magnetic field, in a configuration called a Penning trap.

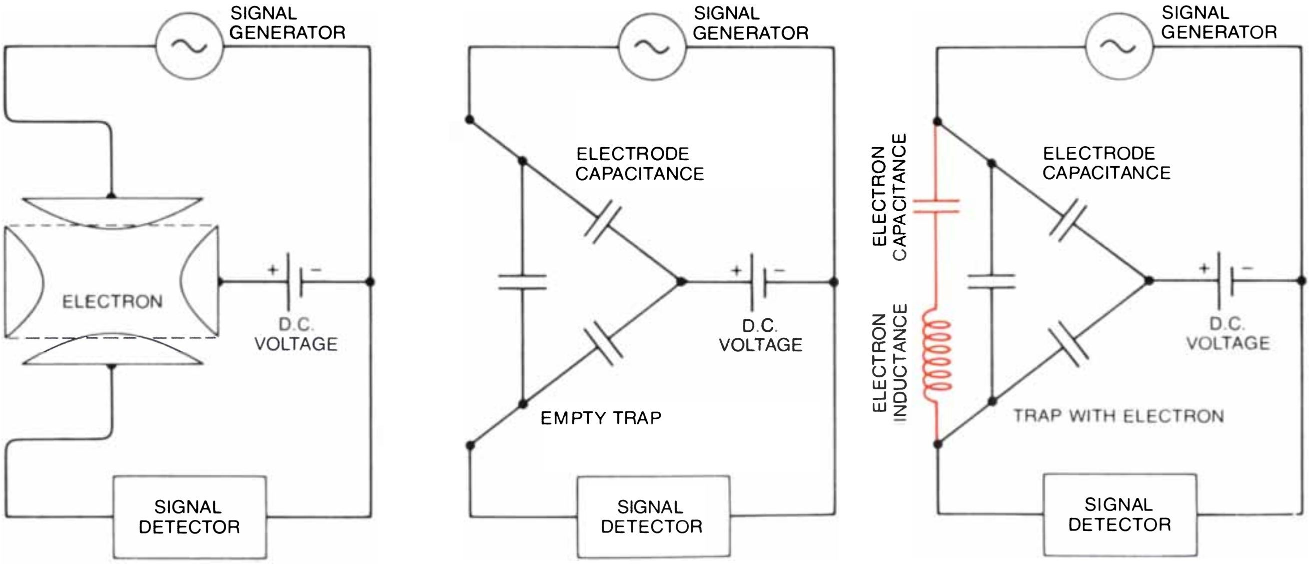
The electric field is formed by voltages applied to three electrodes, namely a cap at each end of the trap and a ring that girdles the midplane. Both caps are given a negative electric charge and the ring is given a positive charge. In the resulting combination of electric and magnetic fields the electron is confined in three dimensions. If it drifts horizontally, the magnetic field diverts it into a circular orbit. If it wanders vertically, parallel to the magnetic-field lines, it is reflected by the electric field on approaching the repulsive, negative charge of the cap electrode.

In general an electron reflected from one cap electrode will overshoot the midplane and then be repelled by the field at the opposite end of the trap, only to overshoot the midplane once again. In this way an oscillation along the symmetry axis of the trap can arise. If the frequency of the oscillation is to be independent of the amplitude, the electrodes must have a certain shape. They must be hyperboloids with cylindrical symmetry around the axis of the trap.

The addition of the electric field complicates the motion of a trapped particle. The electron continues to execute the rapid circles around magnetic-field lines that constitute the cyclotron motion. Superposed on that orbital velocity there is now an axial oscillation parallel to the magnetic-field lines. In addition the interaction of the electric and the magnetic fields gives rise to a third mode of motion. The electric field not only supplies a restoring force that confines the electron along the symmetry axis but also has a radial component that tends to push the electron away from the center of the trap and toward the ring electrode. This radial force might allow the electron to escape if it were not for the magnetic field, which overcomes it through the same mechanism that generates the cyclotron rotation. The radial force acting on the electron is converted by the magnetic field into a circumferential drift, so that the electron is deflected into a circular path.

This last perturbation imposed on the electron's trajectory is called the magnetron motion, after the kind of microwave-generating device in which it plays an important part. The magnetron orbit is much larger than the cyclotron orbit, but the electron moves around it much slower. ("Large" and "slow" are appropriate here only for purposes of comparison. The electron typically executes some 35,000 magnetron revolutions per second, but in each of those revolutions it completes 1.4 million cyclotron orbits.) The magnetron motion slightly modifies all the energy states of the electron, shifting the levels in the ladder diagram. The shifts are small, however, and they can be calculated as well as measured experimentally. Hence in a precision measurement of the g factor it is possible to correct for the effects of the magnetron motion.

The trajectory of the electron in the



EQUIVALENT CIRCUIT defines a configuration of elementary devices that would reproduce the electrical properties of the trap. The motion of the electron is observed by applying a radio-frequency signal at the top of the trap and detecting the transmitted part at the bottom. When the trap is empty, the electrodes are coupled only by small capacitances. The signal transmitted through these capacitances is canceled in the external circuitry. An electron in the trap has the same effect as a small capacitance and a large inductance connecting the cap electrodes. Through these phantom circuit elements a small signal reaches the detector. What actually happens is that the signal applied to the top electrode drives the electron's axial oscillation, which induces a current of the same frequency in the bottom electrode.

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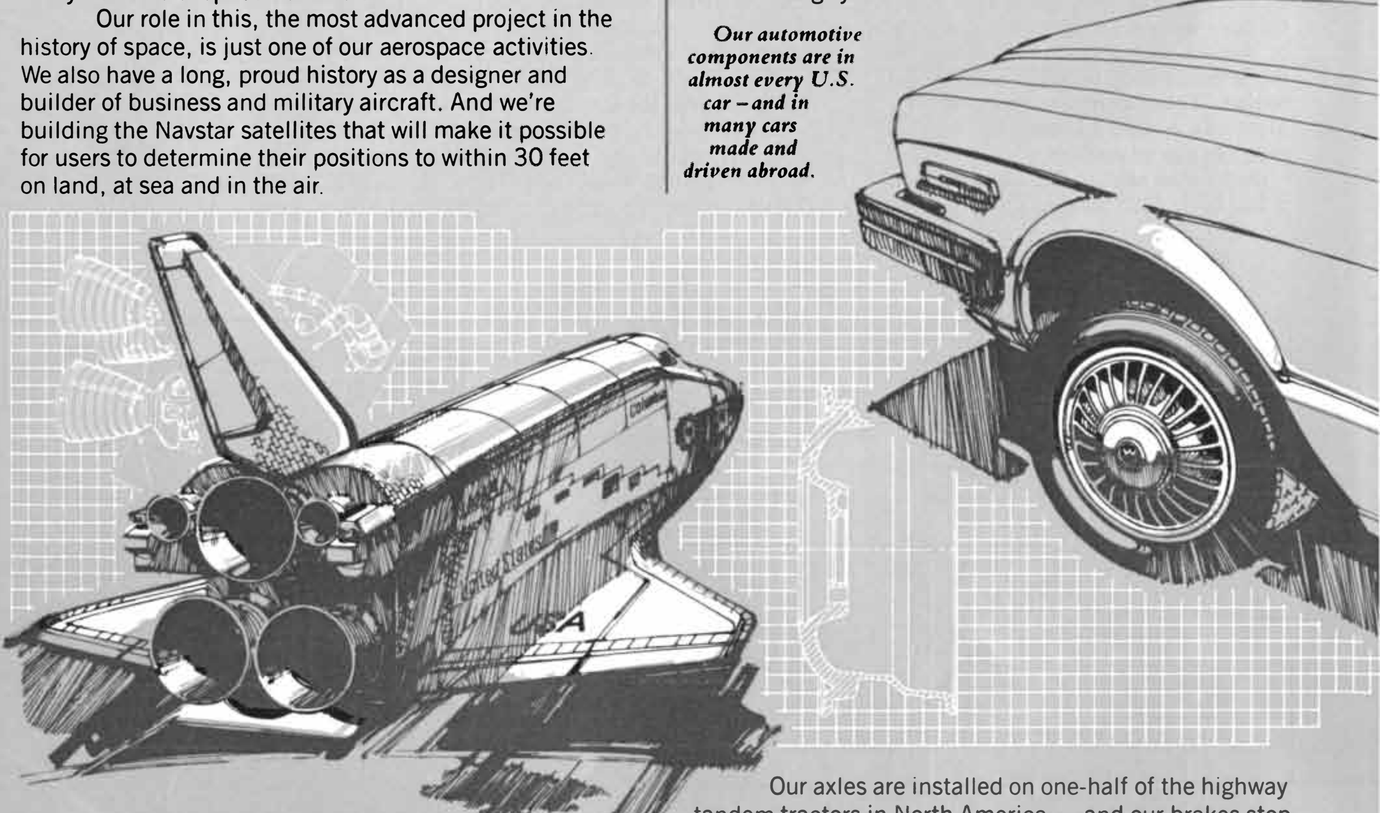

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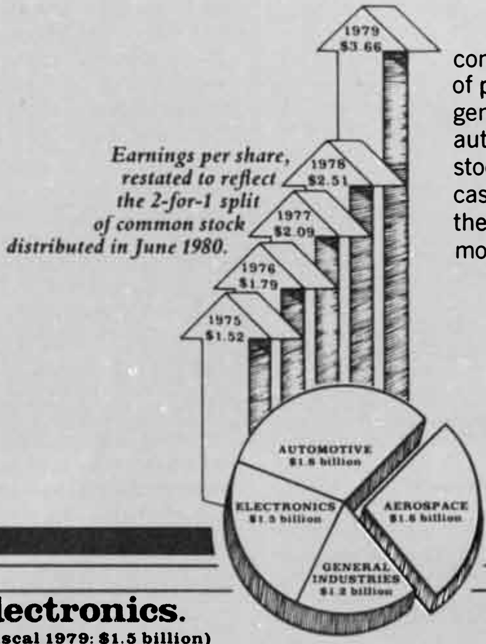

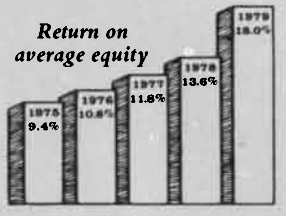

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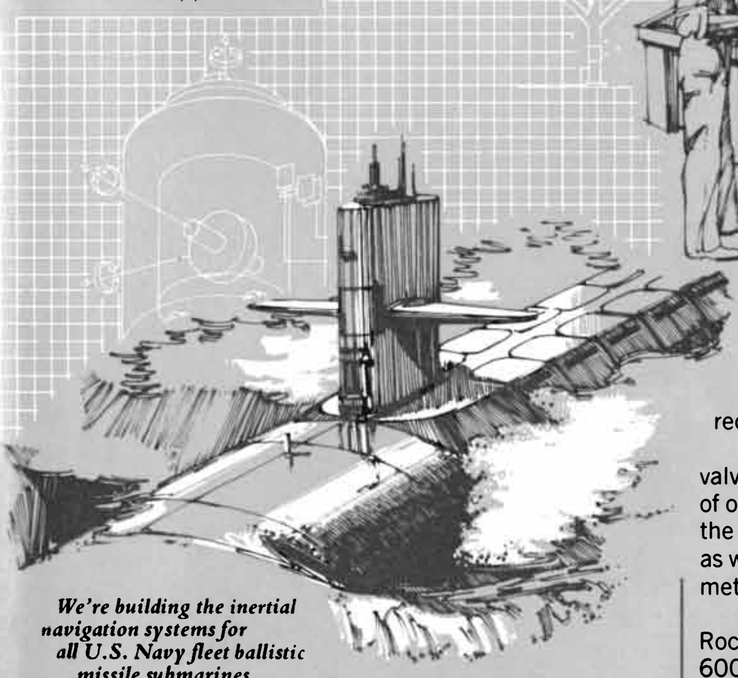

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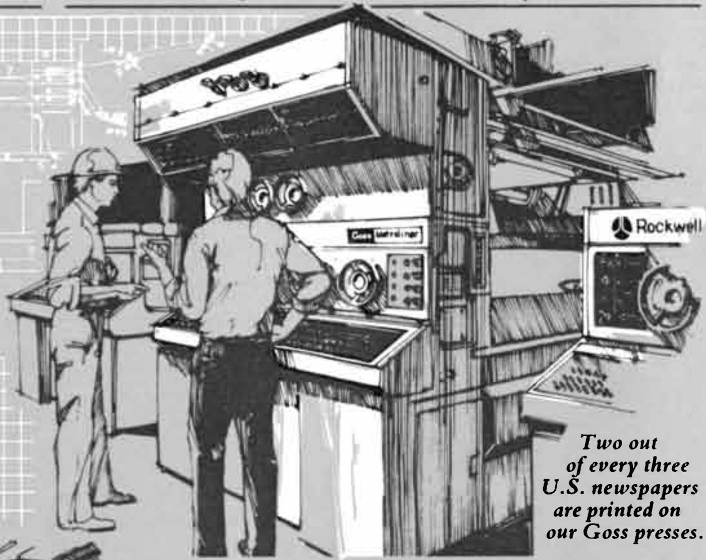

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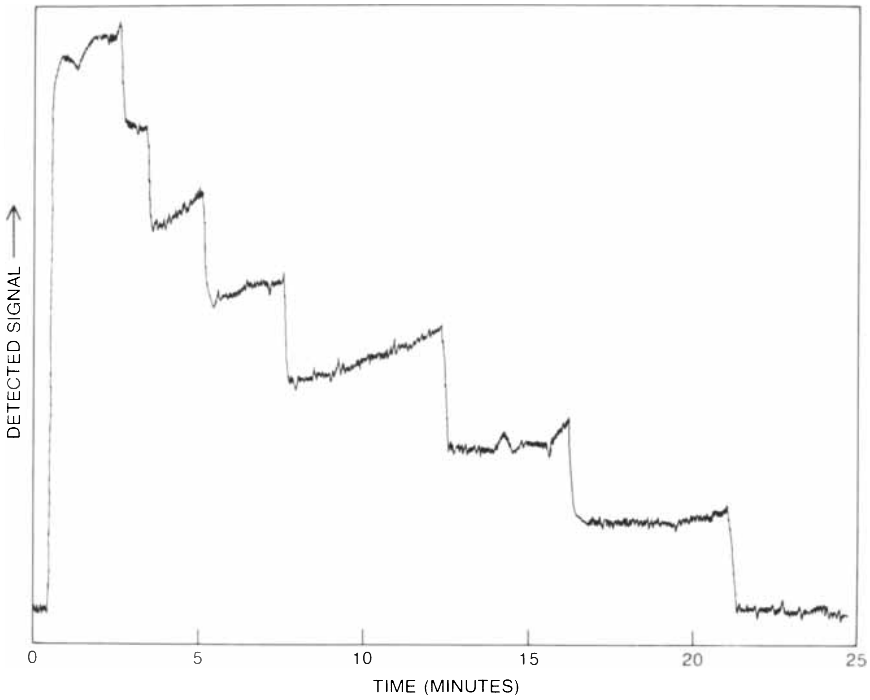


RECORD OF SEVEN ELECTRONS confined in the trap was made by detecting the current induced by the axial oscillation. The applied signal was adjusted to an amplitude near the maximum the electrons could tolerate. As the electrons escaped one at a time seven reductions in the induced current were observed. At a smaller amplitude an electron can be confined for weeks.

Penning trap can thus be analyzed into three components. The electron gyrates rapidly in small loops (the cyclotron motion), and the center of these loops progresses slowly around a larger circle (the magnetron motion). At the same time the electron is vibrating back and forth along the axis of the trap, perpendicular to the plane in which the cyclotron and magnetron orbits lie. The total motion is analogous to that of a carnival ride called the Tilt-a-Whirl, where a carriage pivots in a small circle on a turntable that rotates in a larger circle while at the same time riding over a series of undulations.

In what sense can this system be considered an atom, warranting the name geonium? It is atomlike mainly in that the electron is bound to a field of force like that of an atomic nucleus. The motion of the electron within this field is quantized, and transitions between various modes of motion correspond to definite frequencies of radiation. In other words, the trapped electron has a spectrum, which can be studied in the same way as an atomic spectrum is studied.

It is all very well to create an artificial atom, but if the atom is to be of any use for measurements, there must be a means for observing its spectrum. A single atom cannot emit or absorb much radiation; indeed, the quantity is so small that it can hardly be detected, much less measured accurately. It turns out there is a more practical way to observe the electron's motion; the key is the axial vibration, which induces small currents in the trap electrodes. The currents can be detected in the circuitry to which the electrodes are connected.

The electrical characteristics of the Penning trap can be analyzed in terms of an equivalent circuit: a network of elementary devices such as resistors, capacitors and inductors that could replace the trap and mimic all its properties. In this kind of analysis the trap is imagined as a black box whose inner workings the experimenter does not know; he sees only the three terminals corresponding to the two cap electrodes and the ring electrode.

When the trap is empty, the equivalent circuit consists of small capacitors connecting the three electrodes. If a high-frequency signal is applied to the top of the trap, across the upper cap electrode and the ring, some small remnant of the signal will be conveyed to the bottom of the trap by the capacitance between the cap electrodes. The transmitted signal can be detected by a receiver connected between the lower cap and the ring.

The capture of a single electron dramatically alters the equivalent circuit. When the trap holds an electron, the trap acts as if a resonant circuit consisting of a capacitance and a large inductance were connected in series between the two cap electrodes. Although the contribution of these phantom circuit elements to the transmission of the signal is weaker than that of the trap capacitance, the new path has distinctive properties that allow the electron signal to be isolated and monitored.

Under typical operating conditions the inductance of the equivalent circuit representing the electron is equal to about 10,000 henries, a value that would be associated with a large coil of wire; indeed, such a large inductance cannot ordinarily be obtained in a high-frequency circuit. Of course, the coil of wire does not exist; the inductance merely reflects the small inertia of the trapped electron. What really happens inside the trap is that the electron responds to the applied radio-frequency signal by oscillating in synchrony with it and thereby induces a replica of the signal in the bottom electrodes. There is a strict limit on how much power can be transmitted in this way: if the oscillations of the electron grow too large, the particle strikes the electrodes and is lost. One might say the resonant circuit burns out easily. A sensitive receiver is needed to detect even the largest signals the trapped electron can handle.

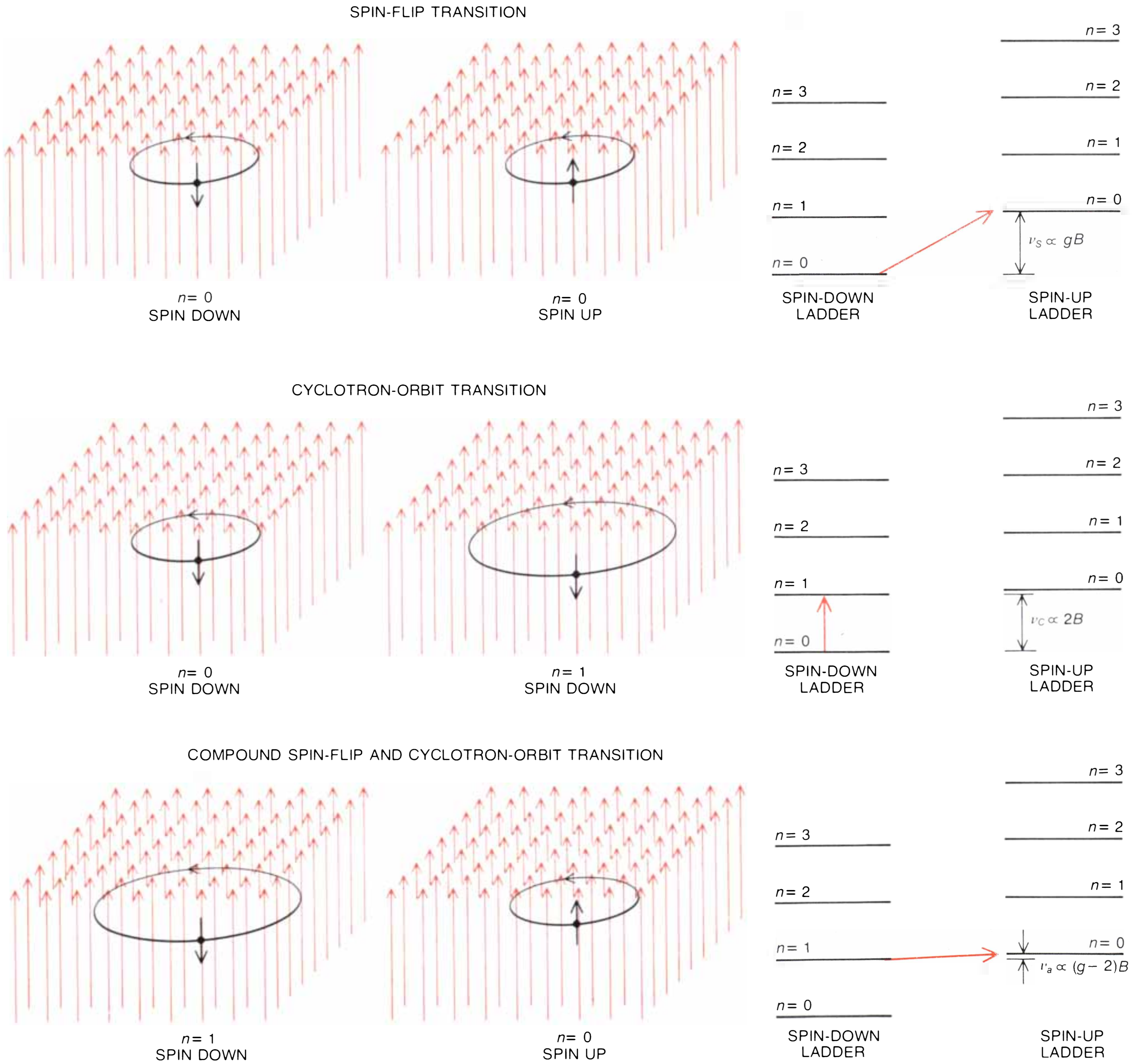
We first observed clear evidence of a single trapped electron by detecting the small induced currents. After pumping to obtain a good vacuum in the trap a small number of electrons from a hot filament were loaded into it. A radio-frequency voltage was applied to the top of the trap and was adjusted to an amplitude near the maximum the electrons could tolerate. The signal reaching the bottom of the trap was then monitored. After several minutes the output diminished a little, then it held steady for several more minutes and dropped again. Over the course of about half an hour there were seven reductions in the magnitude of the received signal, all of about the same magnitude, and after the last reduction the signal had returned to the background level characteristic of the empty trap. What we were observing, of course, was the loss of individual electrons from the population of seven that had evidently filled the trap initially. In subsequent experiments we found that if the driving voltage was reduced when only one electron remained, that last electron would stay in the trap and could be observed for many weeks.

The permanent confinement of a single electron was an exciting result and great fun, but it was only the first step toward measuring the spectrum of geonium and hence measuring g. A number of improvements in the apparatus were needed before precision measurements could be undertaken; Van Dyck and Schwinberg joined us in making some of these changes, and later they took charge of the project.

The geometry of the electric field turned out to be critical, and to obtain better control over it a new trap was constructed with five electrodes instead of three. The extra two elements, which are rings stationed in the gaps between the original cap and ring electrodes, allow small defects in the field to be compensated for electronically. The hot filament, which had tended to spoil the vacuum whenever a new batch of electrons was loaded, was replaced by a field-emission point. The entire apparatus was redesigned to fit in a tube about an inch and a half in diameter, so that it could be inserted in the bore of a powerful superconducting magnet. The magnet had to be cooled with liquid helium, and a separate bath of helium was employed to cool the trap to four degrees Kelvin. The cooling reduced thermal fluctuations in the motion of the electron and helped in maintaining a high vacuum. These practical details, which may seem mundane in the telling, absorbed much of the several years of effort that went into the project.

One modification of a fundamental nature was needed: in the original apparatus there was no way to detect changes in the cyclotron orbit size or in the spin orientation. The frequencies at which these changes take place were what we had set out to determine. Only the frequency of the axial oscillation can readily be observed, and in a uniform magnetic field that frequency is essentially independent of the cyclotron orbit and the spin direction. The solution we eventually adopted was to devise a means of coupling the axial frequency to the energy of the electron.

The coupling was accomplished by inserting a ring of nickel (a ferromagnet-



ENERGY STATES OF THE ELECTRON depend on the size of the cyclotron orbit (given by the value of the quantum number *n*) and on the orientation of the particle's spin vector (denoted "down" or "up"). For each spin orientation there is a series of almost equally spaced energy levels corresponding to the various cyclotron orbits. The diagram of the two series resembles a pair of ladders, which are displaced vertically by slightly more than one rung. The energy intervals between states are proportional to the strength of the applied magnetic field (*B*); the proportionality constant is different for each kind of transition between states. If the electron flips its spin from down to up, the energy change is proportional to *g*. If the size of the cyclotron orbit increases by one unit, the energy needed is proportional to 2. A compound transition in which the spin flips and the cyclotron orbit is enlarged simultaneously requires an amount of energy proportional to the difference between these factors, or $g - 2$. Because the value of *g* is close to 2 this is a small quantity of energy.

ic metal) in the midplane of the trap, encircling the original ring electrode. The nickel ring had the effect of bowing the magnetic field at the midplane, so that it was somewhat more intense near the ends of the trap; the resulting configuration is called a magnetic bottle. If there were no axial oscillation, so that the electron remained in the midplane, the magnetic bottle would have no effect. On each excursion away from the midplane, however, the slight convergence of the magnetic-field lines tends to reinforce the effect of the electric field in pushing the electron back toward the central plane. As a result of this additional restoring force the frequency of the axial oscillation is increased.

The total strength of the interaction between the electron and the distorted magnetic field depends on the energy of the cyclotron orbit and on the spin orientation. The influence of the field is greater when the orbit is larger or when the spin is up. For this reason the magnitude of the axial frequency shift changes with each change in the cyclotron orbit size or in the spin state. The distortion of the magnetic field must be kept small or the energy levels under examination will be too greatly modified, but only a small shift in the axial frequency is needed in order to make the changes in quantum state observable. Typically the axial oscillation has a frequency of 60 megahertz and the frequency shift caused by the magnetic bottle is a few hertz.

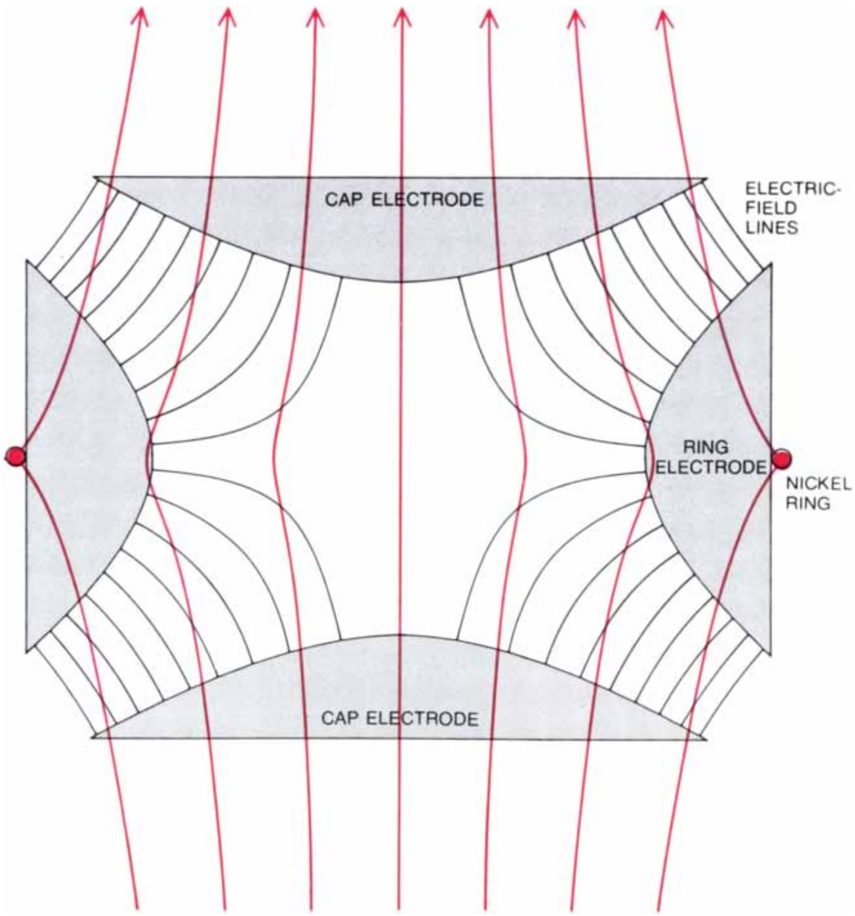
In an ideal experiment the electron would maintain a steady motion in a particular cyclotron orbit and a particular spin orientation until the experimenter supplied the energy needed to change the state. A graph of the energy of the electron as a function of time would therefore show a series of precise steps, all taken under the experimenter's control, and would be flat between the steps. A real experiment is quite different. Even at four degrees K. the thermal agitation of the electron has an average energy equivalent to a few rungs on the ladder of cyclotron states. Because of these random thermal disturbances the electron is constantly moving up and down whichever ladder it happens to be on. The resulting graph of energy as a function of time resembles a crop of grass: the root level corresponds to the lowest rung on the ladder and the blades of grass are energy excursions to higher rungs. Any measurement of the energy levels must be made against a background of this thermal noise.

The measurement is made by carefully searching for the frequencies that work the largest change on the rapidly fluctuating pattern. First a signal with a frequency near the cyclotron-transition frequency is supplied and the average height of the "grass" is monitored. The applied signal is then tuned slowly through a narrow range of frequencies. When the frequency corresponds exactly to the interval between rungs on the ladder, the electron absorbs energy strongly and climbs at least several rungs. Thus the cyclotron-transition frequency is the frequency that gives the tallest grass.

In the measurement of the anomaly frequency the background of thermal noise is less disruptive. The transition to be observed in this case is a compound one (both the spin and the orbit must change), and it is much less likely to happen spontaneously. In general the spin does not flip unless the experimenter does something to cause it to flip, and so all the electron's thermal transitions are normally confined to just one of the ladders in the energy diagram. To induce the lateral transition between ladders a strong signal must be supplied.

How does the experimenter know the orientation of the spin at any given moment, or in other words how does he know which ladder the electron is on? The needed information can be found in the energy diagram itself: the spin-down ladder, it will be remembered, extends about one full rung lower than the spin-up ladder. The root level of the grass therefore lies at a lower energy when the spin is down. The anomaly frequency is the frequency that changes the root level most often.

When both the cyclotron-transition frequency and the anomaly frequency have been measured, it remains only to divide, multiply by 2 and add 2 in order to calculate g. The two frequencies can be determined precisely, even in the noisy background, because both the resonances are very sharp, that is, a small change in the applied frequency causes a large change in the rate at which transitions are observed. The instrument with which the frequencies are generated is ultimately based on a cesium atomic clock, but even the absolute calibration of the instrument does not limit the accuracy of the measurement. Because both frequencies are generated by the same instrument and only the ratio mat-



MAGNETIC BOTTLE is created in the trap by a ring of nickel (a ferromagnetic metal), which slightly distorts the uniform imposed magnetic field. Because of the ring the field lines are bowed outward at the midplane and effectively converge toward the ends of the trap. This tapering of the field contributes an extra restoring force to the axial oscillation of the electron. The magnitude of the force depends on the size of the cyclotron orbit and on the spin orientation, so that changes in those quantities give rise to slight shifts in the frequency of the axial oscillation. As a consequence of this coupling of the three modes of motion, the energy state of the electron can be determined by monitoring the frequency of the axial oscillation.

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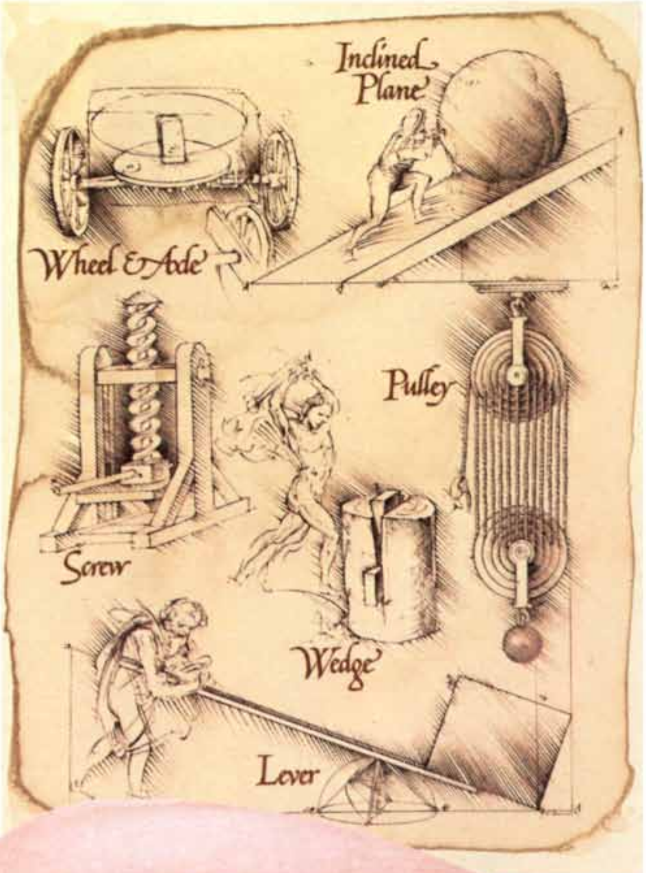

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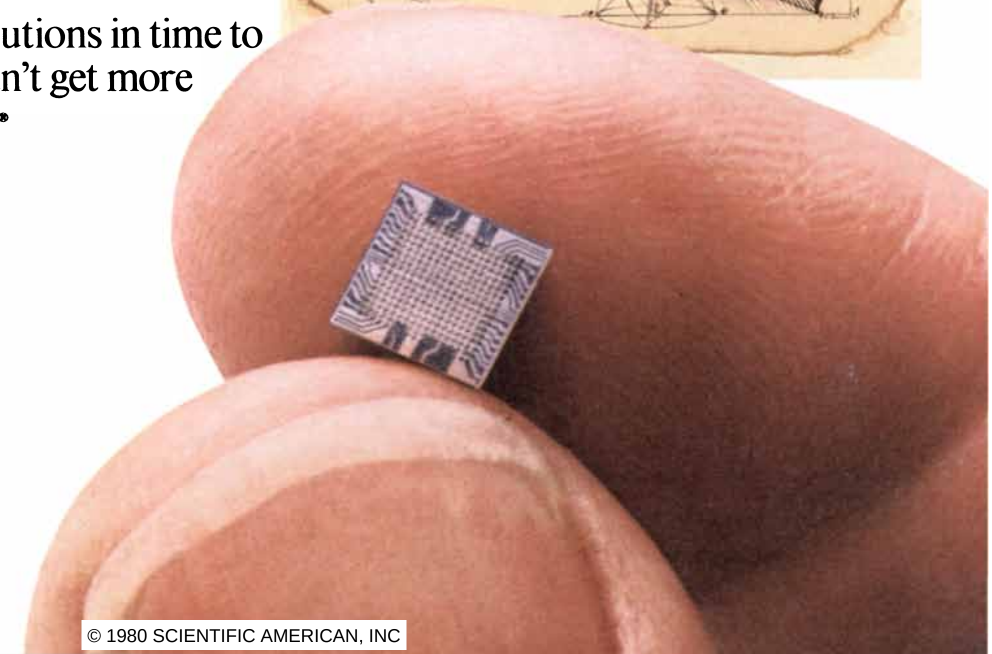
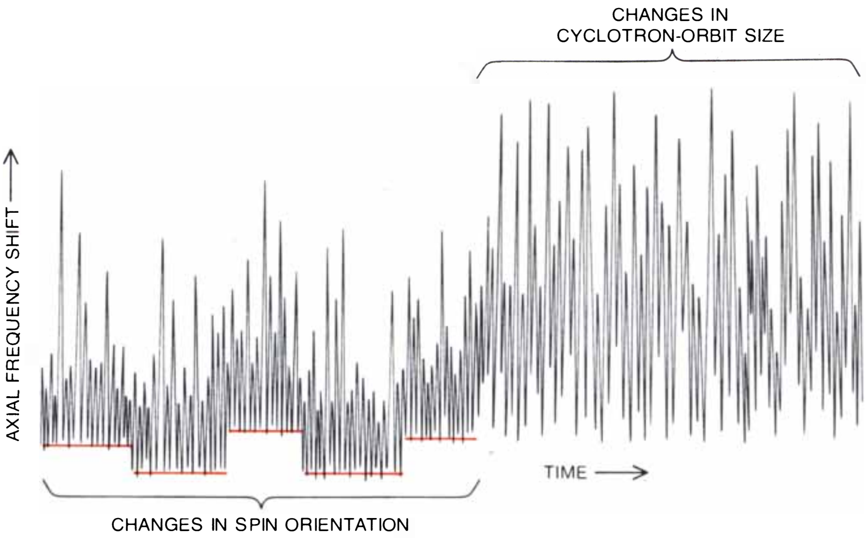




RECORDING OF THE FREQUENCY SHIFT in the axial oscillation yields a graph that resembles a crop of grass. In response to thermal fluctuations the size of the cyclotron orbit changes continually, causing rapid and random excursions in the axial frequency; these are the blades of grass. Reversals of spin orientation are much rarer, and they are observed as a change in the root level of the grass. The *g* factor is determined by irradiating the electron with electromagnetic energy and measuring two frequencies: the frequency that induces changes in the orbit size and thereby yields the tallest grass, and the frequency that flips the spin (with a simultaneous change in orbit size) and hence gives the highest rate of changes in the root level.

ters, it is only the relative accuracy over the range of frequencies employed that contributes to the uncertainty.

As it turned out, both of us had left the geonium project by the time the apparatus was ready for precision measurements. We learned of the first results through a telephone call from Van Dyck. Soon after he first detected transitions at the anomaly frequency he was able to announce an improved value for the *g* factor, and he has since refined the technique to obtain an accuracy of 10 decimal places. The best value of *g* is now 2.0023193044, with a probable error of less than one unit in the last decimal place. Major improvements in accuracy are still to come, through further refinements in the method. The theoretical value, calculated according to the prescription of quantum electrodynamics, is in exact agreement and has about the same uncertainty.

The value of *g* cited above is a statistically weighted average of measurements made with several electrons, but separate results for individual electrons also agree to within about one unit in the last decimal place. The finding of agreement from one electron to the next is hardly surprising, but it should not be dismissed as trivial.

Fundamental to the idea of an elementary particle of matter is the assumption that all particles with the same name are perfectly identical. In this article we have spoken repeatedly of "the electron," meaning an archetype that is reproduced in innumerable identical copies everywhere in the universe. On the assumption that all copies are identical the experimenter makes measurements with any electron he finds at hand in the laboratory, or with any collection of them, and reports his results as information about the properties of "the electron." Some might call this policy presumptuous; in any event it can do no harm to test its validity. Although there is much indirect evidence suggesting that all electrons are identical, geonium offers one of only a few opportunities to carry out a direct test.

The logical sequel to the measurement of the electron *g* factor is a measurement of the corresponding number for the positron, the positively charged antiparticle of the electron. Earlier investigations of the positron *g* factor, carried out by Rich and his colleagues at Michigan, have been hampered by the fact that positrons are much less plentiful than electrons. With the methods devised at the University of Washington the measurement could be made, at least in principle, with a single positron, which would be trapped to form a single atom of antigeonium. The experiment is certainly not without challenge: the positrons are emitted with high energy in the radioactive decay of certain nuclei, and they must be slowed down and installed in a trap without ever encountering an ordinary electron, since the positron and the electron would then annihilate each other. These problems have been solved, however, by Schwinberg. The *g* factor of the positron is expected to be exactly equal to that of the electron. This expectation will soon be given a stringent experimental test.

The techniques developed for the study of geonium can also be applied to the measurement of properties other than the *g* factor, and with particles other than the electron and the positron. For example, the compensated Penning trap could be operated as a high-resolution mass spectrometer, an instrument that determines the ratio of a particle's mass to its charge. By this means Van Dyck is now attempting an improved measurement of the ratio of the electron mass to the proton mass. Dehmelt has suggested that a single heavy ion confined in a miniature trap might serve as an optical frequency standard that would be free of certain defects common to present standards. Toward this end Dehmelt and W. Neuhauser, M. Hohenstatt and P. E. Toschek of the University of Heidelberg have isolated and even photographed a single barium ion in a trap similar to the Penning trap. The common goal of all these undertakings is to see the simplest elements of nature in their simplest setting, where there is the greatest hope of understanding them.

$$\nu_s = \frac{g\mu_B B}{h} \qquad \nu_c = \frac{2\mu_B B}{h} \qquad \nu_a = \nu_s - \nu_c = g\mu_B B - 2\mu_B B = (g-2)\mu_B B$$

$$\frac{\nu_a}{\nu_c} = \frac{\frac{(g-2)\mu_B B}{h}}{\frac{2\mu_B B}{h}} = \frac{(g-2)}{2}$$

$$\frac{(g-2)}{2} = 1.1596522 \times 10^{-3} \text{ [EIGHT SIGNIFICANT FIGURES]}$$

$$g = 2\left[\frac{(g-2)}{2}\right] + 2 = 2.0023193044 \text{ [11 SIGNIFICANT FIGURES]}$$

CALCULATION OF THE *g* FACTOR begins with the measured values of the cyclotron transition frequency (ν_c) and the anomaly frequency (ν_a), which is equal to the difference between the spin-flip frequency (ν_s) and ν_c. Both frequencies depend on the Bohr magneton (μ_B) and on the strength of the imposed magnetic field (*B*); Planck's constant (*h*) also enters the equation. In the ratio of ν_a to ν_c these quantities cancel exactly; what remains is the ratio $(g - 2)/2$. Multiplying by 2 and adding 2 gives *g* itself; moreover, if the ratio is measured to an accuracy of eight significant figures, the value of *g* can be determined to 11 significant figures.

The Antecedents of Civilization in the Indus Valley

One of the three earliest civilizations was that of the Indus. Excavations at Mehrgarh in Pakistan have uncovered farming settlements that flourished in the region 3,000 years earlier

by Jean-François Jarrige and Richard H. Meadow

The earliest civilizations of the Old World rose in river valleys: the Tigris-Euphrates of western Asia, the Nile of North Africa and the Indus of southern Asia. Of the three civilizations that of the Indus is the least known. This is the case even though two of its cities, Mohenjo-Daro in the south and Harappa in the north, were among the largest of the third millennium B.C., and its towns and villages extended from the Arabian Sea to the banks of the Amu Darya in northern Afghanistan. Indeed, until the 1970's just how the Indus civilization began was a puzzle.

Now six seasons of work in the Baluchistan region of central Pakistan have uncovered a series of agricultural settlements that first arose more than 3,000 years before Mohenjo-Daro and Harappa. The discovery is significant because until then it was believed there was no evidence in the region for a long period of settled agricultural habitation. The absence of such evidence even caused Sir Mortimer Wheeler, a leading student of the Indus civilization, to propose that the rise of the civilization resulted from the diffusion to a backward area of an "idea" that was "in the air" once the cities farther to the west in Asia began to flourish.

The excavations are being conducted at the site of Mehrgarh on the Bolan River by the French Archaeological Mission in Pakistan and the Pakistan Department of Archaeology. They now enable us to see that the social and economic patterns characteristic of the Indus civilization had roots deep in the early prehistory of the region. The site lies at the foot of the Bolan Pass, one of the two most famous routes between the Indus valley and the Iranian plateau. Here the Kachi plain, a large expanse of nearly flat alluvial outwash, slopes gently southeastward for more than 200 kilometers to the Indus River. Thus although the area is part of the Baluchistan administrative district, it lies within the Indus drainage system.

On first exploring the Mehrgarh area in 1973 we discovered a small mound that proved to contain the remains of settlements dating back to the third and fourth millenniums B.C. After active excavation began in December, 1974, it was discovered that the mound was only the most obvious site of a much larger cluster of sites that extended to the Bolan River, almost a kilometer to the north, and covered an area of more than 200 hectares (nearly 500 acres). The cluster did not represent the occupational debris of a single large settlement. Rather it was made up of many smaller settlements, each one established after the complete or partial abandonment of some predecessor. In the course of 3,000 or 4,000 years the remains of these successive settlements came to cover the entire area.

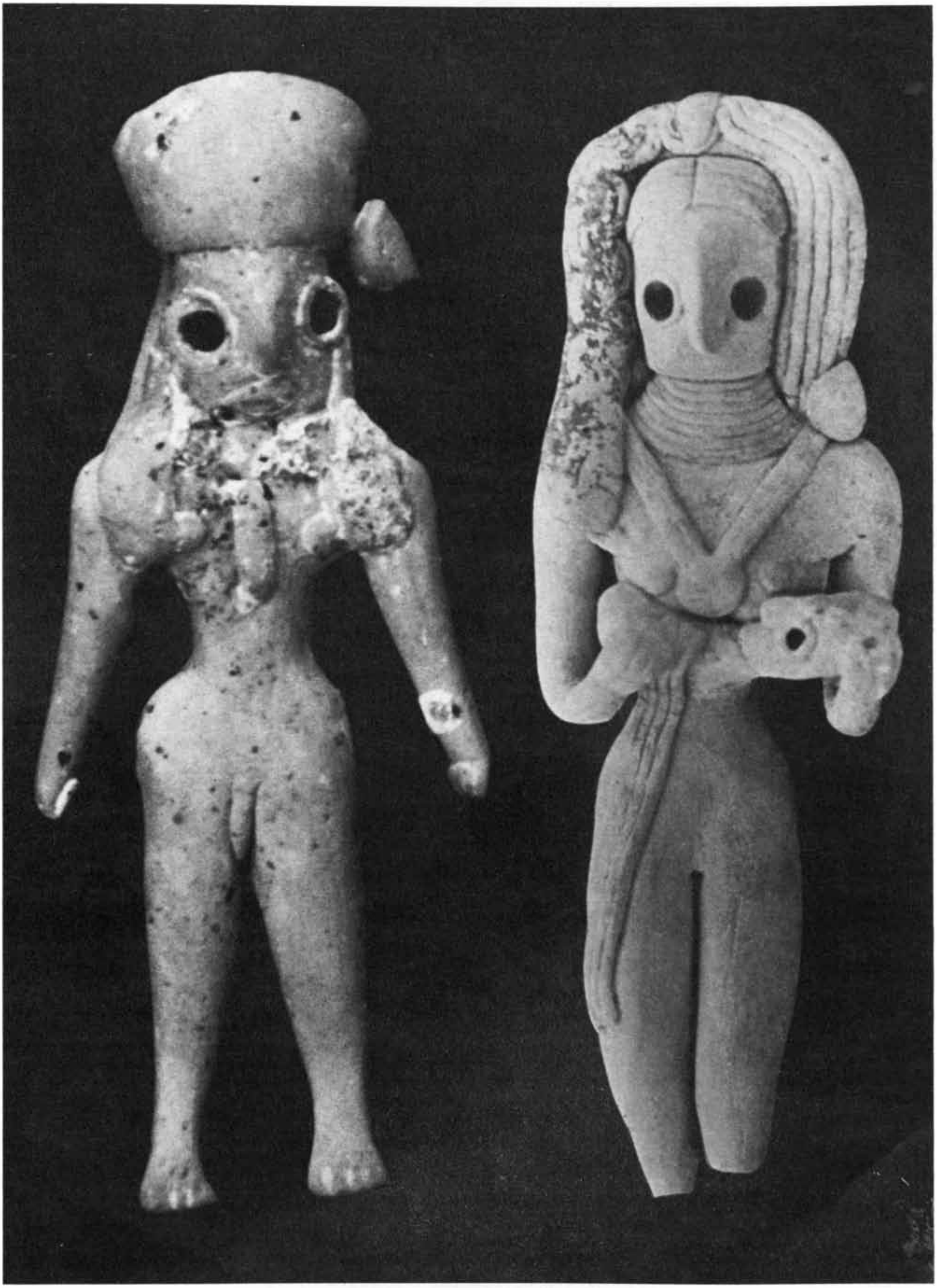
After a flood at the beginning of this century the Bolan River shifted its course to the west and began to flow in a new channel some kilometers away from the old one. In doing so it cut through what has proved to be the oldest part of the site. The clifflike exposure produced by the new channel revealed some 10 meters of superposed Neolithic structures that had been almost completely buried by alluvial deposits. Monique Lechevallier of the French National Center for Scientific Research (C.N.R.S.) has undertaken the excavation of this part of the site, an area we have labeled MR. 3. Four seasons of work have shown that the area was occupied by permanent farming settlements belonging to that early Neolithic period when pottery was still unknown. The most recent of a succession of mud-brick structures here has been shown by carbon-14 analysis to date back to the sixth millennium B.C.

More than 700 square meters of the upper Neolithic levels at MR. 3 have been uncovered, revealing the plan of the last farming village on the site. The settlement consisted of multiroom rectangular mud-brick units separated from one another by open spaces that held numerous human burials. Some of the structures were divided into small square compartments, apparently used for storage. Among the artifacts are grinding stones and small flint blades showing the sheen characteristic of flint used to cut grain. This indirect evidence suggestive of agriculture is backed more directly by impressions of various cereal grains in the mud debris.

From these impressions Lorenzo Costantini of the National Museum of Oriental Art in Rome, who is examining the plant remains from Mehrgarh, has been able to identify several different kinds of grain. They include two-row hulled barley (*Hordeum distichum*), six-row barley (*H. vulgare* and *H. vulgare* var. *nudum*), einkorn wheat (*Triticum monococcum*), emmer (*T. dicoccum*) and bread wheat (*T. durum* or *T. aestivum*). The identifications suggest that Baluchistan was a very early center of cereal cultivation.

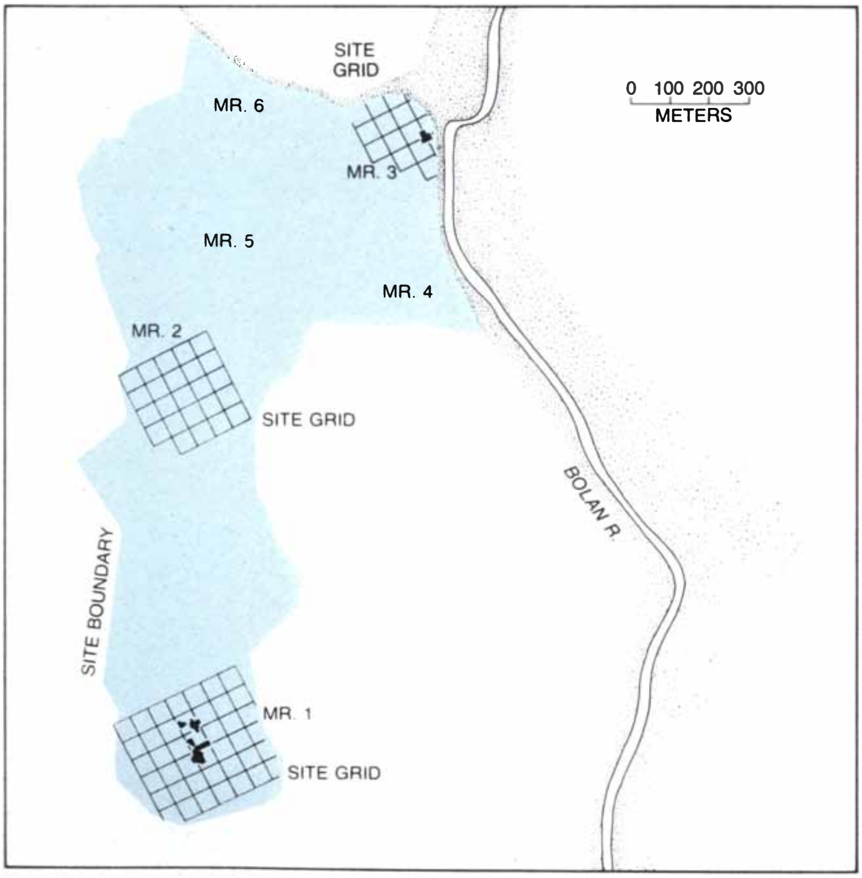
The suggestion has been greatly strengthened by the results of a deep sounding this year that has gone down to the sterile soil underlying the MR. 3 deposit. Some seven meters below the top of the pre-pottery Neolithic strata additional imprints of six-row barley, einkorn, emmer and bread wheat were found. We have not yet been able to get carbon-14 determinations of the age of these lower levels, but we can assume that the deposition of as much as 10 meters of debris on them was not quick. We have therefore tentatively placed the beginnings of the pre-pottery Neolithic settlement at some time before 6000 B.C. To the entire MR. 3 deposit we have given the chronological designation Mehrgarh Period I.

Costantini has also identified the remains of plants other than cereals in the Period I deposits. Charred seeds of the plumlike jujube fruit (*Zizyphus jujuba*) and the stones of dates (*Phoenix dactylifera*) have been uncovered, indicating that both trees were food resources in



TERRA-COTTA FIGURINES of a man and a woman uncovered at Mehrgarh are some 12 centimeters high. The man wears a turban. The woman's hair is elaborately dressed. Figurines came from levels dated to 2600 B.C. (Period VII), when male figures first appear.

SITE OF MEHRGARH is on the Bolan River, near the western margin of the Indus plain in the Baluchistan region of central Pakistan. This map shows the two major cities of the Indus civilization, Mohenjo-Daro and Harappa, and other archaeological sites the authors discuss.



TOTAL SITE AREA of more than 200 hectares (500 acres) is divided into six areas. The earliest area, MR. 3, has a 10-meter deposit consisting of the successive remains of mud-brick structures. The upper levels of the Period I villages excavated here are known from carbon-14 measurements to be 7,000 years old. The age of the lower Period I levels is not yet certain. The most recent remains, just south of MR. 1, are from a cemetery; they are about 4,000 years old.

Neolithic times. There are still large numbers of them in the Mehrgarh area today.

The animal remains are another important source of information about the development of agriculture at Mehrgarh. Within the top two meters of the Neolithic deposit there is a marked shift from faunal assemblages dominated by the bones of wild animals to assemblages characterized almost exclusively by the bones of domesticated animals. For example, in the earlier assemblage the remains of gazelles (*Gazella dorcas*), wild sheep (*Ovis orientalis*), wild goats (*Capra aegagrus*), swamp deer (*Cervus duvauceli*), large antelopes (*Boselaphus tragocamelus*) and wild cattle (*Bos*, perhaps the species *namadicus*) greatly outnumber the remains of possibly domesticated cattle (*Bos*, perhaps the species *indicus*) and goats (*Capra hircus*). By the end of Period I, although a few remains of gazelles, wild pigs (*Sus scrofa*) and onagers (*Equus hemionus*) are still present, almost all the other animal remains are those of domesticated cattle, goats and sheep (*Ovis aries*). Since there were wild cattle, wild goats and wild sheep in this part of Baluchistan in the sixth millennium B.C., it would have been possible for the Neolithic inhabitants of Mehrgarh to have domesticated all three of these animals. At least in the case of the sheep there is good evidence that the process of domestication did take place locally.

If the earliest of the faunal assemblages can be assigned an age of about 6000 B.C., the presence of some small and presumably domesticated cattle (*Bos indicus*) in these assemblages would indicate that cattle husbandry began at Mehrgarh as early as it did in western Asia. Furthermore, a number of bones of the water buffalo (*Bubalus bubalis*) have been found in the Neolithic assemblages. They provide the earliest evidence of this animal at a village site anywhere in Asia outside of eastern China. Hence in Period I at Mehrgarh one sees repeated the pattern known in western Asia: the hunters of a wide variety of wild animals are transformed into the herders of a selected few domesticated ones. At Mehrgarh, however, the pattern has a significant variation: the most important domesticated animals are not sheep or goats but cattle.

In the graves scattered throughout the settlement the farmers, herders and hunters of Period I left the bones of their own dead. In the earliest levels the bodies were buried in both the flexed position (with the knees drawn up to the chest) and the extended one and were covered with red ocher. The grave goods include bead necklaces, anklets and belts. The beads were made out of shell, bone, various local stones and imported turquoise. Sometimes a basket coated with bitumen was included; presumably

MUD-BRICK STRUCTURES in the upper levels of the MR. 3 area are rectangular in form and include several rooms. They were separated by open spaces that often held human burials. One grave can be seen just to the right of the checked meter rod close to the center.

PERIOD VII POTTERY was found in the MR. 1 area. This storeroom contained 200 intact vessels. The people of Mehrgarh began to mass-produce pottery in Period III, 5,700 years ago. By Period VII, 1,100 years later, Mehrgarh wares were exported to eastern Iran.

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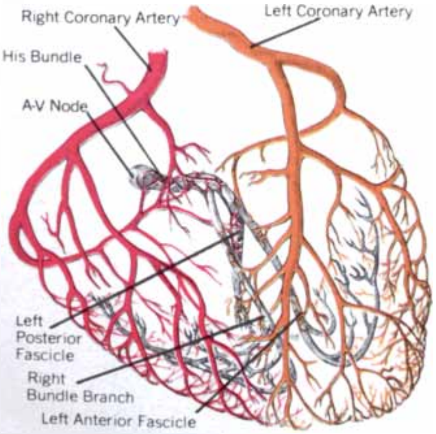

Branches of the right and left coronary arteries supply blood to the AV node and intraventricular conduction system.

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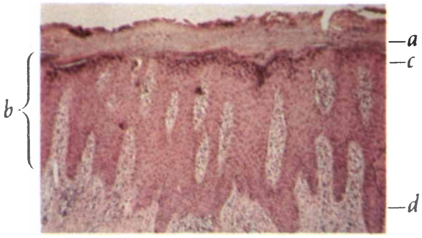
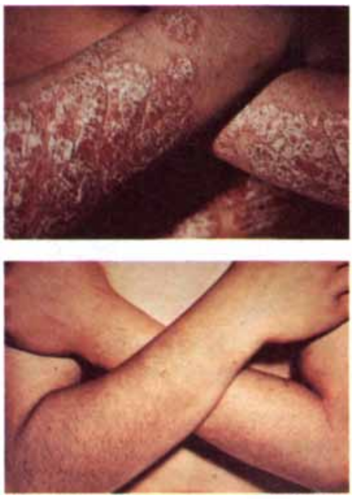


Histopathologic changes in psoriasis.



Extensive psoriasis (top) cleared completely (bottom) after four weeks of treatment with anthralin.

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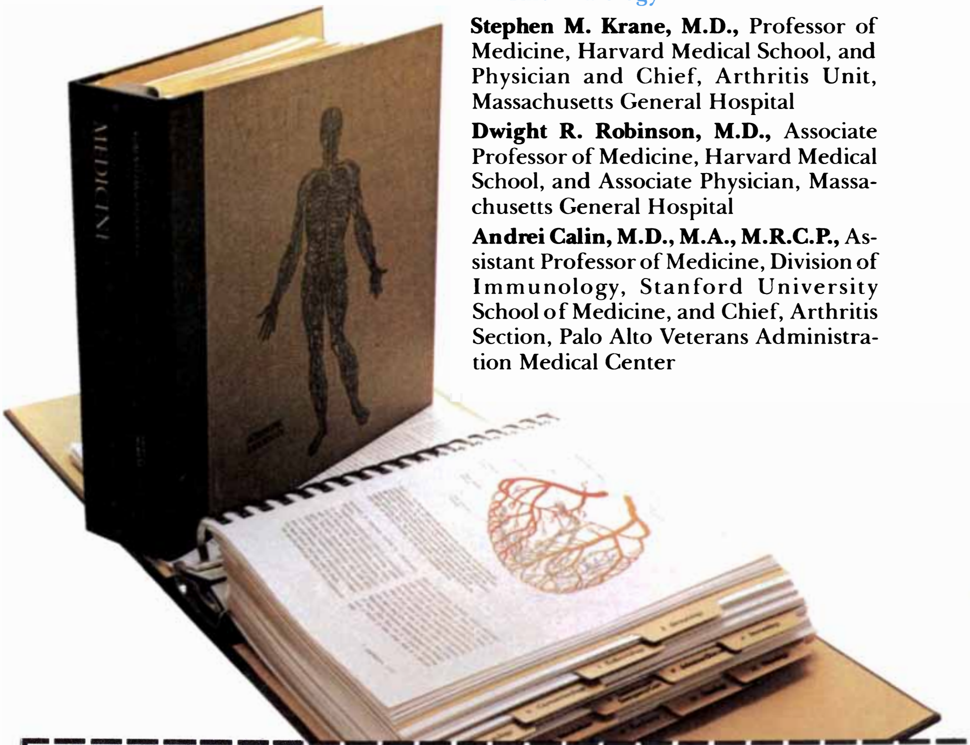

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Gonzague Quivron of the French Archaeological Mission has painstakingly uncovered more than 30 graves in the top level of MR. 3. Each grave was bordered on one side by a wall or platform of mud brick. Here the articles placed in the graves include axes of polished stone, blades and geometrically shaped bladelets of flint, stone vessels, cakes of red ocher and personal ornaments such as strings of beads. The beads from these graves include many made out of imported turquoise and a few made out of imported lapis lazuli. Metal is also present; near a lower leg bone of a child Quivron unearthed a single cylindrical copper bead.

Of the artifacts of Period I the most abundant are pieces of flint; more than 20,000 have been found so far. The tools are representative of a flint industry that emphasized blades. Most of the blades have small chips detached from either one edge or both edges. Geometrically shaped flint bladelets represent a little less than 4 percent of the total. Among them, however, are a number of "trapezes": triangles without an apex. They have been retouched so that the finished bladelets have a concave back; they are directly comparable to concave-backed trapezes found in western central Asia. A fair number of bone tools have also been recovered; most of them are awls.

Exceptional finds of Period I are five figurines made out of unfired clay. Three represent humans and two represent animals. One of the human figurines is conical in shape and has a necklace of appliqué clay lozenges. A second is in a seated position and has two holes representing eyes. Only the lower part of the third human figurine survives; it too is in a seated position with legs and feet joined. Stylistically all three are reminiscent of the early human figurines of western Iran. The two animal figurines are only of a very generalized form. Together with the human representations, however, they are the earliest figurines yet discovered in southern Asia.

GEOMETRIC DECORATION of a polychrome vase is typical of the pottery of Period IV (5,500 years ago) at Mehrgarh. By that time animal motifs of Period III were no longer used.

Immediately to the south of MR. 3 we uncovered evidence of a Chalcolithic occupation dating back to the fifth millennium B.C. (The Chalcolithic is an Old World stage of development intermediate between the Neolithic and the Bronze Age.) We have designated the area MR. 4 and this phase of the occupation of the site Period II. Here the remains, which lie just below the surface, include pottery. Excavation has revealed several rectangular structures that are subdivided into narrow, doorless compartments. In the fill of the compartments of one of the structures were found the imprints of wheat and barley grains. Also uncovered were the remains of two sickles. Both had been made of three flint bladelets set at an angle in bitumen. The bitumen in turn had been laid in a groove cut into a wood handle. The handles decayed long ago; only the impression of the groove is preserved in the bitumen. The sickle blades and the grain impressions suggest that at least some of the compartments served for the storage of food.

Outside the walls of one of the structures several hundred charred seeds were found in a large burned area. They included different varieties of wheat and barley and some seeds of cotton (*Gossypium*). The cotton seeds were so poorly preserved that Costantini has not yet been able to determine whether they came from a cultivated form of the plant. Their presence in association with the seeds of other cultivated plants near a structure apparently used for storage, however, suggests that cotton was indeed cultivated by the farmers of Period II at Mehrgarh because they prized either its fiber or its oil-rich seeds. The earliest previous evidence for the cultivation of cotton in the region has been found at sites of the Indus civilization later than 2400 B.C.

Many thousands of animal-bone fragments have been found in the rubble of MR. 4. Almost all of them come from domesticated cattle, sheep and goats, with those of cattle predominating. It is clear that cattle became at a very early date the dominant animals they were to remain in the prehistory of southern Asia. They almost certainly provided most of the meat in the diet of the inhabitants of Mehrgarh in Period II. They may also have been used for plowing, for threshing, as pack animals and as a source of milk, but evidence for these additional roles is only indirect.

Against the south wall of one of the subdivided structures excavation uncovered a workshop where beads were manufactured out of soapstone. The flint drills and flakes used to work this soft material were found, together with beads in various stages of completion, waste flakes and unworked soapstone. Beads made out of shell were also produced here.

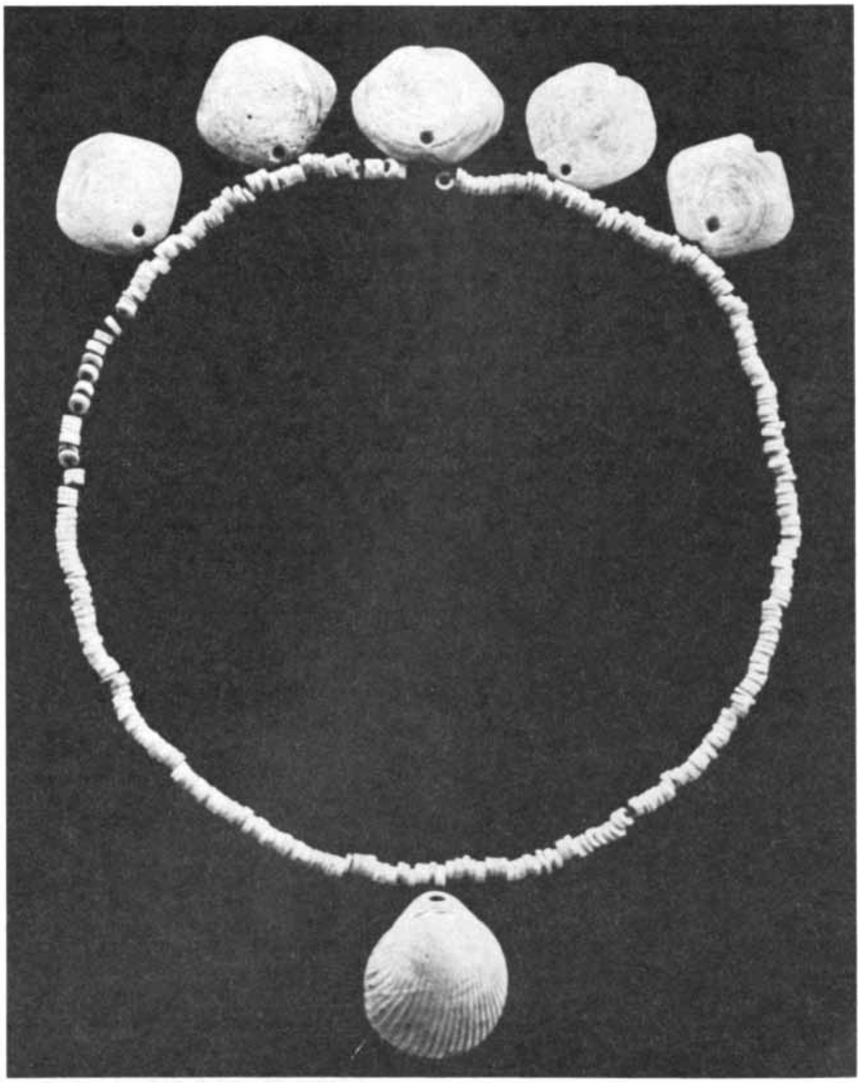
An open space east of the same structure was covered with layers of animal bone mixed with ashes. The space yielded more than 100 bone awls and several of the grooved stones used in shaping their points. Red ocher was prized in Period II as it had been in Period I; grinding stones colored by the substance were found in conjunction with several cakes of it. Flint tools also continued to be abundant in Period II, but metal remained scarce. Only one copper ring and one copper bead have been uncovered.

The pottery of Period II is a fine ware that is found in limited quantities only. The commonest forms are pear-shaped red jars with outward-curving rims. The clay of many of the jars is burnished, and surface markings show that the jars were turned in the course of their manufacture. Other work in clay includes two human figurines in the same highly stylized tradition as that of their Neolithic forerunners. One of them is modeled in a seated position with legs joined together. The other, shaped like a truncated cone, has its base decorated with appliqué clay disks, which are possibly meant to suggest some kind of cloth.

A loose surface fill covers the Period II deposit at MR. 4. It contains fragments of painted pottery and of coarse hand-formed wares that by comparison with similar pottery from other sites in Baluchistan and Afghanistan can be dated back to the end of the fifth millennium B.C. and the beginning of the fourth. Specifically the pottery is assigned to a period called Kili Ghul Mohammad II, from the name of a site dating back to about 4000 B.C. that Walter A. Fairservis, Jr., of the American Museum of Natural History excavated near the town of Quetta in the highlands of Baluchistan in 1951.

To summarize the significance of the sixth- and fifth-millennium findings at Mehrgarh, they give prehistorians the first substantial body of information about a period that was previously almost unknown in the archaeological record of southern Asia. The settlements of Period I and Period II were sizable and permanent; their architectural repertory included symmetrical multiroom structures and what were evidently granaries. The cultivation of cereal crops and the husbandry of animals were practiced in addition to hunting and gathering in Period I and to their

FLINT BLADELETS were set at an angle in bitumen to serve as a sickle. The bitumen was laid in a groove in a wood handle that decayed during more than 6,000 years of burial. Two of these sickles were found in a grain-storage compartment in the MR. 4 area (Period II).



SEASHELL BELT, 72 centimeters in circumference, was found in one of the graves of Period I. Nearest source of shells is the coast of the Arabian Sea, 500 kilometers south of Mehrgarh.

exclusion in Period II. Specialized crafts existed, and a network of long-distance contacts brought to Mehrgarh turquoise from Iran or central Asia, lapis lazuli from northern Afghanistan and shells from the coast of the Arabian Sea.

Both the variety of funerary offerings and the inequality of their distribution suggest that here one is dealing with a population that had some degree of social differentiation. Further excavation of the deeper strata of Period I should broaden our understanding of the part played by the Neolithic peoples of this area in the beginnings of a food-producing way of life in southern Asia. Already Mehrgarh offers proof of the existence of an early agricultural center close to the Indus valley and strongly supports the hypothesis that the Neolithic revolution was a complex event involving more than simply a single nuclear center in western Asia.

In about 4000 B.C. the settlement at Mehrgarh shifted south to the area labeled MR. 2. The occupational debris there, almost three meters deep, contains the record of the third period in the archaeological sequence at the site. Continuity is demonstrated by the presence at MR. 2 of pottery similar to that found at the surface of MR. 4 and of a number of compartmented structures. These are somewhat larger and more elaborate than those of Period II.

The initial phase of Period III is marked by important developments in the crafts. Where the fine ware of Period II shows signs of having been turned by some means during manufacture, the pottery of Period III is definitely wheel-thrown and mass-produced. It is a fine ware, decorated with geometric motifs and seminaturalistic ones such as rows of birds or goats.

Lapis lazuli, turquoise and carnelian were worked into beads with cylindrical drill bits made of green jasper. Wear marks on the jasper bits indicate they were rotated by means of bow drills. The jasper bits of Period III are the earliest specimens known of a type that was used during the third millennium B.C. at Shahr-i-Sokhta and Shahdad in eastern Iran and in the Indus valley, where (most notably at Chanhu-Daro) they were associated with the carnelian workshops of the Indus civilization.

This evidence for the early use of the potter's wheel and the bow drill marks Mehrgarh as a center of technical innovation more than 1,000 years before the beginning of more elaborate craft practices to both the east and the west. We also uncovered the fragments of several crucibles that had been used to melt copper. Traces of the metal still adhered to them.

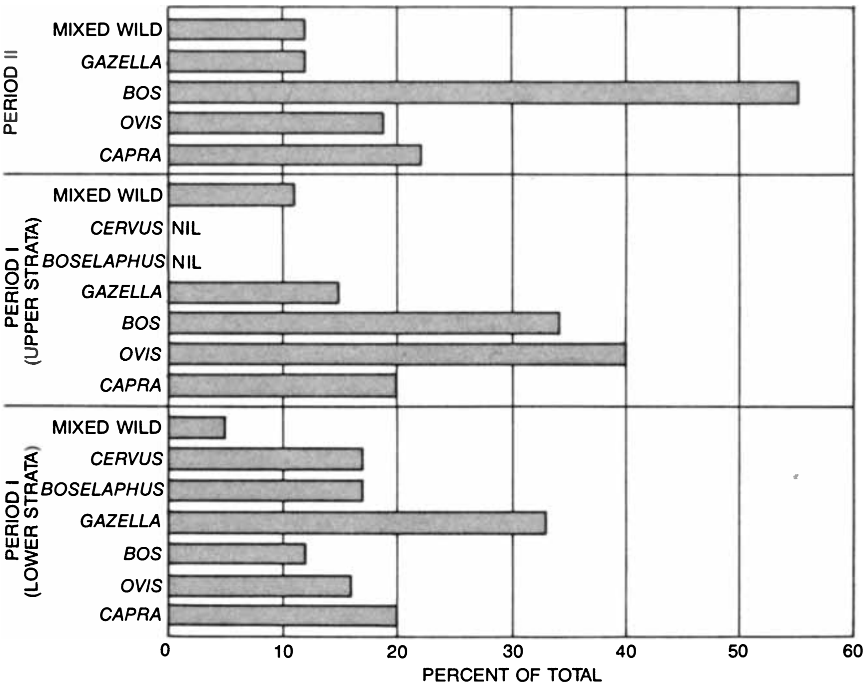
Another important development in Period III was agricultural diversification. In addition to the cereals of the earlier periods two new bread wheats, *Triticum aestivum compactum* and *T. aestivum sphaerococcum,* and a new barley, *Hordeum hexasticum,* were cultivated. An entirely new cereal genus, oats (*Avena*), has also been identified by Costantini. Evidence that the practice of mixed cereal farming and the continued herding of cattle, sheep and goats supplied the population of Period III with abundant food is provided by an increase in the size of the settlement. Before the end of the period the MR. 2 area had grown until it covered almost 50 hectares (125 acres).

In about 3500 B.C. the settlement at Mehrgarh again shifted to the south. The new area is designated MR. 1. Here excavation has exposed buildings that contain large storage jars. The potters of Period IV also mass-produced plain wares in a variety of shapes and thicknesses, including eggshell-thin goblets. They did not abandon the manufacture of decorated wares, but the goat and bird motifs of Period III disappear, to be replaced by geometric decorations, including intricate polychrome patterns. The increasing variety of pottery shapes and sizes suggests that the potters were responding to a much more diversified demand.

The production of female figurines also continued, and as before the figures are in a seated position. Their appearance is more naturalistic, however, and they are made out of terra-cotta. The same material was used to make stamp seals; these, and other seals made of bone, are the first stamp seals to appear at Mehrgarh.

In about 3200 B.C. we reach a period in the occupation of Mehrgarh (Period V) that is reasonably familiar from excavations in eastern Iran and western Pakistan. It was once thought to represent the start of regional growth and prosperity; a number of sites in Baluchistan and the Indus valley seem to have been founded at this time. Indeed, before the even earlier cultural phases at Mehrgarh were known the end of the fourth millennium B.C. was considered to mark the real beginning of developed farming economies in southern Asia.

The impetus for change in Baluchistan was then thought of as coming from sites in central Asia belonging to the Namazga III phase of cultural development, an impetus that had been mediated by such sites as Shahr-i-Sokhta in Iran and Mundigak in Afghanistan. It is now clear, however, that indigenous peoples, among them the residents of



TRANSITION FROM HUNTING TO HERDING by the Neolithic villagers of Mehrgarh during Period I is evident from an analysis of the animal bones found in the MR. 3 and MR. 4 areas. In the lower Period I deposits, represented at the bottom of this bar chart, the remains of gazelles (*Gazella dorcas*), wild goats (*Capra aegagrus*), wild sheep (*Ovis orientalis*) and wild cattle (probably *Bos namadicus*) are the most abundant. The category "Mixed wild" includes relatively rare food animals, such as wild pigs, onagers, Indian spotted deer, blackbucks and water buffaloes. Two other wild species, the large antelope called the nilgai (*Boselaphus tragocamelus*) and the swamp deer, or barasingh (*Cervus duranceli*), together account for 14 percent of the animal remains in the lower deposits. Neither species is represented in the upper deposits of Period I (*middle*), and the reduced size of the cattle, sheep and goat bones indicates that by then all three of those animals were domesticated. By Period II, after the Neolithic at Mehrgarh, game does not contribute significantly to the remains; domesticated cattle are dominant.

SCIENCE/SCOPE

Ultra high-speed satellite communications are closer to reality with the development of unique pseudo-random code generators. The hybrid circuits, which operate at more than 1 billion bits per second, were built with gallium-arsenide field-effect logic. They demonstrate that the problems of making such chips -- problems including layout, construction, die and wirebonding, and chip handling -- can be solved. Researchers at Hughes will use the chips as signal sources for gigabit logic experiments.

The process that enables tree branches to obtain water may eventually be used for cooling avionics or other systems where fluid pumping against high-pressure heads or high g forces is required. Under U.S. Air Force sponsorship, Hughes engineers are developing a closed metal tube which moves heat from one place to another using direct osmosis, the passing of a fluid through a semipermeable membrane into a solution where its concentration is higher. Unlike conventional devices using capillary wicks to pump liquid, the osmotic heat pipe would operate regardless of gravitational or centrifugal forces.

Three U.S. weapons are closer to sharing common guidance systems now that Hughes has delivered advanced development models of an imaging infrared seeker. The units, developed under an Air Force contract in parallel with a seeker for the Maverick air-to-ground missile, fit the Air Force GBU-15 and Navy attack weapons. They detect heat and track the target by sensing small temperature differences, providing precision guidance capability both night and day and in low visibility conditions. All three seekers are virtually identical, and use of the common unit will considerably reduce the military's costs for development, production, training, and maintenance.

Hughes is seeking engineers to develop advanced systems and components for such weather and communications satellites as GOES D, E, and F, Anik C, GMS II, Leasat, SBS, Westar IV, and Palapa B. Immediate openings exist in advanced communications, scientific and engineering programming, systems test and evaluation, microwave and RF design, power system design, spacecraft alignment, thermal and vibration test, and reliability and quality assurance. Please send your resume to Tom W. Royston, Dept. SE, Hughes Space & Communications Group, P.O. Box 92919, Los Angeles, CA 90009. Equal opportunity M/F/HC.

A spacecraft designed for a variety of missions will carry the most versatile propulsion module ever developed. The new Hughes module will be installed on NASA's Multimission Modular Spacecraft (MMS), which starting in the mid-1980s is to be used for a wide range of communications and scientific missions. In addition to new electronic controls and support structures, this compact module contains a unique monopropellant hydrazine thruster that requires no heater. Conventional thrusters, if used on certain proposed MMS missions, would need extra equipment to heat their catalyst beds to avoid reductions in performance or a complete loss of power.

Creating a new world with electronics

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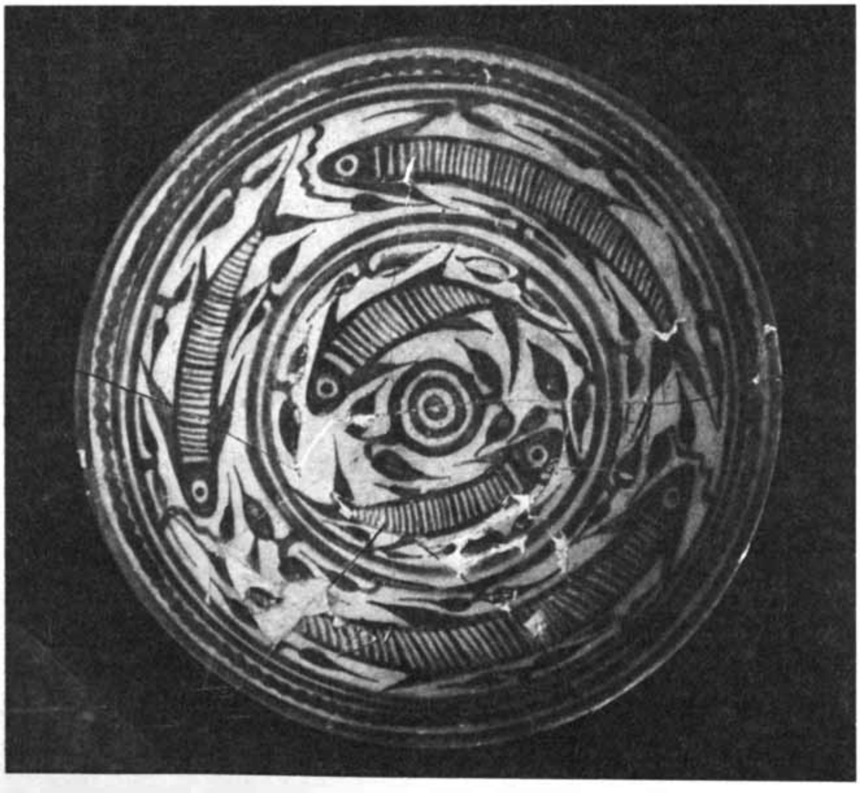
TWO STAMP SEALS bear a symmetrical design and a stylized animal figure. Made of terracotta, the seals were fashioned in negative relief; a drawing to the right of each shows the imprint that would be left in clay. The design is from Period VI. The zebu bull is from Period VII.



SHALLOW BOWL decorated with black-painted fishes and aquatic plants is representative of the fine gray wares the Mehrgarh potters mass-produced in the last phases of Period VII.

Mehrgarh, played an active role rather than a passive one in the transformation of this part of Asia in the first half of the fourth millennium.

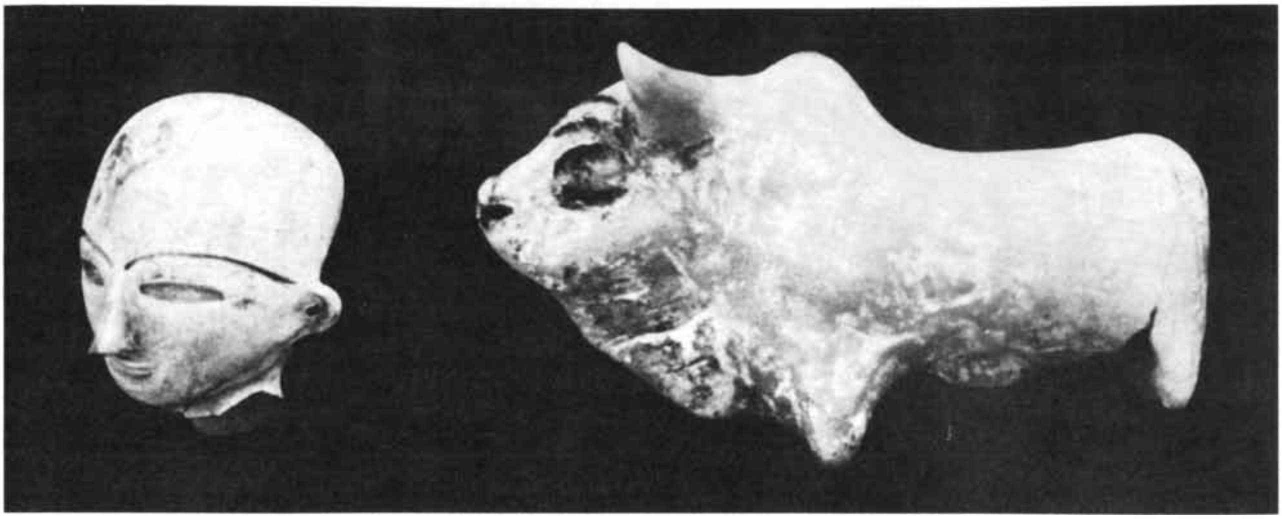
It is also now evident that even before 3200 B.C. extensive trade networks linked Baluchistan with eastern Iran and southern Turkmenistan. These lines of communication facilitated the exchange not only of goods but also of ideas. The exchanges are reflected in the similar styles of artifacts that came to characterize this larger region. For example, compartmented stamp seals and a number of complex motifs for the decoration of pottery are the same or similar from one end of the region to the other.

After the end of Period V the MR. 1 area remained a prosperous agricultural center. The end of the fourth millennium B.C. and the beginning of the third millennium comprise Periods VI and VII at Mehrgarh. Excavation in the area has uncovered rooms containing large storage jars. At fireplaces the charred remains of wheat, barley and oats have been found along with milling stones. Sickles are unchanged from those of Period II: flint bladelets set in bitumen. A new addition to the agricultural inventory is the wine grape (*Vitis*), which appears in about 3000 B.C.

The most impressive feature of periods VI and VII is the production of pottery and figurines on a massive scale. To the north of MR. 1, Françoise Audouze and Catherine Jarrige of the C.N.R.S. have located an area where pots were fired in about 2900 B.C. More than 200 jars of various sizes had been piled up there, stacked in alternating rows or placed one inside the other. A sudden flare-up during the firing made the process go wrong, and the potters simply abandoned the spoiled jars where they stood.

The same firing technique is used in the area today. The potters first spread a layer of straw on the ground and put on it as many as 500 to 1,000 unfired pots. These are covered with more straw, a layer of broken pottery and finally a roof of clay. The straw is ignited, the fire burns for about 24 hours and then the pile is allowed to cool for a week. In analyzing the spoiled wares Audouze and Catherine Jarrige found that the identical procedure had been followed some five millenniums earlier. This is significant evidence for the semi-industrial manufacture of standardized vessels by that time. The pots were probably intended for regional distribution, just as the pots made in the area today are.

The production of female figurines also increased. In Period VI they were still being modeled in a seated position, but the legs are now encircled by a coil of clay, the face bears goggled appliqué eyes and large coils of clay on each side of the face give the impression of fantastic hairdressing. The torso is ren-



POTTERS' REPERTORY in Period VII included finely modeled human likenesses such as the head at left and more stylized animal figures such as the zebu at right. The head, for which the body was not found, is 4.5 centimeters high; the zebu is 9.5 centimeters long.

dered more realistic by being molded with pendulous breasts that are partially concealed by multistrand necklaces.

Period VI extended from about 3000 B.C. until about 2700, when Period VII began. In the last phase of Period VII, which ended a century later, an intricate series of rooms occupied the MR. 1 area. Several of the rooms were two stories high, the downstairs being a low room, used for storage, with a ceiling only a meter above ground level. Wood ceiling beams and parallel rows of joists supported the floor of the upper room, where storage jars often stood. In one of the low downstairs rooms some 200 pots had been stored; the vessels are remarkable for their variety of shapes and decorations.

North of this combined residential and storage area were open spaces where pottery was fired in kilns. As many as three layers of kilns have been uncovered, one above the other. The kiln bases are oval or circular and the kilns themselves, as excavated, have only one level. It seems likely that they were not actually so simple but that a second level, perhaps made of flimsy materials, was torn down after each firing. In any event, the kilns were efficient enough to attain temperatures capable of vitrifying the material being fired. In the ash heaps associated with them the charred remains of seeds and animal feces indicate that straw and dung were used as fuel, as is the practice today.

To judge from the enormous heaps of broken pots and figurines the potters of the last phase of Period VII were engaged in large-scale production. Some of the vessels are such elegant examples of fine craftsmanship that they rank as works of art. Among them are goblets and bowls of a fine gray ware decorated with black-painted geometric, plant and animal designs. Some examples of this gray ware have been found as far away from Mehrgarh as eastern Iran.

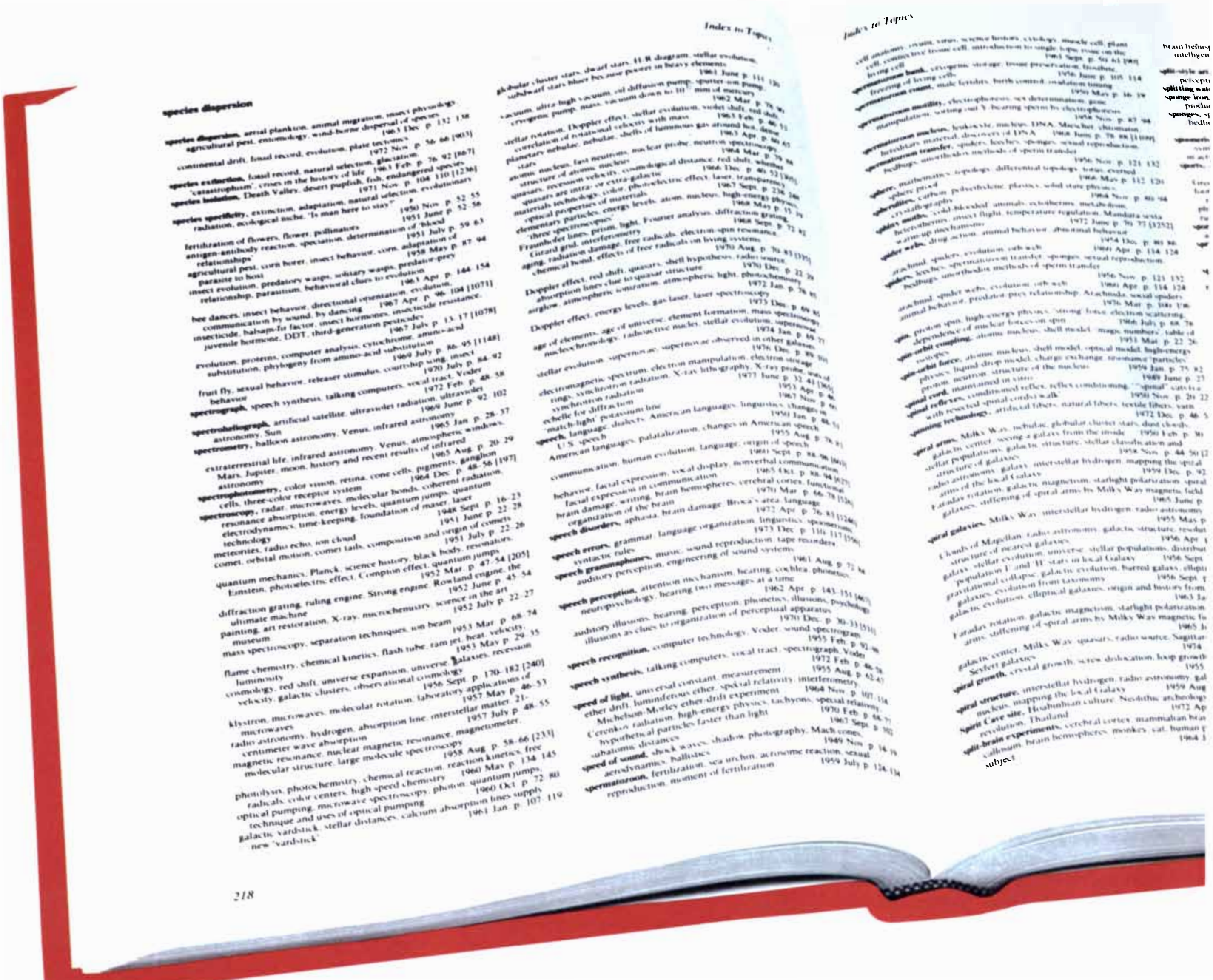
The Period VII figurines are represented by thousands of fragments, mostly arms and legs, and by some specimens that are intact, or nearly so. No other site in Baluchistan holds such a large concentration of these objects. The figures are no longer seated but stand upright. The heads remain stylized, with goggled eyes and beaked noses, but for the rest the modeling is more naturalistic than before. For example, a slight arching of the hips to the side gives the female figures a charm that seems to foretell later Indian representations of females. Male figures now appear at Mehrgarh in significant numbers for the first time; they account for about 30 percent of the figures identifiable by sex. The female figurines exhibit a wide range of hairstyles painted in black and ornaments painted in yellow. The male figures have a large turban and a necktie-shaped pendant. By the end of Period VII the poses have become stiffer and the figurines are modeled in the rather stereotyped manner characteristic of those found at many other sites in Baluchistan and neighboring areas.

Animal figures made of terra-cotta include representations of a humped bovine, the zebu (*Bos indicus*), of wild pigs and of various birds. All are of good workmanship and resemble the animal representations of the Indus civilization. A unique find is the figure of a ram carved from alabaster. Many stamp seals have also been uncovered. Most of them are made out of terra-cotta; one bears the figure of a running zebu bull. The majority of the stamp seals are circular in outline.

Some of the kinds of pottery and other objects from the later levels of Period VII also resemble artifacts characteristic of the Indus civilization. Among them are triangular "cakes" made out of terra-cotta and parallel-sided flint blades, some of them 18 centimeters long. Indeed, the surface remains at a small mound some eight kilometers south of Mehrgarh are evidently the products of a mature phase of the Indus civilization. There is no evidence, however, of an Indus-civilization occupation at Mehrgarh itself, although a cemetery later than Period VII may have been contemporaneous with that period.

South of MR. 1, Marielle Santoni of the C.N.R.S. has excavated a large number of graves and cenotaphs (funerary monuments). The pottery, bronze vessels and other artifacts she has found are identical in all respects with the grave goods found in cemeteries at various sites in southern Turkmenistan. Similar cemeteries have also been reported in Afghanistan at sites belonging to the Dashli cultural complex. The presence of such material at Mehrgarh, dating back to 2000 B.C. or even earlier, on the margins of the homeland of the Indus civilization, is paralleled inversely in northern Afghanistan, where an Indus settlement has been uncovered at Shortugai on the bank of the Amu Darya.

Much work remains to be done at Mehrgarh. The preliminary results of our first six campaigns nonetheless demonstrate that the theoretical models used to interpret the prehistory of southern Asia must be completely reappraised. This rich site provides an archaeological record with a long sequence of occupations. The sequence reveals a process of continuing elaboration that affected cereal cultivation, animal husbandry, crafts, architecture and even ideology. Step by step one can see the stage being set for the development of the complex cultural patterns that became manifest in the great cities of the Indus civilization in the middle of the third millennium B.C.



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00044

Disk-Storage Technology

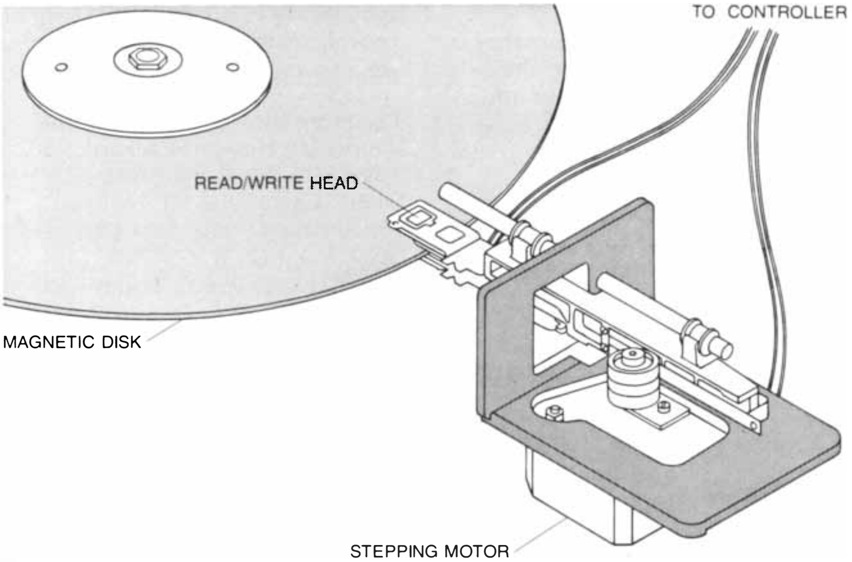
On the surface of a spinning disk the data for a computer are stored as minute magnetic regions. In devices being developed the data will be "written" and "read" by a laser

by Robert M. White

The speed with which computers process data has increased a hundredfold in recent years. Such progress has been supported by progress in other technologies. In particular the technology of data storage has also advanced dramatically. The information in a book the size of a large unabridged dictionary can now be stored in the form of minute magnetic patterns on a rapidly rotating disk. Even that capacity will be surpassed. In the near future an optical system in which information is stored and retrieved by laser will make possible the storage on a disk of the contents of a library of several thousand books.

In many ways the magnetic and optical systems are alike. Both require disks. Both require a head to "write" and "read" the data onto and off of the surface of the disk. In the one case the head is an electromagnetic device that resembles in principle the head of a conventional tape recorder. In the other case the head is a laser and its associated optics. Furthermore, both magnetic and optical systems require mechanisms that properly position the head in relation to specific tracks of data at particular radii on the disk, and both require an electronic system that mediates between the disk memory and a computer. The electronic system encodes the data in a way that makes them appropriate for storage and decodes them for their return to the computer. In many designs it adds signals to the data entering the memory that can be used later to locate any errors made in storage.

It is likely in addition that magnetic and optical disk memories will be part of the same information system. Perhaps, for example, a large optical disk memory will serve as an archive. It could store a year's accumulation of documents and replace filing cabinets throughout a large organization. Meanwhile smaller magnetic disk memories distributed throughout the organization would serve individual users. The disks in these smaller systems could have the advantage of being removable. The disadvantage would be a greater aptness to "crash," or lose data, because access to the disks makes them vulnerable to dirt. Even a dust particle the size of a bacterium can disrupt the writing or reading of the data. Nonremovable disks could offer better performance (and lower cost), but a power failure would make their data unavailable.



MAGNETIC-DISK DRIVE is the secondary memory in a modern computer system. In the system's primary memory (part of the central computer itself) the retrieval of data is faster. On the other hand, the secondary memory costs less for its storage capacity. The configuration here is typical. A motor positions a read/write head over tracks of data on a spinning disk.

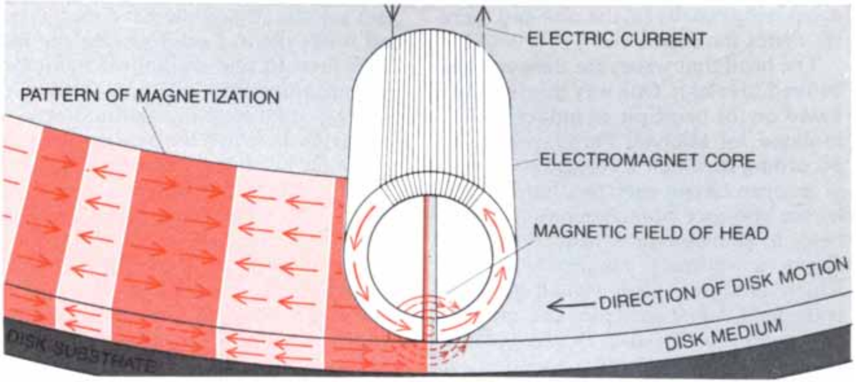
The storage of documents is not the only use for the disk technology. An audio signal such as the electric current generated by a microphone can be sampled many thousands of times per second and the intensity of each sample can be represented as a number. In this way a signal that is continuous in time, an analogue signal, is converted into a discontinuous, or digital, signal. A picture can likewise be converted into a map of digital data by sampling the picture in two spatial dimensions. One application already being examined is the storage on disks and in digital form of the thousands of X-ray images that accumulate in a hospital.

The fundamental advantage of the conversion of signals from analogue into digital is that data in digital form can be processed, transmitted and stored almost without error, even if there is no recourse to error-locating signals. The reason is as follows. Digital information is customarily represented by a sequence of digits in which each digit is a bit: either a 0 or a 1. Small areas of the medium in which such binary information is stored (for example the iron oxide coating of a magnetic disk) must be put in one state or another to represent the data. For magnetic storage the two states are the extremes at which the dipole magnetic field in the medium is saturated, or at a maximum, in one orientation or in the opposite orientation. The two states can be distinct to such an extent that the stored information is virtually never corrupted by vagaries such as a stray electromagnetic field from the writing and reading head or from the neighboring stored information. In a high-performance magnetic-disk memory the errors caused by dirt and other mechanical problems corrupt approximately one bit in 10 billion bits. Coding for the detection of errors reduces the error rate to one bit in 10 trillion bits.

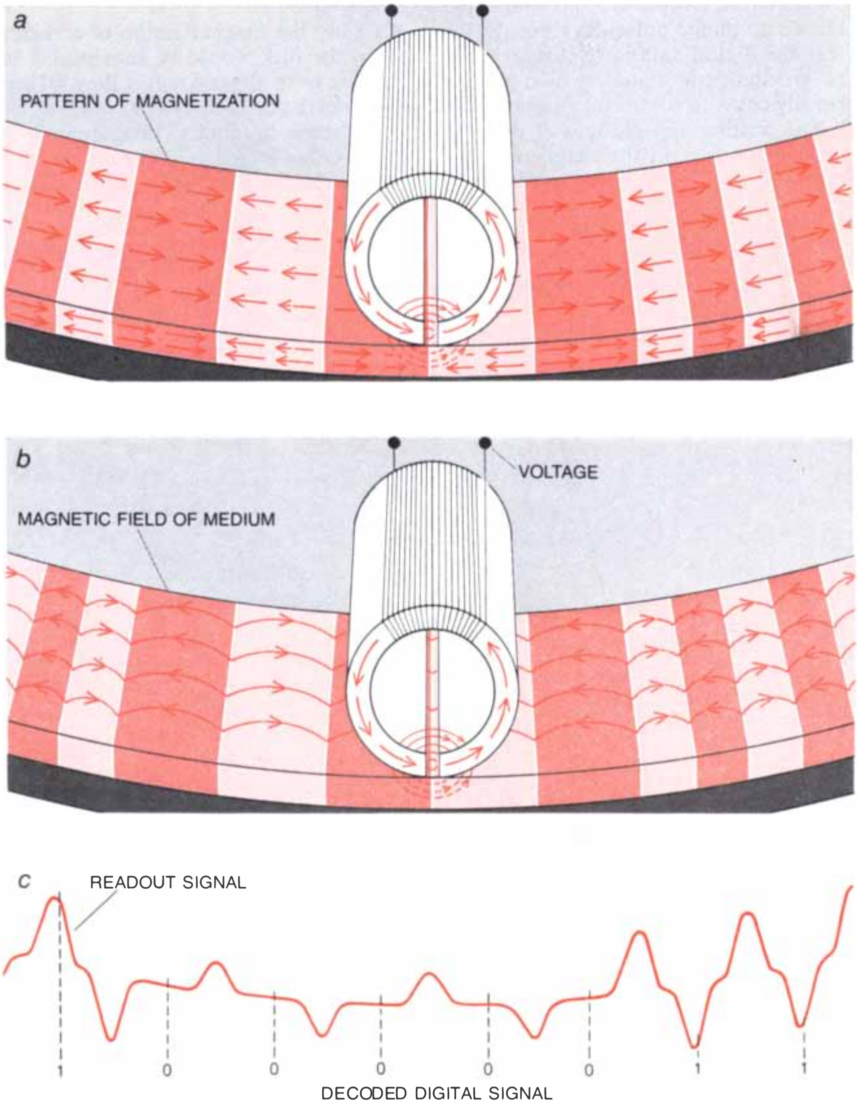
The Danish engineer Valdemar Poulsen exhibited the first magnetic recorder at the Paris Exposition of 1900. It came 23 years after Thomas Edison had built the phonograph. In Poulsen's device a steel piano wire followed a spiral groove around the surface of a drum. An electromagnet made contact with the wire and was free to slide along a rod positioned parallel to the axis of the drum. The drum's rotation pulled the electromagnet down the rod. When current from a microphone passed through the electromagnet, a segment of the wire was magnetized in proportion to the current. Although Poulsen's invention created a sensation, the recorded signal was weak. It was not until the invention of the vacuum-tube amplifier in the 1920's that magnetic recording began its steady evolution. The piano wire evolved into plastic tape with a coating of magnetic material. In another configuration a rotating drum was coated with a magnetic medium on which signals could be recorded on numerous circular tracks. Each track had its own electromagnet. Such devices became memories for the first modern computers. Indeed, they were primary memories: devices for the fastest storage and retrieval of data.

Today technologies based on semiconductor elements provide the primary memory of a computer. The secondary memory is larger and slower but stores information at a lower cost per bit. The devices serving this function are now based on magnetic disks. The tertiary memory, which is still larger, slower and cheaper, is based on magnetic tape at present. This hierarchy of memories enables the users of computers to optimize performance and cost. In fact, the flow of information can be managed by certain computer systems so that data anywhere in the hierarchy is in the primary level of storage when it is needed. It is as if all the data were on that level. The principle is known as virtual memory.

Magnetic writing—the recording of data in a magnetic medium—is based on the same principle today that applied in Poulsen's device. If a current flows in a coil of wire, it produces a magnetic field. The field is largely confined in a ring-shaped core of magnetic material around which the wire is wound. A narrow slot is cut in the magnetic material. It is the field in the vicinity of the slot that magnetizes the magnetic me-



WRITING OF DATA into storage in the magnetic medium on a disk requires a head that resembles in principle the head of a tape recorder. Electric current supplied to the head flows through a coil around a core of magnetic material. The core throws a magnetic field into the disk, thereby magnetizing the medium. When current is reversed, the magnetization reverses.



READING OF THE DATA employs the head that wrote them. The data in storage (*a*) are digital; each datum, or bit, is a 0 or a 1. Here a 1 is stored as a place on the disk where the magnetization reverses and a 0 as the absence of a reversal. A reversal also lies between each stored bit. As the disk spins, the magnetic fields of the stored data (*b*) pass successively under the head. The changing fields induce in the head a voltage signal (*c*), which is converted back into a digital form. The first seven bits of the decoded signal are 1000001, which represent the letter *A*. An eighth, or check, bit is 1 because the preceding seven bits add up to an even number.

dium lying nearby on the disk and thereby writes the data.

The head that writes the data can also be used to read it. One way this is done is based on the principle of induction, formulated by Michael Faraday in 1831, according to which a voltage is induced in an open circuit such as a loop of wire by the presence of a changing magnetic field. In the case of a head positioned above a spinning magnetic disk on which data have been written the magnetic fields emanate from the magnetized regions on the disk. During the time the head is over a single magnetized region the field is more or less uniform. Hence no voltage develops across the coil that is part of the head. When a region passes under the head in which the magnetization of the medium reverses from one state to the other, however, there is a rapid change in the field. Hence a voltage pulse develops. In this way the digital data in storage are read as an analogue signal, which can be readily converted back into digital form.

The writing and reading of data depend of course on the magnetic properties of both the medium in which the data are stored and the head that writes and reads them. I shall discuss the medium first. In one method of manufacture an aluminum disk is coated with a slurry containing the gamma form of iron oxide, in which the oxide consists of needlelike particles approximately a micrometer (10^{-4} centimeter) in length and a tenth of a micrometer wide. The iron atoms in each particle have their own minute magnetic fields, but the elongated shape of the particle forces the fields into alignment along the particle's long axis. Each needle is therefore a bar magnet and has a dipole magnetic field. The only possible change in the field is a reversal of the north and south poles at the ends of the needle. The overall magnetization in any given region of the disk is the sum of the fields of the needlelike particles within it.

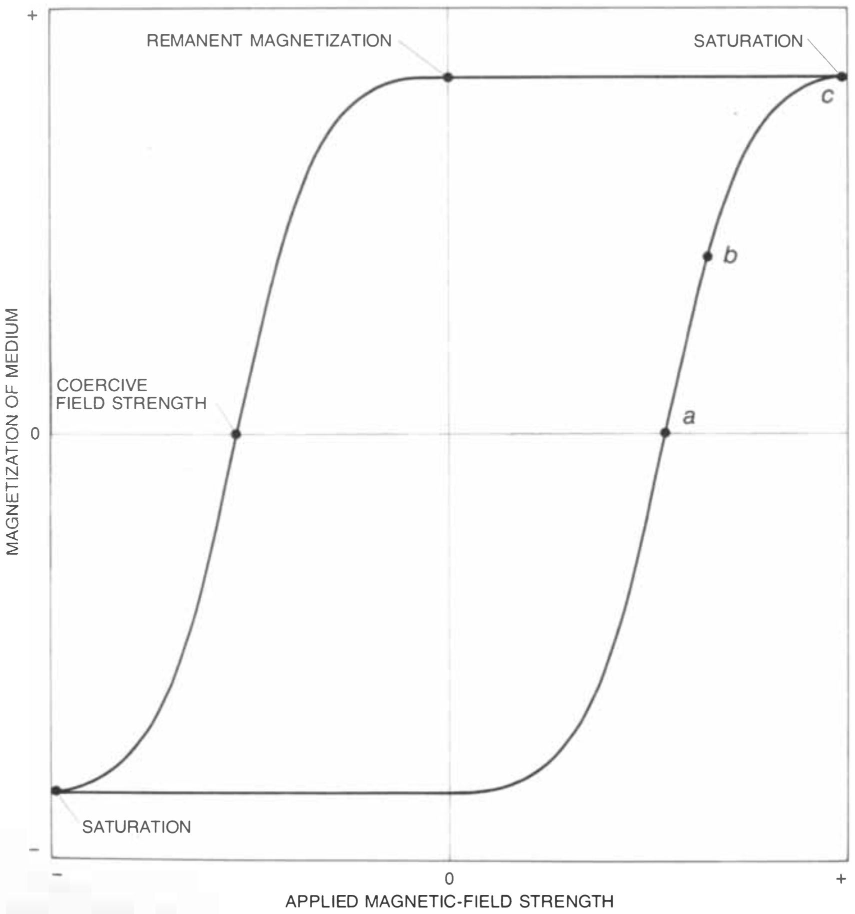
Plainly the magnetization of a region of the disk would be maximal if its needles were aligned and if they all had their north (or their south) pole facing in the same direction. The alignment of the needles is achieved when the disk is manufactured, by rotating the disk in the presence of a magnetic field before the slurry has dried. The needles come to lie in the plane of the disk and more or less perpendicular to a radius of the disk. In an operating disk memory they are more or less aligned with the direction of motion of the disk.

The alignment of the poles is achieved when data are written. Specifically, it is achieved when the head applies a magnetic field to the medium. The magnetic particles are sufficiently far apart so that their own fields do not interact appreciably with one another. As the strength of the applied field increases, however, some of the magnetic particles whose dipoles are opposite to the direction of the applied magnetic field reverse their dipole field. Ultimately the applied field becomes strong enough to polarize all the particles. Two complications must be noted. First, the field of the head falls off rapidly with distance from the head. Second, the medium is moving. It therefore passes out of the region in which the field is strong enough to polarize the medium. It is the trailing edge of the field that governs the final orientation of the magnetization.

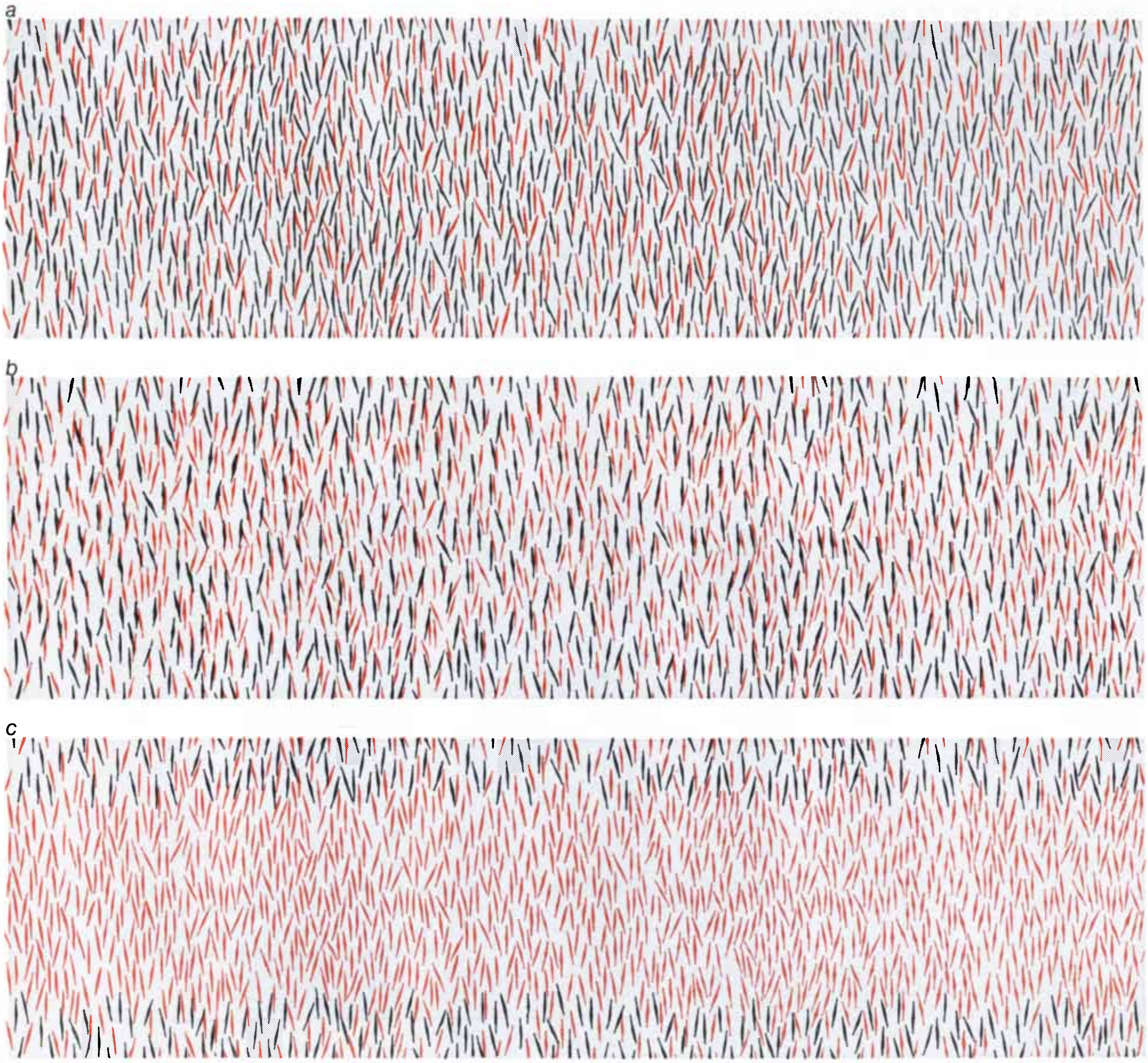
When the field of the head is removed, the region of polarized medium remains. That is why the data can be stored. The magnetization can be driven back to zero, and beyond it to saturation in the opposite sense, by reversing the flow of current through the coil in the head and thereby applying to the magnetic medium a reversed magnetic field. Since the magnetization persists in the medium, the reversal of the magnetic field does not immediately reverse the course of events by which the medium was magnetized in the first place. The term hysteresis is applied to this phenomenon. In general hysteresis signifies the delay of an event because of something that has happened previously, in this case the earlier magnetization. As the magnetic field is cycled the degree of magnetization in the medium follows a pattern called a hysteresis loop.

For a magnetic medium it is desirable that the remanent magnetism (the magnetism that persists when the magnetic field is absent) be large. It also is desirable that a moderately large field strength be necessary to demagnetize the medium. Both of these requirements help to ensure the permanence of the stored data. In addition it is desirable that the reversal of the magnetization of the medium be accomplished over a small range of applied field strength. This helps to ensure that the states of the medium that are used for data storage will be well defined. All these criteria are summarized by the requirement that the hysteresis loop for the magnetic medium be large and nearly square.

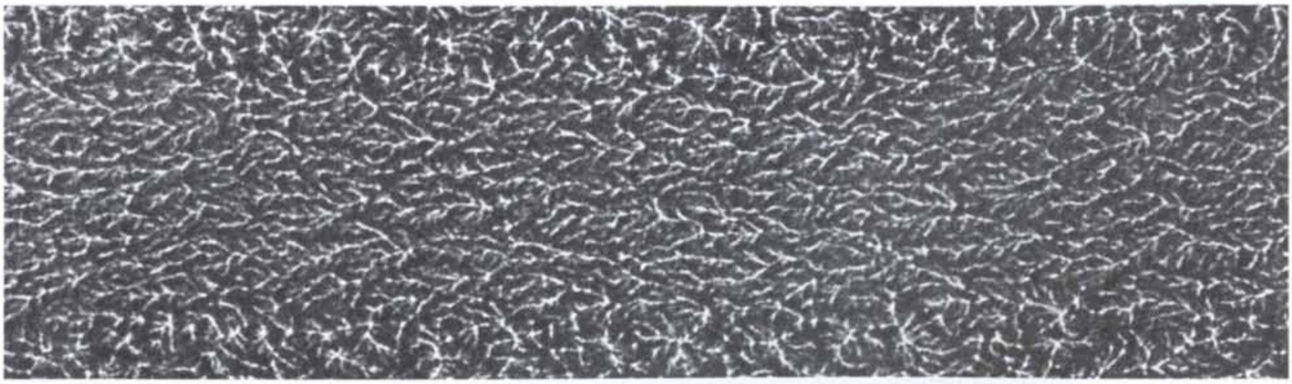
The two possible saturations of the magnetization of the medium are the two states that serve for the storage of



HYSTERESIS LOOP plots the magnetization of a material to which a magnetic field is applied. At first the material's magnetization increases from zero (*a*) to a maximum, or saturation (*c*). If the strength of the field is then decreased, the magnetization persists. A reversal of the field drives the material to saturation with magnetism oriented in the opposite direction.



THREE STAGES IN MAGNETIZING the medium on a disk are shown schematically; they correspond to the points labeled *a, b* and *c* in the hysteresis loop on the opposite page. The medium here consists of needlelike particles of iron oxide. Each particle has its own magnetic field. In *a* the net magnetization is zero. In *c* the magnetization is saturated in a region that measures eight by 40 micrometers.



ACTUAL PATTERN OF MAGNETIZATION is suggested by this Lorentz electron micrograph. To produce the image electrons were beamed through a magnetized cobalt-rhenium film; their trajectories were bent by the magnetization. Featherlike ripples are evident in the image because the magnetization (hence the bending) is not uniform. Branches of each feather are approximately half a micrometer long.

digital data. It is not the case, however, that one state of saturation signifies a 1 and the other a 0. More complex schemes are used, in part to introduce a periodic variation in the readout current. Such periodicities are useful as synchronizing signals in computer systems. In part the schemes are used because, as I have noted, the readout of the data depends on placing a coil in the presence of a changing magnetic field and not a field that is constant. In a code called double frequency modulation a 1 is represented by a reversal of magnetization and a 0 by the absence of a reversal. An additional reversal is inserted between each bit to provide a timing signal. The encoding requires a maximum of two reversals per bit. Other codes do better: they require fewer reversals. Such codes, however, are more susceptible to error, so that part of the extra capacity must be used for extra bits that serve for error correction.

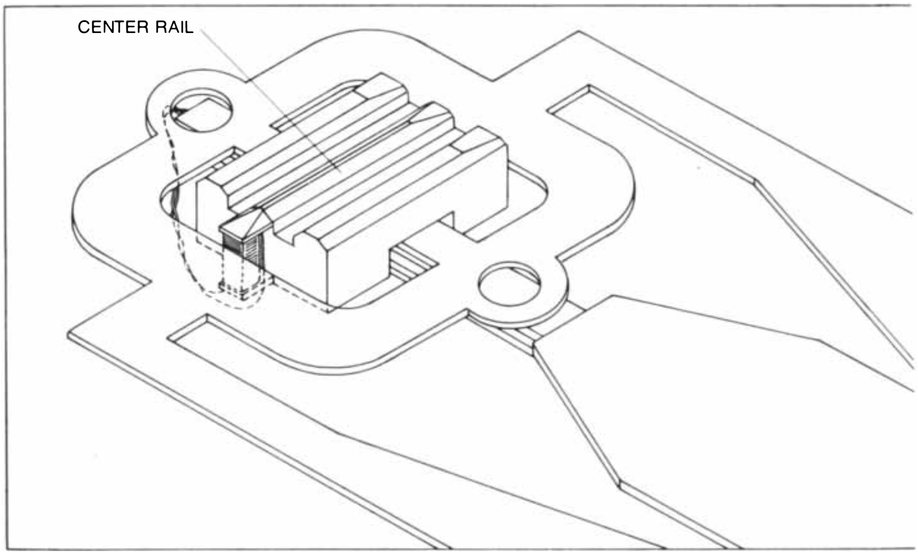
The storage of a document will provide an example of the simplest such scheme. In the American Standard Code for Information Interchange each character in a language is represented by seven bits. The letter *A*, for instance, is 1000001. An eighth bit is often added to each character in storage as a "parity" bit, or check bit, to aid in determining whether the preceding seven bits are correct. The value of the parity bit is 0 if the preceding seven bits add up to an odd number and 1 if they add up to an even number. Thus the letter *A* in storage is 10000011.

This use of parity bits can aid in locating an error only to within the preceding seven bits. A more complex code developed by R. W. Hamming in 1950 employs a greater number of bits and yields the precise address of a single bit that is in error. The correction of the error then requires simply the conversion of a 1 into a 0, or the reverse. In a still more complex scheme the data bits are treated as the coefficients of a polynomial. The polynomial is manipulated algebraically to yield a smaller set of bits. These bits are put in storage. In the event of an error they can be called up to reconstruct the data. The last scheme is particularly well suited to the correction of bursts of errors, which is generally the way errors develop on a magnetic disk.

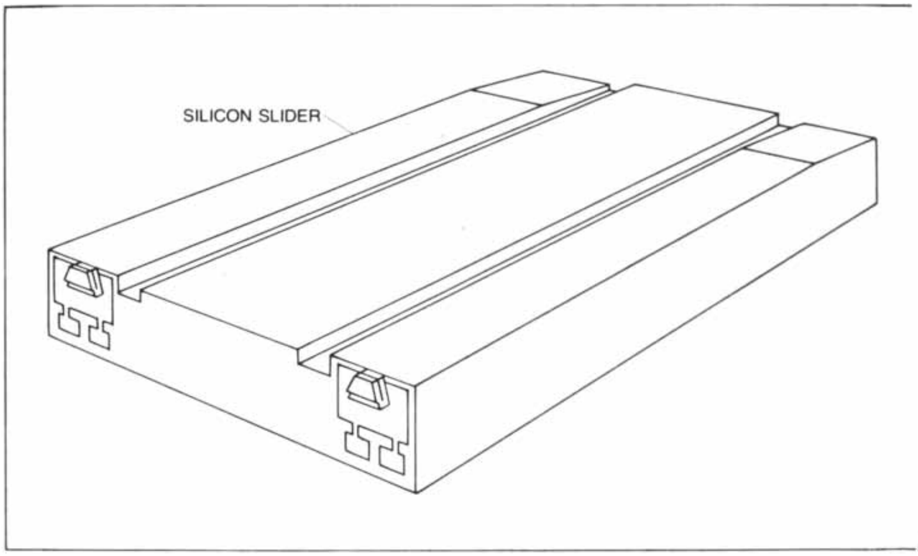
For the magnetic material that is the core of the electromagnet in the head the requirements are distinctive. Here a small flow of current through the coil around the core should yield a large magnetization, and when the flow of current stops, the magnetization should return as nearly as possible to zero. Moreover, a reversal of the direction of the flow of current to only a modest value should yield a reversal of the magnetization. In many heads the core is a ceramic consisting of spherical ferrite particles. A ferrite is an oxide of iron together with another metal or a mixture of metals. In the case of a magnetic head the metals are usually nickel and zinc; sometimes manganese is added.

The design of the head must conform to the design of the disk. In one technology the disk is "floppy": it is a thin sheet of Mylar plastic on which the gamma form of iron oxide is coated. The standard diameter of the disk is eight inches, except for minifloppies, in which the diameter of each disk is $5\frac{1}{4}$ inches. In floppies and minifloppies the head actually makes contact with the surface of the disk. On occasion the head is bounced from the surface by a particle of dirt. Therefore the error rate of the device is relatively high, as is the wear on the medium. Of necessity the disk in such a device spins slowly.

In high-performance memories the magnetic medium is the coating on a rigid aluminum disk eight or 14 inches in diameter, and the head is kept from touching the medium by what is called the air-bearing effect. Consider a head that is nearly in contact with the surface



WINCHESTER HEAD was introduced by the International Business Machines Corporation in 1973. It is shown upside down; actually the rail-like surfaces of the head confront the disk at a distance of half a micrometer. The flow of air under the outside rails generates an aerodynamic force that supports the head; the trailing end of the center rail holds the electromag-

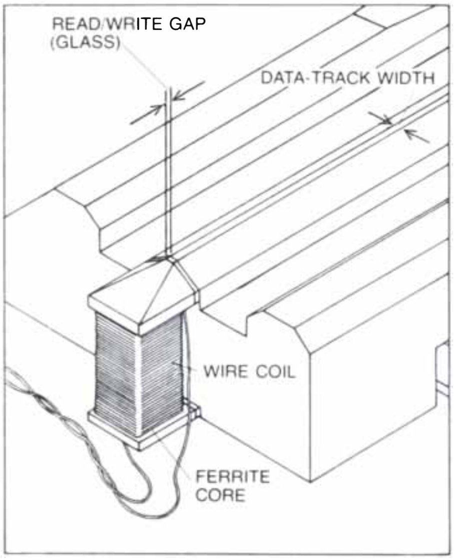


THIN-FILM HEAD (also shown upside down but not at the same scale) has no coil of wire in its electromagnet. Instead it employs a spiral film of electrical conductor. The core of the electromagnet is Permalloy, a mixture of nickel and iron. (The core in a Winchester head is ferrite: an oxide of iron in combination with other metals.) The electromagnet again is at the

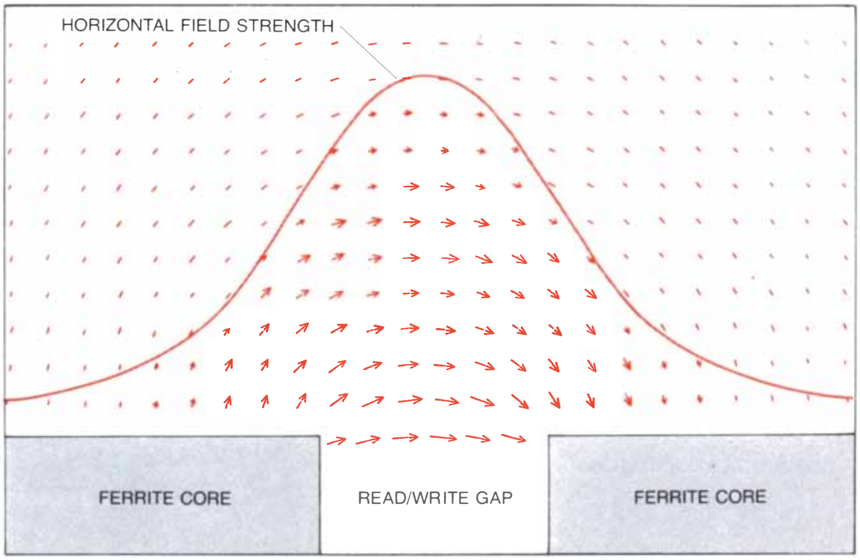
of a 14-inch disk spinning at 3,000 revolutions per minute. The velocity of the head with respect to a data track in the medium on the disk is approximately 100 miles per hour. If the length of the head along the direction of relative motion is two orders of magnitude longer than the separation between the head and the medium, the flow of air between the head and the medium provides support for a head weighing up to several grams.

In 1973 the International Business Machines Corporation introduced the Model 3340 disk memory. The technology of the system has since been adopted by many manufacturers. It is now known generically as Winchester technology, that being the code name under which the device was developed at IBM. A Winchester disk memory has one or more rigid disks, either eight or 14 inches in diameter. Each disk is coated on both sides with a magnetic medium, so that two surfaces per disk are available for the storage of data. Each Winchester head has three rails, or raised surfaces. The trailing end of the middle rail holds a magnetic core with wire coiled around for writing and reading the data. The two outer rails govern the flow of air. The force that results is sufficient to support a weight of 10 grams at a height of half a micrometer above the disk. The disks and the head assemblies in such a memory are sealed in a small "clean room": a chamber approximately the size of a hatbox, in which the air is continuously recirculated and filtered to exclude any dust particles larger than .3 micrometer in diameter.

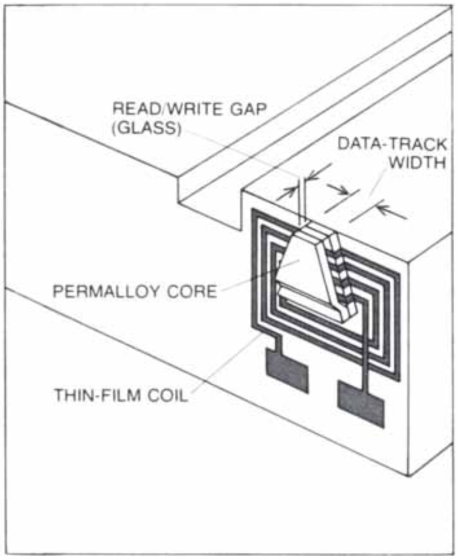
The quantity of data that can be



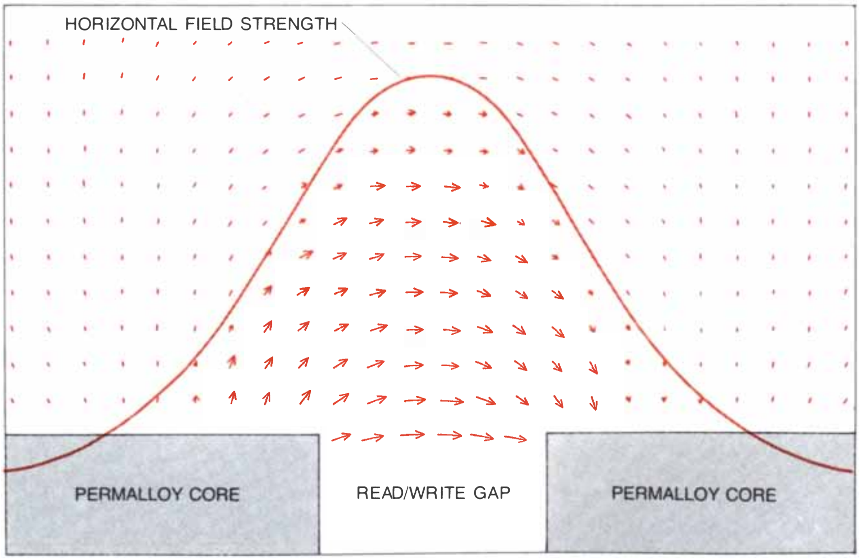
net that writes and reads the data. At the right the electromagnet is seen in closer view. The width of the beveled part of the center rail corresponds to the width of a track of data.



FRINGE FIELD OF WINCHESTER HEAD is the magnetic field that lies outside a gap in the core of the electromagnet. It is the field that writes the data. The arrows show the orientation of the field; their lengths show the intensity. The curve shows the intensity too; it plots the horizontal field strength at a distance from the head equal to half the width of the gap.



trailing end of a structure designed to generate a supporting aerodynamic force when a disk is spinning under it. A memory with thin-film heads was introduced this year by IBM.



FRINGE FIELD OF THIN-FILM HEAD decreases steeply at each side of the electromagnet's gap. The steepness of the decrease allows the writing (and subsequent reading) of data at a greater packing density on a disk. Specifically, a Winchester head can record about 10,000 reversals of magnetization per inch along a data track. A thin-film head can record 15,000.

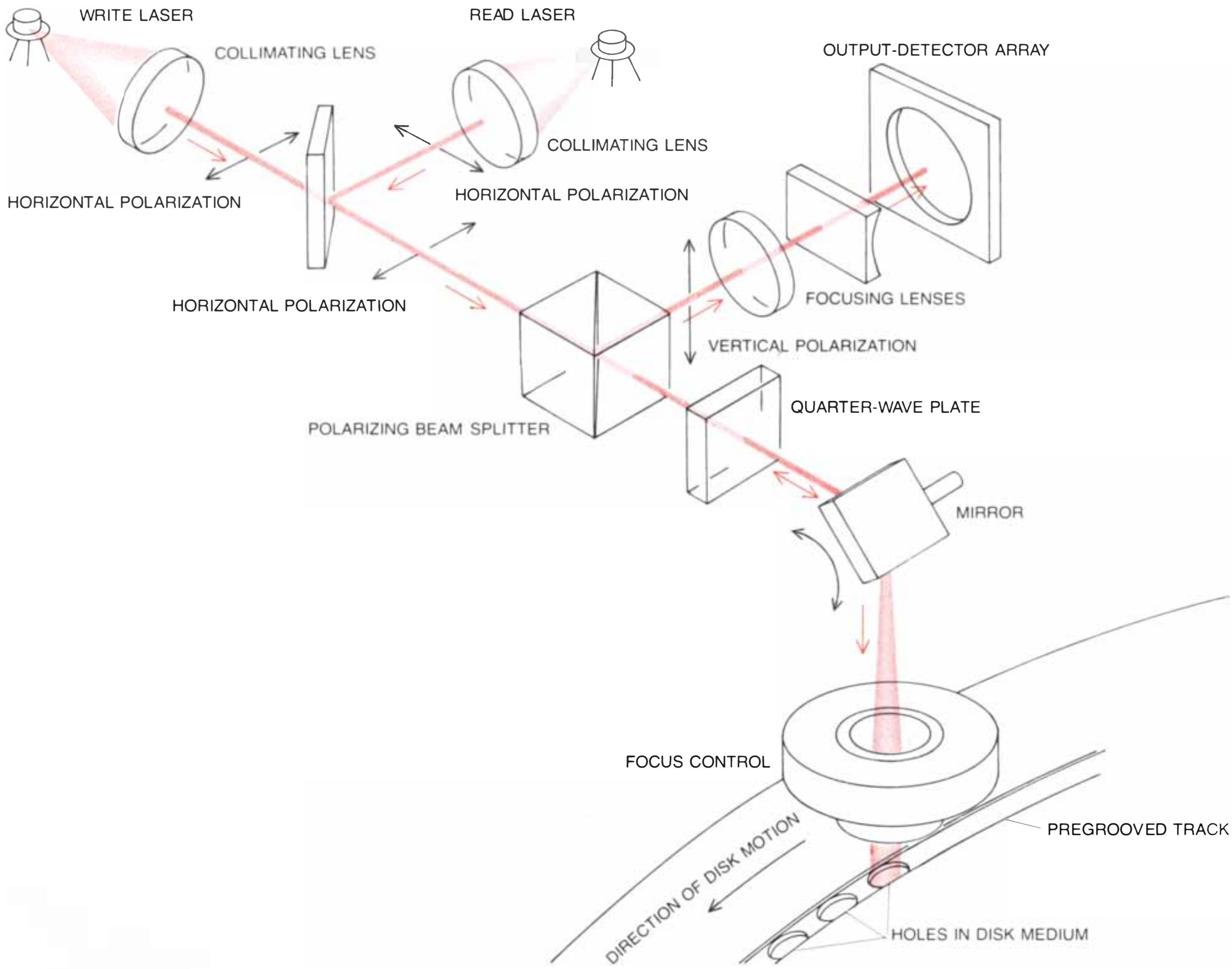
stored on a disk depends on how much of its surface area is magnetized for the storage of a bit. In the first place the width of a magnetized region, or equivalently the width of a data track, is affected by limitations on both the head and the disk. For example, the width of the center rail of a Winchester head is limited by a problem of durability: if the rail is too thin, it is fragile. This limit on the width is some 20 micrometers, which corresponds to a track density on the disk of about 1,000 per inch of the radius.

On a floppy disk the track density is only 48 tracks per inch. The reason is that the Mylar of the disk expands unevenly with increasing temperature, and so a thin data track can wander away from under a head. In high-performance memories the manufacturer devotes one of the surfaces of a disk to patterns of bits that continuously yield information on the position of the head. Any deviation from the proper position causes the generation of a signal in the head that actuates a motor for repositioning. A new strategy is to embed such patterns of bits within the stored data itself.

The number of bits that can be written along a track also is affected by limitations on both the head and the disk. For one thing a reversal in the magnetization of the medium cannot be infinitely sharp, because then it would correspond to the confrontation of north and north (or south and south) magnetic poles, and like poles repel each other. Then too a reversal in the direction of the flow of current through the coil in the head ceases to reverse the head's magnetic field if it happens too quickly. For example, the ferrite particles in a Winchester head begin to fail to respond to reversals of current flow at a frequency of some 10 million reversals per second. As a result of all these constraints the number of reversals in magnetism along a data track in a device that records digital data by magnetic saturation and employs a Winchester head is about 10,000 per inch. The quantity of data stored ranges from about 20 million bits for one surface of a floppy disk to billions of bits for high-performance rigid disks.

The rate at which bits are written or read along a track is called the data rate. It ranges from hundreds of thousands of bits per second for floppy-disk systems to 10 million bits per second for rigid-disk systems. The main reason for the difference is the fact that floppy disks must rotate at lower speeds. The bits are written onto what are called sectors of a track. A sector is typically hundreds of bits long. In one scheme its location is marked by a slot along an inner radius of the disk.

The speed with which a particular sector is found for the writing or reading of data is gauged by the access time. First the head must be positioned over the proper track. This requires a "seek time." Then the proper sector of the track must come under the head.

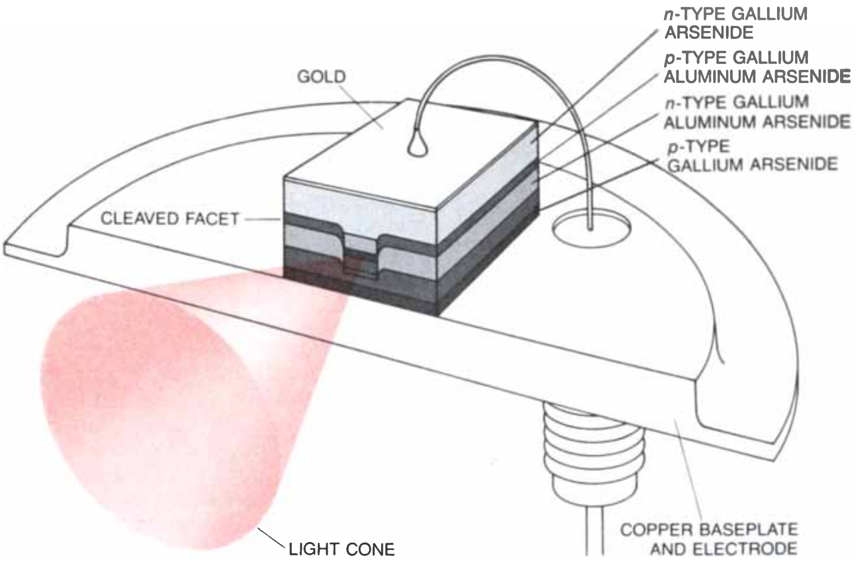


SIMPLEST OPTICAL DISK MEMORY employs laser light to write data by burning holes in the medium on a spinning disk. The laser for writing the data is at the far left. A laser for reading the data is at the top. Its light reflects from the disk in places where a hole has not been burned, then makes a second passage through the optical train of the device, arriving back at a beam splitter with a vertical polarization. This reflects the beam to a detector array. The reflected light also yields feedback signals for control of tracking and focus.

This requires a "latency time." For disk memories the access time is typically between 10 and 100 milliseconds.

Plainly each advance in disk memory must be a constellation of changes made throughout the technology. Nevertheless, I shall describe certain possible changes as if they could be made individually.

Over the past two decades improvements in disk mediums have taken the form of increases in the density of the magnetic particles and in the homogeneity of their size, but the material has remained the gamma form of iron oxide. More recently an effort has been made to increase the coercivity of the medium (the resistance of its magnetism to erasure) by modifying the chemistry of the particles themselves. It turns out that if particles of the gamma form of iron oxide are added to a solution containing cobalt ions and then are heated, the particles acquire a thin surface layer of cobalt, which increases the coercivity for reasons that are not yet completely understood. The particles are being employed in magnetic tape but have not yet appeared in disks, whose high rate of spin means that the magnetic medium must be remarkably durable.



SEMICONDUCTOR LASER the size of a pinhead will probably be used in future optical disk technology. The device consists of layers of gallium arsenide or gallium aluminum arsenide, each with impurities that give the material either an excess of electrons (*n*-type semiconductor) or an excess of "holes," which are states of energy that electrons can occupy (*p*-type semiconductor). When a voltage is applied, electrons flow downward into a narrow layer of *p*-type gallium arsenide at the center of the laser. There they combine with holes and give up energy in the form of photons: quanta of light. Flanking the light-emitting region are semiconductor layers whose electrical and optical properties keep electrons and photons from moving sideways.

The magnetization of the medium (and thus the strength of the readout signal) can be increased by using a material that attains a greater magnetization than iron oxide. Pure metallic cobalt, for example, has a magnetization much greater than that of the gamma form of iron oxide, and many research groups have made disks in which it is the medium. In one method of fabrication ions of an inert gas, typically argon, are accelerated into a target consisting of cobalt. The bombarding ions cause the ejection of cobalt atoms, which deposit themselves as a film on a metal disk. By controlling various aspects of the process it is possible to control the microscopic structure of the film and therefore its magnetic properties.

What has kept such disks from being manufactured commercially is economic inertia. The production of disks based on iron oxide requires the entirely different technology where the medium is applied to the disk as a slurry. In addition, however, thin metal films are intolerant of defects in the metal disk that is their substrate. They also appear to be less durable than the iron oxide disks. On the other hand, the greater magnetization of cobalt means that the medium can be thinner. As a result the magnetic field of the head varies less through the medium, and so the magnetized regions acquire greater definition. In particular the transition length between reversals in the magnetization is shorter. The need for greater storage densities for data will make metallic disks more attractive.

In an effort to improve the head the manufacturers of disk memories are beginning to exploit thin-film technology, in which layers of materials are deposited by a plating method. IBM, for example, has recently introduced a thin-film head in its Model 3370 disk memory. Here the inductive circuit is not a coil of wire; it is a thin-film conductor deposited as a spiral that makes eight turns on the face of a silicon substrate that becomes the rail of the head. The magnetic core of the head is Permalloy: a mixture of nickel and iron. The head can respond to reversals of current as rapidly as 100 million times per second. Moreover, the pattern of the magnetic field thrown off by the head makes it possible to record 15,000 magnetic reversals per inch along a data track. (If the magnetic medium were a metal film, 25,000 reversals per inch might be attained.) It happens that the electrical resistance of Permalloy increases notably in the presence of a magnetic field. The degree of the increase depends on the strength of the magnetic field and not on its rate of change. Hence in future thin-film heads the readout could be independent of the rate of spin of the disk.

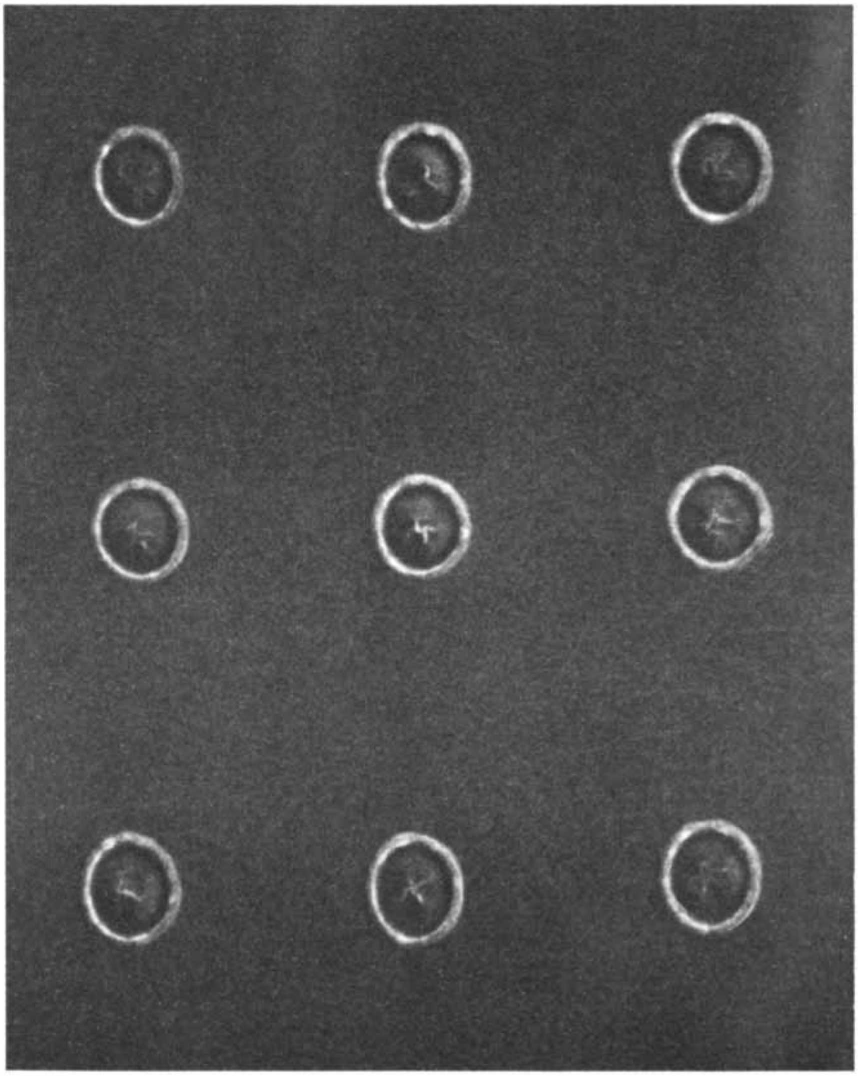
S. Iwasaki of Tohoku University has suggested that data might be stored perpendicular to the plane of the disk. Here the end of the core of a head, and therefore a pole of a dipole magnetic field, confronts the disk and throws field lines deep into the magnetic medium. As a result the data are stored, so to speak, on end. More than 100,000 magnetic reversals per inch might be possible, but the implementation awaits the development of both the head and the medium for it. By the technique described above the magnetic dipoles of iron oxide can be oriented in the plane of a disk. The problem is to find a way in which such dipoles can be oriented perpendicular to the plane of a disk.

Even with all the advances I have described it is inescapable that in magnetic memories the energy responsible for the readout signal is contained in the medium itself. To put it another way, the strength of the readout signal depends on the strength of the medium's remanent magnetization. Digital memories employing beamed energy would have the advantage that for the readout of data the beam itself provides all the required energy and the stored data act as "gates." A further advantage is that the head giving rise to the beam would not have to be nearly in contact with the medium. As a result the medium could be protectively enclosed, so that the disk would be removable without the penalty of an increased error rate. Data could then be safely stored off line (outside the memory) for merely the cost of the memory's disks.

The simplest possibility for a beam-addressed memory is a device in which the data are written when a laser beam burns holes in the coating of a disk. If the coating is a metallic film on a transparent substrate, each hole will transmit light when the laser is later used at lower power for readout. Elsewhere the silvery metal will reflect the readout beam. For a laser whose energy lies in the red part of the electromagnetic spectrum holes a micrometer in diameter are easily achieved. A disk 14 inches in diameter can hold 10 billion such holes. To be sure, a memory of this kind would be nonerasable: the data, once written, could not be changed. Even so, it could be an archival storage in a computer system that also included magnetic disks.

The burning of holes is accomplished most neatly by ablation. The laser beam is focused to a small spot on a thin metal film, melting a small area of the film. At the center of the spot, where the beam is most intense, an even smaller hole opens. Because of surface tension the surrounding molten metal then curls back on itself to produce a toroidal rim. The energy that initiates the ablation is the sum of the heat that raises the temperature of the metal and the heat that changes its phase from solid to liquid and in the center of the spot from liquid to gas. The desirable properties of the metal are therefore a large absorption of energy at the frequency of the laser light and a low heat of liquefaction and of vaporization. On the other hand, the medium should not be too sensitive to heat, because if it is, the reading of the data, which requires a certain minimum intensity of laser light, will alter the information in storage. The properties of the metal tellurium are promising, and so studies of tellurium (as well as of many other mediums) are in progress at Philips, RCA, Hitachi, Xerox, Thomson CSF and elsewhere.

Suppose a hole a micrometer in diameter is to be written on a tellurium film 300 angstrom units (.03 micrometer) thick. The laser pulse that does it must last long enough to heat the metal, open a very small hole by vaporization and keep the metal molten until the rim curls back. The curling takes the longest. The velocity of the rim is approximately 1,000 centimeters per second, and so a



HOLES BURNED BY A LASER in a film of the metal tellurium are shown in an electron micrograph. To make each hole the laser melted a circle of metal and vaporized the center of the circle. The metal then curled back on itself. The distance between holes is five micrometers.

hole a micrometer in diameter opens in some 50 billionths of a second. The laser power needed is 20 milliwatts. During the time the laser is on, the disk advances by approximately a micrometer, giving the hole an elliptical shape. A scheme for encoding data might capitalize on such elongation. The holes, for example, might overlap to produce slots. In Magnavision, a device manufactured by the Magnavox Company that "reads" prerecorded disks but cannot make recordings, variations in the length of holes modulate a laser beam to yield a video signal.

Devices such as Magnavision rely on gas lasers, of which even the smallest are rather large and require an apparatus resembling a shutter to modulate the beam. The rapid development of the much smaller semiconductor lasers makes it likely that in data-storage systems they will be used instead. The simplest semiconductor laser consists of two layers of semiconducting material, each layer "doped" in a different way with a small amount of impurity so that the energies of the electrons in one layer are higher than those of the electrons in the other. When the layers are in contact, the electrons soon stop flowing, because their initial motions establish an electrostatic field that prevents any further movement. If a voltage is applied, however, the field is overcome. The electrons with the higher values of energy move into the other layer, where they give up their energy in the form of light.

A cascade of events then gives rise to the laser beam. Specifically, some of the light that has been generated propagates to the front and the back of the semiconductor, where it is partially reflected by mirrorlike surfaces. As a result of these reflections the light wave grows in amplitude, because each photon, or quantum of light, interacts with electrons in the semiconductor and gives rise to the emission of additional photons.

The only semiconductors now known to be suitable for lasers are gallium arsenide and its related alloys, whose laser light is red or infrared. That is somewhat unfortunate for a disk memory, because tellurium is only weakly absorbing of energy at those wavelengths. On the other hand, the semiconductor lasers are becoming more efficient. The light-producing layers are being sandwiched between additional layers of semiconductor that reflect the moving electrons and thereby confine them to the active regions of the device. The same layers confine the photons. By means of such designs Hitachi has obtained 80 milliwatts of continuous laser output from an experimental semiconductor laser the size of a pinhead. The properties of the medium on the disk thus may cease to be limitations.

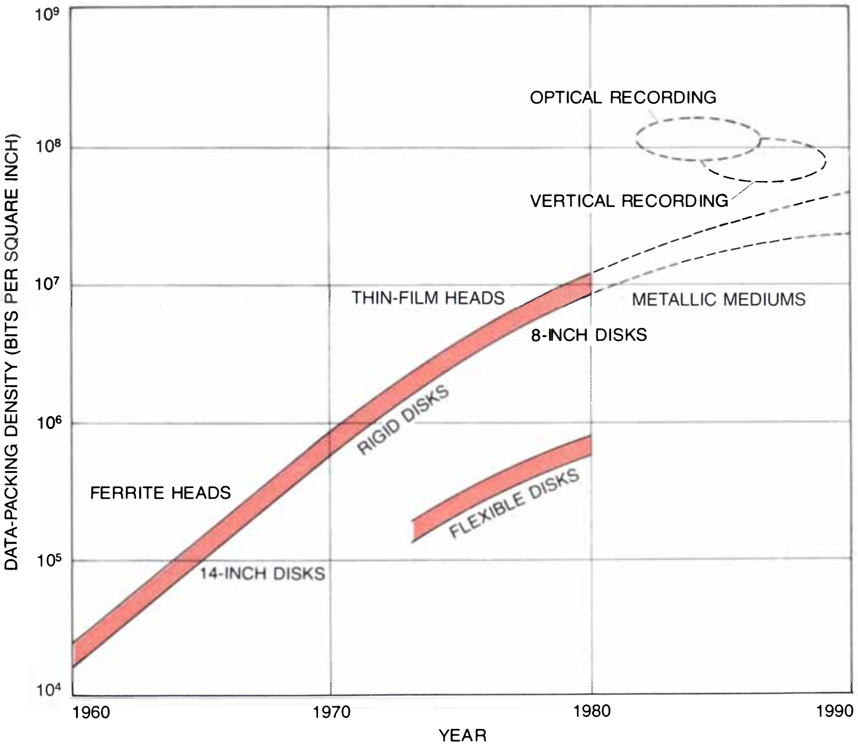
Alan E. Bell and Robert A. Bartolini

of RCA have proposed another possibility: a disk where the tellurium is coated on a transparent substrate so that the thickness of the tellurium and the substrate is a quarter of the wavelength of the light. Under the substrate is an aluminum reflector. The light reflected from the aluminum would be half a wavelength out of phase with the light reflected from the tellurium and so the destructive interference between the two would be complete. An equivalent description is that the tellurium is black as seen from the viewpoint of the laser. Hence all the incident energy is absorbed; it contributes to the heating of the medium.

It is still hoped that an optical disk memory can be devised in which the data can be erased and rewritten. One attempt to develop such a memory is based on the interaction of a magnetic medium with light. For the writing of data the medium is heated above its Curie temperature: the temperature at which its magnetism disappears. As the medium cools, a magnetic field is applied, so that when the magnetism reappears, its orientation is established preferentially. For the reading of the data light is either reflected from the magnetic medium or transmitted through it. The magnetism slightly changes the polarization characteristics of the light. To maximize the effect the magnetization must be perpendicular to the plane of the disk. That is the orientation also required for the vertical recording proposed by Iwasaki.

In the late 1960's IBM experimented with an erasable optical disk memory employing europium oxide as the medium. Unfortunately the Curie temperature of this substance is less than room temperature, and so the memory must be refrigerated. Later the properties of manganese bismuth were investigated. Then it was discovered that the atoms in manganese bismuth rearrange themselves at the Curie temperature, so that the repeated writing of data degrades the material.

Optical disk technology is therefore just emerging. It promises to increase the capacity of disks a hundredfold and to reduce the cost of data storage correspondingly. This is not to say that optical disks will promptly replace their magnetic precursors. Thin-film heads and metallic mediums will improve the performance of magnetic disks, and so can vertical recording. Many issues remain to be resolved that will affect the integration of the optical technology into computer systems.



ADVANCES IN DISK TECHNOLOGY are reflected by advances in the packing density of data, expressed in this chart as bits per square inch on the surface of a disk. In rigid disks the magnetic medium is coated on an aluminum substrate; in "floppy," or flexible, disks it is coated on Mylar plastic. Two improvements are foreseen for the magnetic technology: the use of metal film instead of iron oxide as the medium on rigid disks and the recording of data in regions of magnetization oriented vertically, or perpendicular to the plane of the disk, instead of horizontally, the current practice. Optical disk technology might attain the greatest storage density.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Newton's Apple and Galileo's Dialogue

Newton did see the apple fall, but what was it that inspired him to link the apple's descent to the moon in orbit and arrive at the law of universal gravitation? It may have been a diagram in the "Dialogue"

by Stillman Drake

The final section of Isaac Newton's *Philosophiae Naturalis Principia Mathematica* develops the law of universal gravitation and shows how it explains the falling of objects to the earth, the orbiting of the moon, the motions of the planets and the phenomenon of tides. How did Newton discover this powerful law? He told a friend that the sight of an apple falling from a tree started him thinking in the right direction. Perhaps the moon happened to be in the daylight sky as he watched the apple. In any event he asked himself why the moon did not move away from the earth or fall to it as the apple did. He knew that the force of gravity extends without sensible diminution to the peaks of high mountains. Since it must extend farther, why not to the moon? If the familiar story of the apple is true, it still does not fully explain how Newton came to formulate his question about the moon. I believe what might have inspired his extension of gravity to the moon was a section he had read in Galileo Galilei's *Dialogue on the Two Chief Systems of the World.*

The question about the moon started Newton on a chain of reflections in which a chief consideration was the weakening of gravity with distance. He made a calculation based on the weakening's being proportional to the square of the distance and found that it worked "pretty nearly." That was in 1666, when the University of Cambridge was closed because of an outbreak of the plague and Newton was back on the family farm in Lincolnshire. The data he had were inexact, and he put the matter aside for the time being. It was 20 years before he developed his complete theory of gravitation. It became the crowning achievement of the last section of the *Principia,* called "The System of the World," which unified terrestrial and celestial physics.

The story of Newton and the apple is well known all over the world for what I think are two main reasons. First, it makes something that has always been mysterious seem understandable in terms of everyday experience. Second, and perhaps more appealing, it shows that even the greatest achievements of profound genius can have small beginnings accessible to ordinary minds. This encourages us even as it heightens our admiration of genuinely innovative human beings.

Galileo, who died in 1642 about a year before Newton was born, recognized that great ideas often spring from simple phenomena. He praised William Gilbert, who in 1600 treated the earth as a huge magnet, because he had "framed such a stupendous concept by regarding an object that innumerable men of splendid intellect had handled without paying attention to it." Galileo went on to say (in translation, of course):

"I do not doubt that in the course of time this new science will be improved with still further observations, and even more by true and conclusive demonstrations. But that need not diminish the glory of the first observer. I do not have smaller regard for the original inventor of the harp because of the certainty that his instrument was very crudely constructed and even more crudely played; rather, I admire him much more than I do a hundred artists who in ensuing centuries have brought this profession to the highest perfection.... To apply oneself to great inventions, starting from the smallest beginnings, and to judge that wonderful arts lie hidden behind trivial and childish things, is not for ordinary minds; these are concepts and ideas for superhuman souls."

What Galileo wrote about Gilbert captures what people feel when they first learn about Newton, the apple and the gravitational law that unites the earth and the heavens. It explains why a Japanese artist in about 1869, soon after interchanges between Occidental and Oriental cultures first began in earnest, chose the story of Newton's apple to symbolize Western science. Yet everyone realizes that the simplicity of Newton's great discovery is only apparent. The actual events must have been much more complex. Something was in his mind when the famed apple fell that was different from anything that had occurred to other people in similar circumstances. It would be good to know what that something could have been. I do not say "what it was," because there is no way to be certain of it, but I can suggest something it could well have been.

Newton's early notes on gravitation and dynamics were published together only recently with indications of when they had been written. In 1965 John Herivel of Queen's University in Belfast published *Background to Newton's Principia* and I. Bernard Cohen of Harvard University presented a detailed study of the sources from which Newton learned of Galileo's work. Herivel showed conclusively that Newton took the law of inertia from the writings of René Descartes. And Cohen presented convincing evidence that before Newton had published the *Principia* in 1687 he had not read anything of Galileo's except an English translation of the *Dialogue.*

The law of inertia was fundamental to Newton's first investigation of the moon's orbit because he assumed that

JAPANESE PRINT of Newton watching the apple was part of a series of prints that depicted great men of the Western world. The artist, Hosai, chose to represent science by the story of Newton's apple. The characters are translated, "Isaac Newton, very great head of school but not pompous." The print, which was made in about 1869, is part of the author's collection.

a large body such as the moon would move uniformly in a straight line in the absence of an external force. He sought the force that prevented the moon from doing so. Because the law of inertia was never stated by Galileo historians of science have understandably emphasized Descartes's influence on Newton.

Nevertheless, both Herivel and Cohen acknowledge Newton's early reading of the *Dialogue*. By 1666 Newton had taken notes on the English translation published in 1661 in London by Thomas Salusbury. In the book is a demonstration that could scarcely have failed to interest Newton. Moreover, the diagram that accompanies the demonstration suggests the kind of analysis Newton first applied to the orbit of the moon.

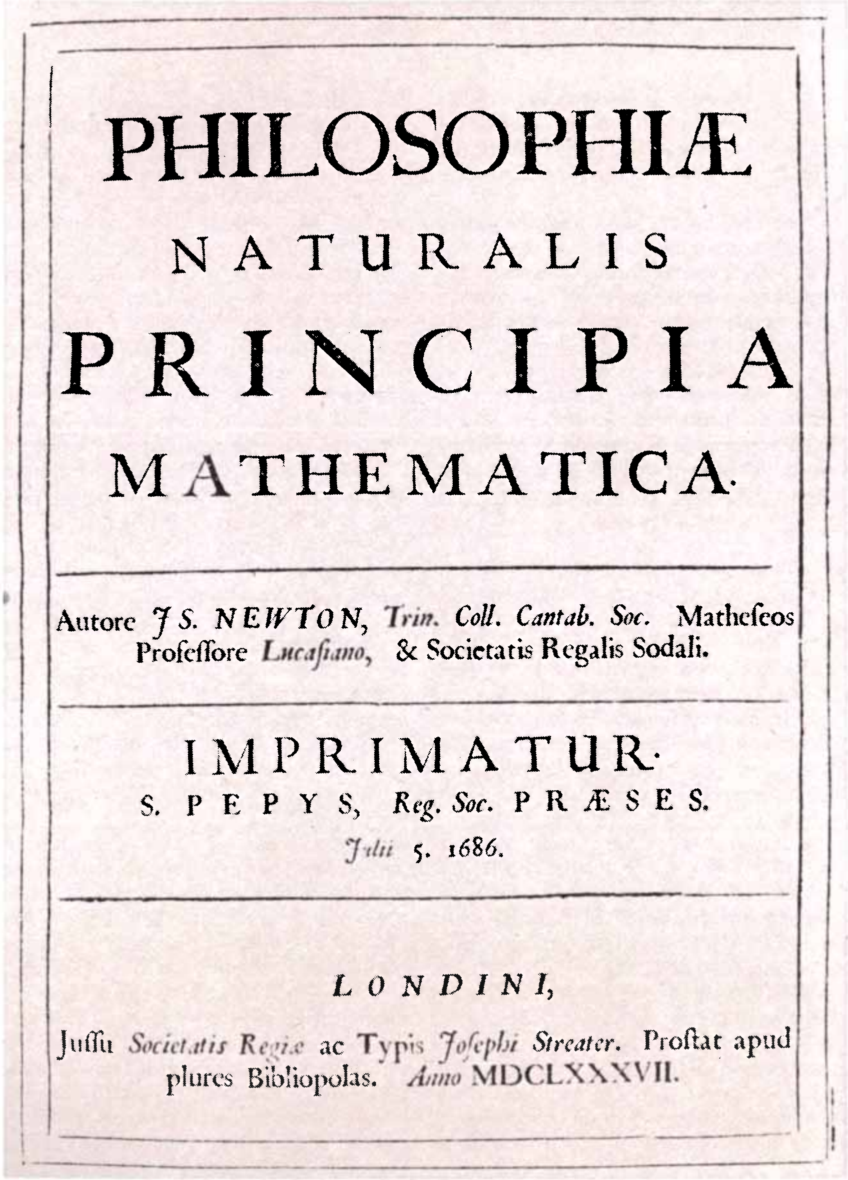
What Galileo had set out to prove had nothing to do with the moon. In fact, Galileo never tried to apply his physics to celestial bodies. He only discussed heavy bodies moving through measurable distances near the surface of the earth. The demonstration was supposed to prove that no heavy body resting on the earth would be flung off by the earth's rotation regardless of the weight of the body or the angular velocity of the earth. Herivel characterized the proof as "unconvincing," and until recently I agreed with other historians that it was ingenious but fallacious. That a dubious proof about heavy bodies resting on the earth had been ignored in all discussions of Newton and the apple is not at all surprising.

Let me emphasize, however, that what may have set a particular man on a given line of thought at a given time is not necessarily something that is clearly and easily related to it, any more than it is something that would naturally and logically give rise to it. A passage Galileo wrote and particularly a diagram he drew may have been applied by Newton to a purpose that never occurred to Galileo. I think this was probably the case with Newton's first analysis of the motion of the moon about the earth. The illustration on page 154 shows Galileo's diagram designed to prove that a heavy body at rest could not be sent off along a tangent by the earth's rotation. He made the diagram to refute his contemporaries who thought this would happen if the earth really had a rotational velocity as high as 24,000 miles per day, or 1,000 miles per hour.

Galileo assumed that if a heavy body resting at *A* in the diagram were flung off by the earth's rotation, it would move uniformly along the tangent *AB*. How far the body would move horizontally in equal times would be proportional to the lines designated *AF, FH* and *HK*. The speeds of its fall in those times would be proportional to the verticals *FG, HI* and *KL* in the right triangle *AKL*. Galileo had shown that the vertical distance the body falls depends not on the time but on the square of the time. Indeed, the time-squared rule is his famous law of free fall. Here, however, he preferred to explain his reasoning about bodies in terms of the speeds with which they would fall in assigned times.

Galileo relied on Euclid's proof that a "mixed" angle (consisting of a line and a circular arc) is always smaller than a rectilineal angle between that line and any other straight line whatsoever. In the diagram this means that the (mixed) angle of tangency between *AB* and the surface of the earth (represented by the arc *AP*) is smaller than any rectilineal angle that can be constructed. Therefore if the body ever left the earth, its downward speed would be more than enough to bring it back to the surface.

Such was the burden of Galileo's demonstration, although he phrased it differently. Consider *F* to be arbitrarily close to *A*. Since the resting heavy body at *A* would not have left the earth where *FG* intersects its surface, a new tangent could be drawn at that point. The same analysis could then be applied to that point to show that the body would remain on the earth, still another tangent could be drawn and so on. Any central


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore *JS. NEWTON, Trin. Coll. Cantab. Soc.* Matheseos Professore *Lucasiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Jussu *Societatis Regiæ* ac Typis *Josephi Streater*. Prostat apud plures Bibliopolas. *Anno* MDCLXXXVII.

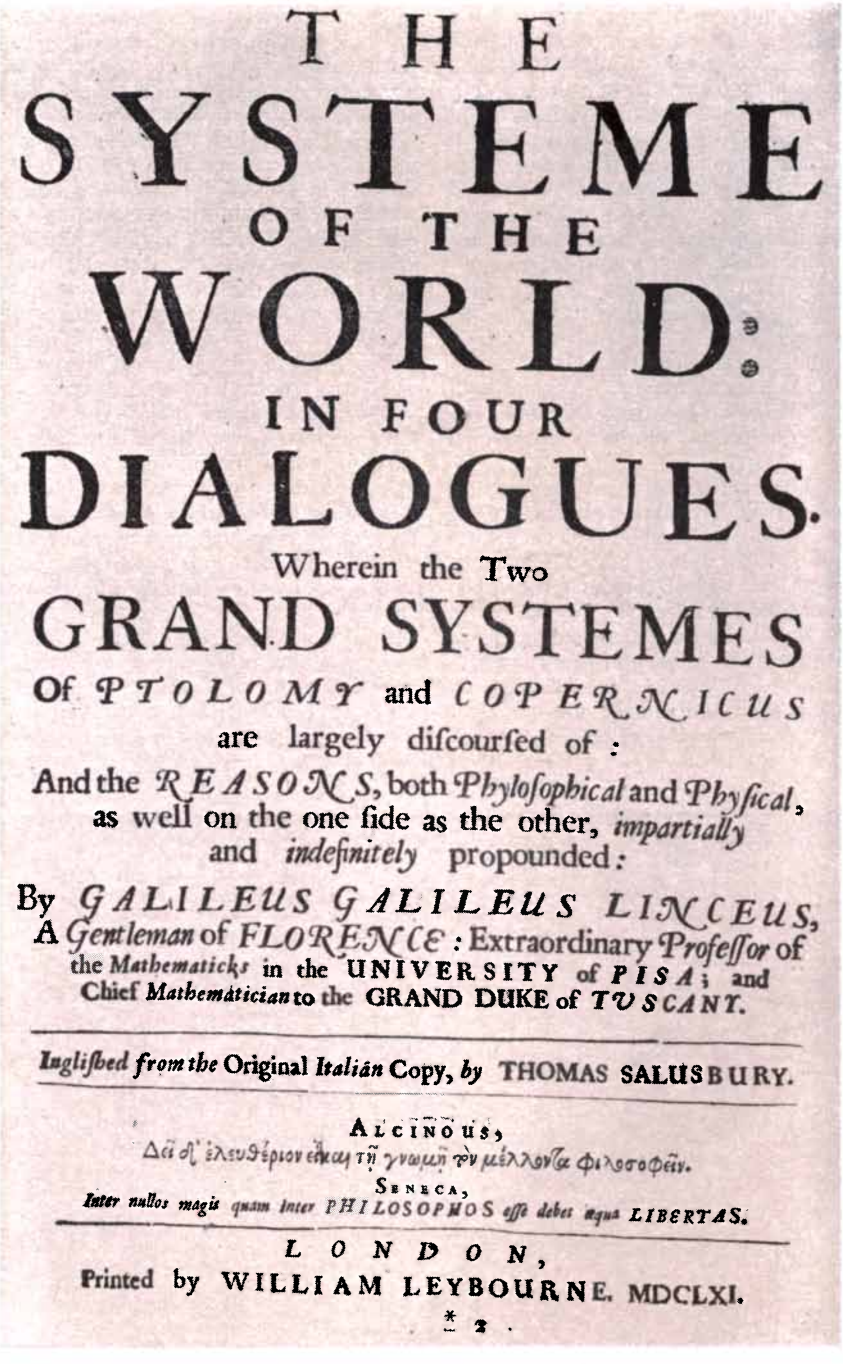
TITLE PAGE OF THE "PRINCIPIA" introduces the magnum opus in which Newton put forward the law of universal gravitation. He was then Lucasian professor of mathematics at Trinity College, Cambridge, and a fellow of the Royal Society of London. The imprimatur, or license to publish, bears the name of Samuel Pepys as the president of the Royal Society. The *Principia* is divided into three "books," or sections. In the first book Newton lays down his three laws of motion. In the second he analyzes motion in fluids. In the third he takes up gravity.

tendency giving rise to uniform acceleration would serve to hold down the resting body forever, regardless of the earth's speed or the body's weight as long as it weighed something. Galileo carefully specified that he spoke only of heavy bodies.

Galileo's Aristotelian adversaries believed the speed of fall was proportional to the weight of the body, and so he included for their benefit the line *AD* representing a lighter body. He went on to point out that in fact the weight did not affect the speed of fall and that he had included *AD* merely to convince his opponents that even if the speed of descent did depend on the body's weight, the body would never be cast off along the tangent as they supposed. The fact that Galileo included this superfluous consideration makes his demonstration even more interesting in the light of Newtonian dynamics. If the rotational speed of the earth were to increase, the resting body would lose some weight. At a certain rotational speed it would become completely weightless (the one possibility Galileo had excluded). Nevertheless, it would not be flung off. It would begin to orbit the surface of the earth, having reached the appropriate orbital speed for that radius.

If the earth were then to rotate faster, it would not be able to impart any new speed to the orbiting body because the body would no longer be resting on it. As a result the body would begin to move opposite to the projection (in the direction *BA*). Yet as Galileo correctly said, in no case would a heavy body be thrown off along the tangent solely by the earth's rotation. Whether this demonstration is adequate is a matter of opinion. It is now known that Galileo's conclusion was correct because bodies cannot by their own motion change their common center of gravity (Newton's fourth corollary to his laws of motion). In any case, the physics as well as the mathematics of Galileo's demonstration would have fascinated Newton, particularly because comparing the angle of tangency with a rectilineal angle suggests in a way the concept of infinitesimals of higher order in the calculus Newton invented.

The case Newton investigated was the special one Galileo had excluded: a weightless body. What made the moon weightless was precisely a certain orbital radius and a certain speed. Newton's notes show that at the time he first worked on the orbit of the moon he was also investigating centrifugal force. In the *Dialogue* Galileo touches on centrifugal force only a few pages after the demonstration. Therefore it is highly plausible that Newton's basic question about the apple and the moon was inspired by his recent reading of the *Dialogue*.


THE SYSTEME OF THE WORLD: IN FOUR DIALOGUES. Wherein the Two GRAND SYSTEMES Of PTOLOMY and COPERNICUS are largely discoursed of: And the REASONS, both Phylosophical and Physical, as well on the one side as the other, impartially and indefinitely propounded: By GALILEUS GALILEUS LINCEUS, A Gentleman of FLORENCE: Extraordinary Professor of the Mathematicks in the UNIVERSITY of PISA; and Chief Mathematician to the GRAND DUKE of TUSCANY.

Inglished from the Original Italian Copy, by THOMAS SALUSBURY.

ALCINOUS,
Δεῖ δ' ἐλευθέριον εἶναι τῇ γνώμῃ τὸν μέλλοντα φιλοσοφεῖν.
SENECA,
Inter nullos magis quam inter PHILOSOPHOS esse debet æqua LIBERTAS.

LONDON,
Printed by WILLIAM LEYBOURNE. MDCLXI.

TITLE PAGE OF THE "DIALOGUE" introduces the contemporary English translation of Galileo's work that Newton had read by 1666. The word Linceus indicates that Galileo belonged to the Academy of Lynxes, the first strictly scientific society, founded in Rome in 1603.

I want to return now to the origin of the law of inertia, which Herivel showed was taken by Newton not from Galileo but from Descartes. Newton could not have got the law from the *Dialogue* because not only is it not stated there but also it seems to have been denied in certain passages. Nevertheless, in the section of the *Dialogue* before the demonstration Galileo added three successive marginal notes expressing the three conditions that would later come to underlie Newton's law of inertia. The notes, which were in the English translation of the *Dialogue* Newton had read, are as follows:

"The motion impressed by the projicient is onely in a right line.

"The project[ile] moveth by the Tangent of the circle of the motion precedent in the point of separation.

"A grave project[ile], as soon as it is separated from the projicient, beginneth to decline."

The notes mean respectively that if a body is projected, the motion imparted to it is exclusively straight. If a body is released from whirling, it proceeds straight along the tangent at the point of release. And if the body is heavy, it starts dropping as soon as it is free. Since Galileo's diagram shows he considered the imparted motion to be uniform in speed, his discussion gave all three conditions of Newton's law of inertia: uniform speed, rectilinearity and the effect of deviation by another force (in this case weight). Yet it is true that Galileo did not state any universal law of inertia as Descartes did and that Newton took the form of his law from Descartes. All these points deserve more explanation.

Galileo never stated any kind of universal physical law. He rejected the traditional physics of his time chiefly because of its tendency to postulate universal laws without paying close attention to the actual physical world. In the *Dialogue* he explicitly denied that a body could actually move uniformly and perpetually in a straight line, because in that case it could leave the universe. Descartes ignored Galileo's law of free fall and offered a universal principle of uniform straight motion but went on to posit vortexes of "subtle matter" that prevented any body from moving in accordance with his law. Newton's law of universal gravitation excluded in principle the perpetual uniform straight motion of a massive body, since every body was continually subject to attraction by other bodies. With Einstein the Euclidean straight line simply disappeared from the physical universe. It could be said that in the realm of inertia Galileo stayed out of trouble, Newton got Descartes out of trouble and Einstein showed where the trouble had always been.

When I try to guess what was on Newton's mind when he asked his pregnant question about the moon, I need not speculate about what was on Galileo's mind when he forged the physics of the *Dialogue*. It is enough to read with care what he published in the *Dialogue*, because that is what Newton did. Newton regarded Galileo not as a confused philosopher who frequently contradicted himself and made physical assumptions unworthy of an intelligent child but as a competent mathematical physicist. Newton would not have been sidetracked by statements in the *Dialogue* that may seem paradoxical. Instead he would have critically examined any interesting physical demonstrations in the book.

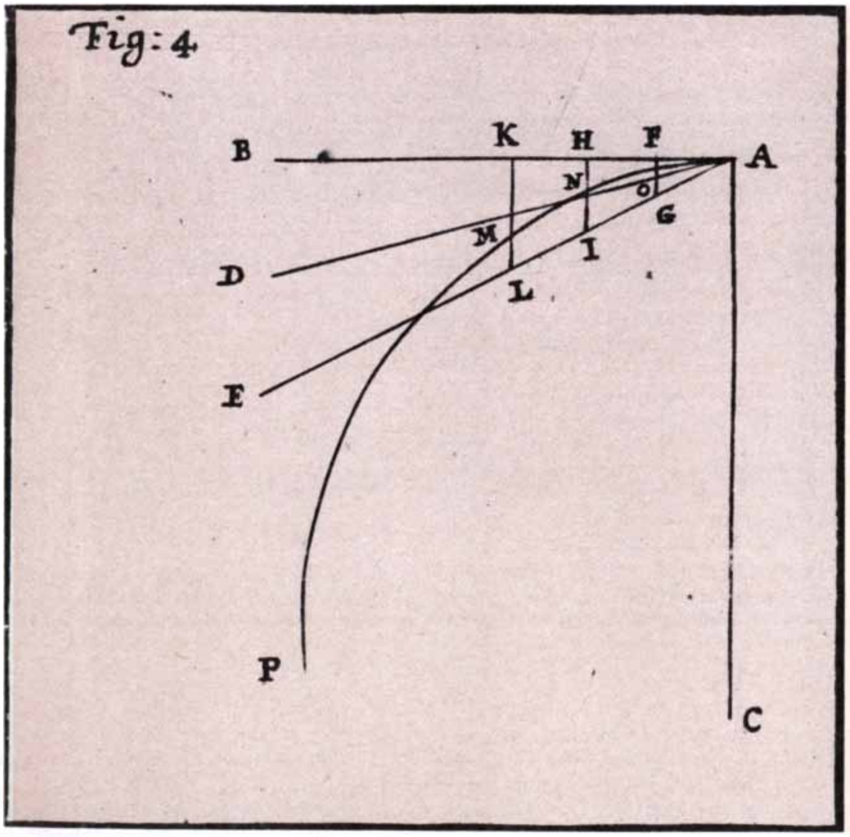


FIGURE 4 OF THE "DIALOGUE" may have inspired Newton to ask himself why the moon did not move away from the earth or fall to it as the apple did. Galileo's diagram was supposed to demonstrate that an object could not be flung off the earth (represented by the arc *AP*) by the earth's rotation. Whether or not the demonstration is ultimately convincing scarcely matters. An invalid proof could still have interested Newton, particularly because the case of a weightless body (which Galileo did not consider) would have resembled the case of the moon.

I believe it is a mistake to suppose that embedded in Galileo's world view was the conviction that all impressed motion must be circular, not straight. He certainly recognized exceptions, as the marginal notes I quoted above make clear. He did say that the particular motion arising in heavy bodies from the rotation of the earth is circular. "Keeping up with the earth," Galileo wrote, is a motion "indelibly impressed" in bodies that are or have been in contact with the earth. For example, he pointed out that a bird beats its wings only to move with respect to the earth, not to keep up with its rotation.

Galileo's demonstration that objects cannot be flung off the earth by the earth's own rotation indicates only what he thought about the particular circular motion of "keeping up with the earth." To him the motion was not purely inertial in the sense of that term in modern physics but was the result of two straight motions, one inertial and one directed toward the earth's center. There is now a tendency to generalize this compound motion beyond the range to which Galileo limited it. It was not a simple "natural tendency" to move circularly but a combined motion. Some historians have postulated "circular inertia" as Galileo's fundamental conviction without specifying what circle (or circles) they mean. Newton probably did not read the *Dialogue* in the way these historians have. In fact, in the *Principia* Newton credited Galileo with having relied on the law of inertia, even though Newton had taken the statement of the law from Descartes, who was the first to make it universal.

There is another passage in the *Dialogue* that must have intrigued Newton. In the passage the imaginary discussant Salviati speaks for Galileo and Simplicio speaks for the contemporary Aristotelians.

"*Salviati:* I did not say that the earth has neither an external nor an internal principle of moving circularly; I say that I do not know which of the two it has. My not knowing that does not have the power to remove it. But if this author [a German anti-Copernican] knows by which [kind of] principle other world bodies are moved around, as they certainly are moved, then I say that what makes the earth move is a thing similar to whatever moves Mars and Jupiter, and which he believes also moves the stellar sphere. If he will advise me as to the motive power of one of these movable bodies, I promise I shall be able to tell him what makes the earth move [around the sun]. Moreover, I shall do the same if he can teach me what it is that moves earthly things downward."

The last comment is certainly a remarkable prophecy for Galileo to have made, because it is the promise Newton ultimately carried out with his law of universal gravitation. Whatever Galileo may have had in mind, the words he published might have suggested to Newton his question about the apple and the moon. No less interesting are the lines that follow in the *Dialogue.*

"*Simplicio:* The cause of this effect is well known; everyone is aware that it is gravity.

"*Salviati:* You are wrong, Simplicio; what you ought to say is that everyone knows it is called 'gravity.' What I am asking you for is not the name of the thing but its essence, of which essence you know not a bit more than you know about the essence of whatever moves the stars around. I except the name that has been attached to it and that has become a familiar household word through the continual experience we have of it daily. But we do not really understand what principle or what force it is that moves stones downward, any more than we understand what moves them upward after they leave the thrower's hand, or what moves the moon around."

For Galileo science differed from philosophy in concentrating less on finding principles or forces of nature than on learning all it could from "sensate experiences and necessary demonstrations." From such experiences he had discovered the law of free fall and the parabolic trajectory of projectiles. For Descartes, on the other hand, anything of consequence in science came from principles, and he called his major work *Principles of Philosophy.* Galileo named his chief book *Two New Sciences.* The English title of Newton's magnum opus, *Mathematical Principles of Natural Philosophy,* falls neatly in the middle because in his day "natural philosophy" meant "physical science." There Newton set forth his celebrated three laws of motion: the law of inertia, the law of force and the law of action and reaction. Then he remarked in a scholium:

"By the first two laws and the first two corollaries, *Galileo* found that the descent of heavy bodies is in the squared ratio of the times, and the motion of projectiles is parabolic, experience agreeing except to the extent that their motion is somewhat retarded by resistance of the air."

If it was unfair of Newton not to add that Descartes was the first to state the inertial law as a universal principle, he was just as unfair to himself by not mentioning that the first statement of the force law was his own. Galileo had spoken only of acceleration, not of force, and only in connection with the fall of heavy bodies. When Newton identified force with acceleration in his second law

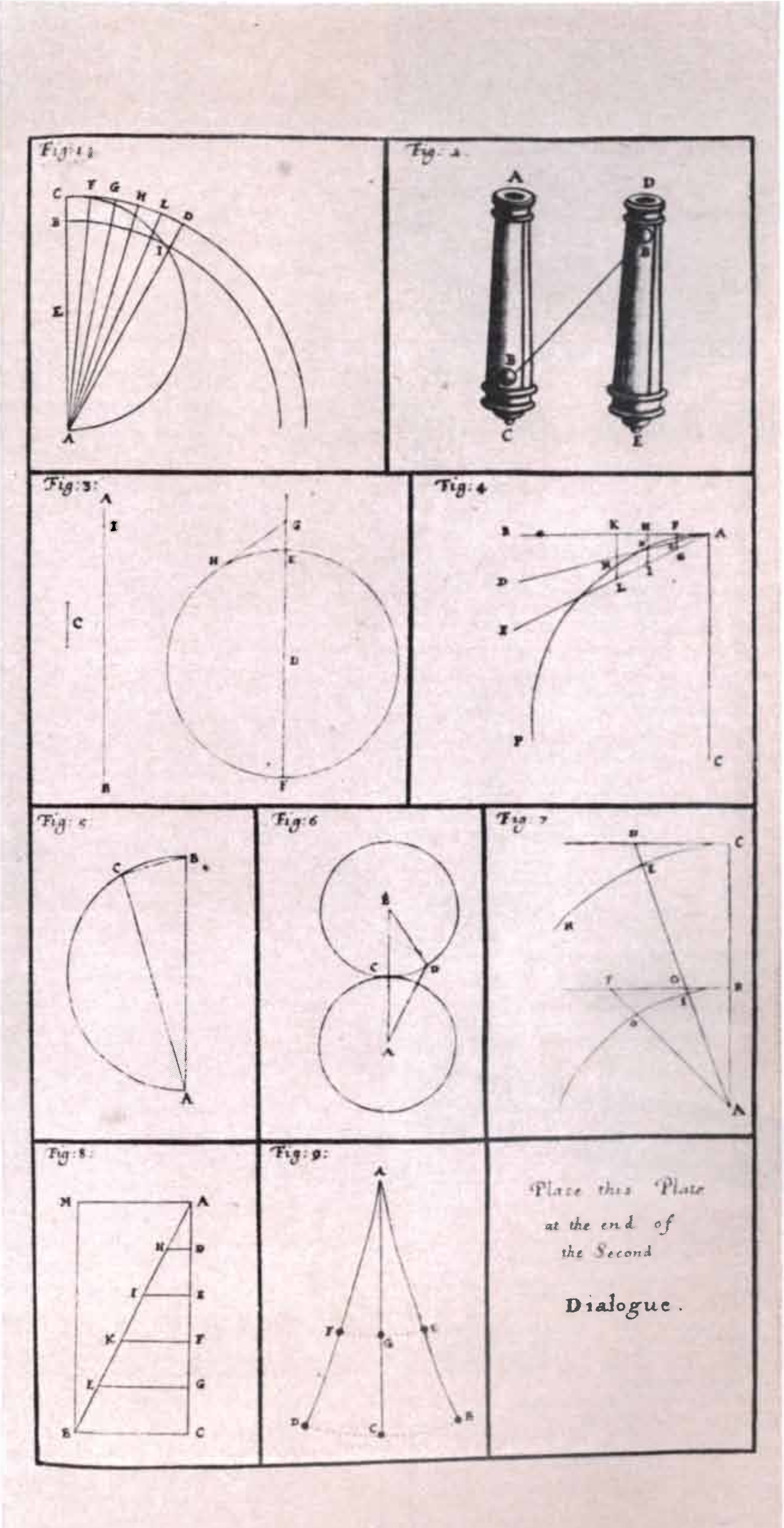
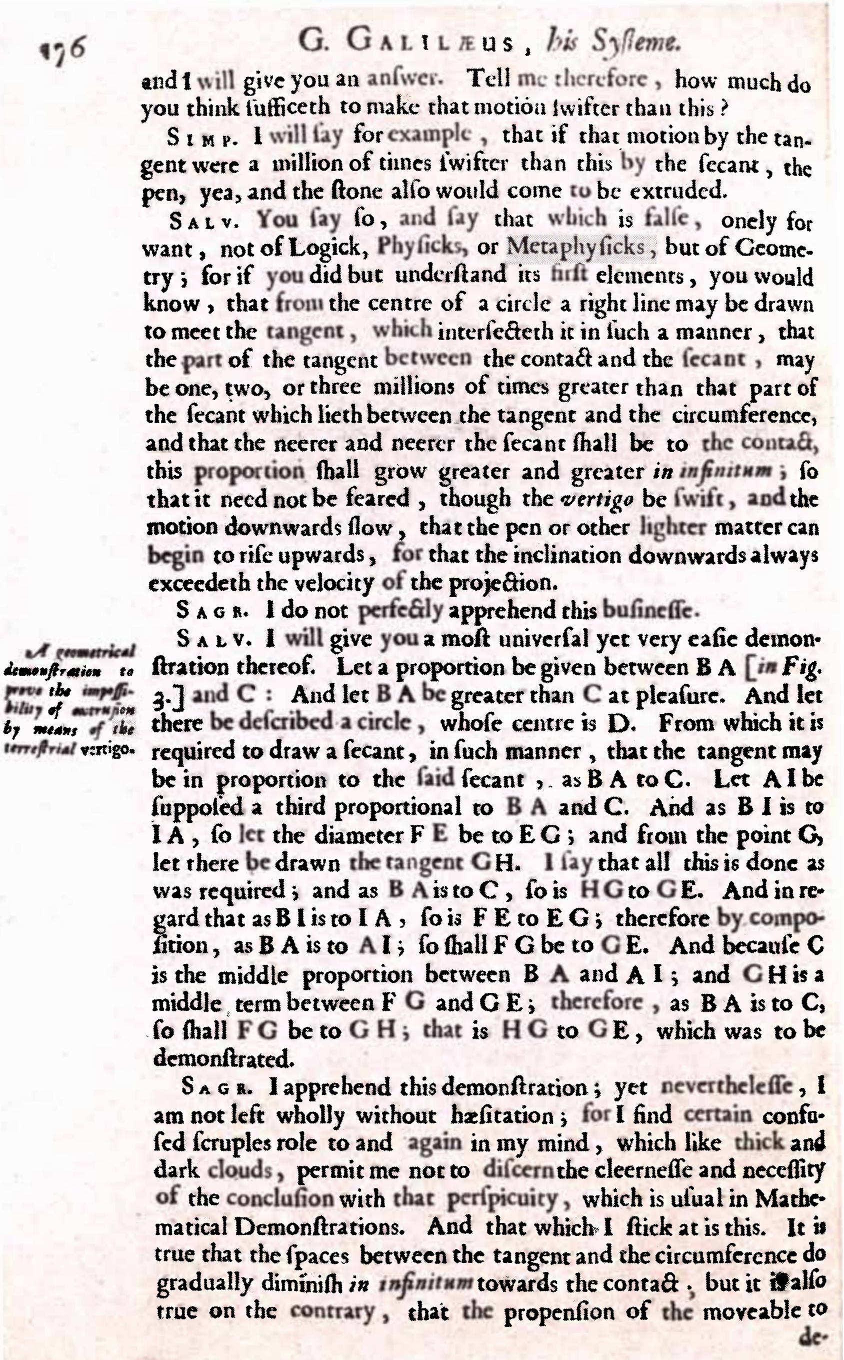


PLATE AT THE END OF THE SECOND "DIALOGUE" has the Figure 4 Newton may have studied. Figure 3 also bears on the discussion of flung bodies and the earth's rotation.

and made acceleration a universal measure of force, he went far beyond anything Galileo had ever had in mind. Newton of course knew that. Before he developed the science of dynamics the concept of forces in nature was considered to be self-contradictory: what was forced was not natural by definition. I suppose Newton felt that Galileo, with his mathematical treatment of the acceleration of falling objects, had taken the first small step toward the dynamics that would come to link terrestrial and celestial physics. If Newton began to develop the science of dynamics when he contemplated the apple and the moon, and if he remembered that his reflections were inspired by Galileo's *Dialogue*, it is no wonder he paid exaggerated tribute to him. He may have felt about his Italian predecessor as Galileo did about his English predecessor, Gilbert.


176 G. GALILÆUS, *his Syſteme.*

and I will give you an anſwer. Tell me therefore, how much do you think ſufficeth to make that motion ſwifter than this?

SIMP. I will ſay for example, that if that motion by the tangent were a million of times ſwifter than this by the ſecant, the pen, yea, and the ſtone alſo would come to be extruded.

SALV. You ſay ſo, and ſay that which is falſe, onely for want, not of Logick, Phyſicks, or Metaphyſicks, but of Geometry; for if you did but underſtand its firſt elements, you would know, that from the centre of a circle a right line may be drawn to meet the tangent, which interſecteth it in ſuch a manner, that the part of the tangent between the contact and the ſecant, may be one, two, or three millions of times greater than that part of the ſecant which lieth between the tangent and the circumference, and that the neerer and neerer the ſecant ſhall be to the contact, this proportion ſhall grow greater and greater *in infinitum*; ſo that it need not be feared, though the *vertigo* be ſwift, and the motion downwards ſlow, that the pen or other lighter matter can begin to riſe upwards, for that the inclination downwards always exceedeth the velocity of the projection.

SAGR. I do not perfectly apprehend this buſineſſe.

A geometrical demonſtration to prove the impoſſibility of extruſion by means of the terreſtrial vertigo.

SALV. I will give you a moſt univerſal yet very eaſie demonſtration thereof. Let a proportion be given between B A [*in Fig.* 3.] and C: And let B A be greater than C at pleaſure. And let there be deſcribed a circle, whoſe centre is D. From which it is required to draw a ſecant, in ſuch manner, that the tangent may be in proportion to the ſaid ſecant, as B A to C. Let A I be ſuppoſed a third proportional to B A and C. And as B I is to I A, ſo let the diameter F E be to E G; and from the point G, let there be drawn the tangent G H. I ſay that all this is done as was required; and as B A is to C, ſo is H G to G E. And in regard that as B I is to I A, ſo is F E to E G; therefore by compoſition, as B A is to A I; ſo ſhall F G be to G E. And becauſe C is the middle proportion between B A and A I; and G H is a middle term between F G and G E; therefore, as B A is to C, ſo ſhall F G be to G H; that is H G to G E, which was to be demonſtrated.

SAGR. I apprehend this demonſtration; yet neverthleſſe, I am not left wholly without hæſitation; for I find certain confuſed ſcruples role to and again in my mind, which like thick and dark clouds, permit me not to diſcern the cleerneſſe and neceſſity of the concluſion with that perſpicuity, which is uſual in Mathematical Demonſtrations. And that which I ſtick at is this. It is true that the ſpaces between the tangent and the circumference do gradually diminiſh *in infinitum* towards the contact, but it is alſo true on the contrary, that the propenſion of the moveable to de-

PAGE 176 OF THE "DIALOGUE" begins the ingenious discussion that may have inspired Newton to develop the law of universal gravitation. The note in the margin states: "A geometrical demonstration to prove the impossibility of extrusion by means of the terrestrial *vertigo*."

THE AMATEUR SCIENTIST

Dazzling laser displays that shed light on light

by Jearl Walker

Laser art was invented almost simultaneously with the laser. Because a laser emits coherent light it can be employed to give dazzling displays of interference effects, visual spectacles that could not be achieved with ordinary lamps. This month I shall describe some of the laser-art techniques I use in my slide shows at Cleveland State University.

In each show 10 slide projectors cast five simultaneous slide images on wall-to-wall screens. All the images are synchronized to music. During certain parts of a show the projectors hold blanks and therefore do not project an image. Instead two 15-milliwatt helium-neon lasers are turned on and directed through an optical array to create displays of interference patterns and Lissajous figures on the screens. Immediately before introducing the lasers I set off four explosions in front of the screens. When the laser beams pass through the smoke, the paths of light above the audience sparkle brilliantly, giving the impression that the narrow lines of bright red are less than real.

The laser techniques I shall describe are of two kinds, one kind based on the interference of light waves and the other on mechanical oscillation to redirect the laser beam. The interference techniques were worked out by David Yoel, a student at Cleveland State, to whom I am indebted for his labors. The best displays were created with diffraction gratings sold by the Lumens Corporation, a California-based company that supplies optical materials for laser-light shows. The gratings I have give a dispersion of medium quality, but the company also sells gratings that give high-quality dispersion.

All the gratings are made of transparent plastic on which a pattern has been laid. The procedure for making the gratings is undisclosed. One grating generates a diffraction pattern of the kind seen in an introductory physics class; when the grating is held in a laser beam, a row of bright dots is cast on a screen. A second grating creates a cluster of bright dots surrounded by dimmer ones. A third grating creates a similar cluster except that the bright dots are arranged rectangularly.

A fourth kind of filter has been constructed from pie-shaped segments of the first type of grating. All the apexes of the segments are grouped at the center of the filter. When the filter is placed in an expanded beam from the laser, a row of dots is produced by each segment. Since there are 48 segments, 48 rows of bright dots extend radially outward from the center of the pattern.

The display is impressive, but it is outshined by the pattern cast by the fifth filter, which Lumens calls a Chromasphere grating. That filter creates the illusion of a Christmas-tree ball brilliantly decorated in red. The center of the pattern has an extremely bright dot of light. Around it is a circle of bright dots. On both sides of the circle are dots of red in an array that gives the illusion of the surface of a ball. (For a limited time I can supply readers with a small sample of this Christmas-ball diffraction grating that is suitable for use with a student-oriented laser. Send $1 and a mailing label to me: Physics Department, Cleveland State University, Cleveland, Ohio 44115.)

All the gratings work by means of the wave interference of light and particularly by the diffraction of light. The simplest example of diffraction involves light passing through a small slit in an otherwise opaque filter. The slit is very long and narrow, being, say, a few micrometers wide. Indeed, the width is close to the wavelength of the light being passed through the slit. With such a narrow aperture the light is diffracted, that is, it is spread outward along a line parallel to the width of the slit. Hence the light passing through the slit does not entirely continue traveling in its initial direction; instead it spreads to the sides.

Something else happens to the light. It is not spread uniformly to the sides but is relatively intense at certain angles and less intense or even absent at other ones. If the light falls on a screen, a pattern of bright and dark lines (usually called fringes) can be seen. This diffraction pattern (both the spreading of the light and the resulting bright and dark lines) arises from the interference of the light waves passing through the aperture.

In the mathematical construction of the interference one imagines that the wave front in the slit at any instant consists of a series of small wave generators, each generator sending out a semicircular wave. With a large number of generators side by side the semicircular waves would interfere with one another as they expanded, thereby creating another straight wave front displaced to the side from the initial one. The new wave front would also have an infinite number of such wave generators, each of which would send out a semicircular wave. Again the semicircular waves would interfere with one another and create still another straight wave front displaced from the preceding one. With this model one can describe mathematically how a wave front moves.

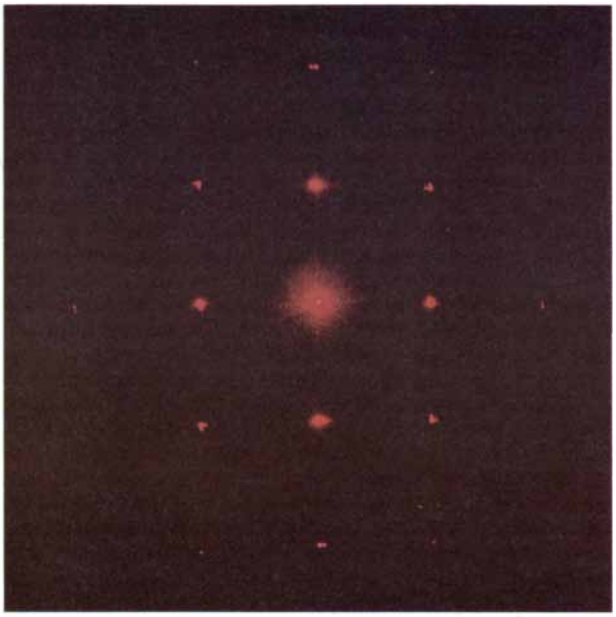
Although such wave generators are imaginary (at least there is no compelling evidence that nature truly works this way), describing the model of a light wave as the composite interference of small semicircular wave generators enables one to predict the outcome of a host of experiments in optics and in particular to predict the pattern cast by a narrow slit illuminated with laser light. As a wave passes through the slit there is no longer an infinite number of wave generators on each side of the generators in the slit. The number was infinite before the wave front entered the slit, but the opaque screen eliminated the rest of the generators.

Still, each generator that did enter the slit sends out its usual semicircular wave. The important difference is that the number of semicircular waves is now too small to interfere to reconstruct the straight wave front that entered the slit. Some of the semicircular waves will spread to the sides instead of going straight in the direction perpendicular to the filter. Moreover, at some angles with respect to the forward direction the wave produced by some of the generators will be exactly out of step with the wave produced by the other generators. As a result no net light wave will be sent out at that angle. If a screen is inserted into the diffracted light, this cancellation of a light wave results in a dark line on the screen. At other places the waves reinforce one another and produce a bright line on the screen.

A diffraction grating, which consists of many slits, works in essentially the same way except that the light diffracted through each slit interferes with the light from each of the other slits. A grating may have tens of thousands of slits. The effect on the diffraction pattern on the screen is that the bright places are narrower and sharper than they are in the pattern cast by a single slit.

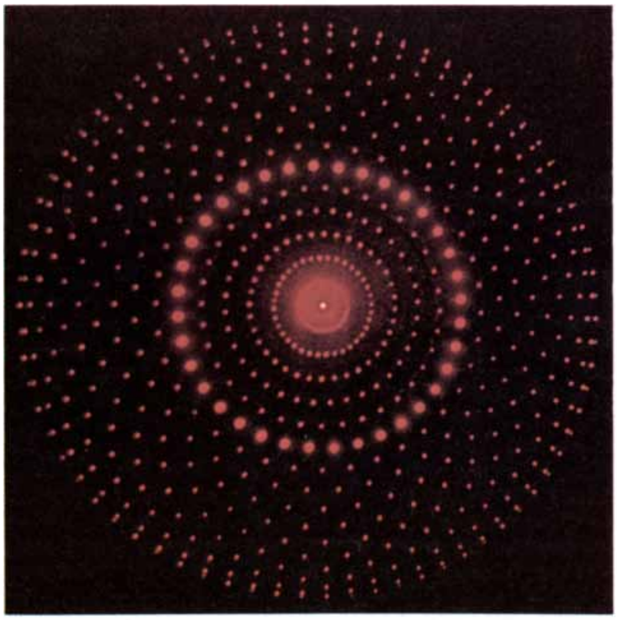
Many of the inexpensive gratings now on the market are plastic replicas of a master grating etched on glass or metal. I do not know how Lumens makes gratings, but one can detect the grating structure by examining a grating under a microscope. The "lines" are about two micrometers wide. This estimate is consistent with one I can make when I compare the Lumens grating with the replica grating sold by the Edmund Scientific Company. The bright fringes on the side from the Lumens grating are approximately one-third as far from the center as the ones from the Edmund grating, which means that the Edmund grating has lines spaced three times closer, providing greater dispersion. Dispersion is not the objective, however, when one uses the diffraction gratings in a laser show. One wants the side fringes to be distinctly bright. Therefore the Lumens grating is better suited for the purpose.

A grating with equally spaced lines of transmission and opaqueness is termed a Ronchi filter. Such a filter creates a diffraction pattern that consists of one bright central spot and two other bright spots, one on each side of the central spot. Dimmer spots lie farther out to each side. The entire pattern lies along a line. The first side spots are almost as bright as the central spot, but the others



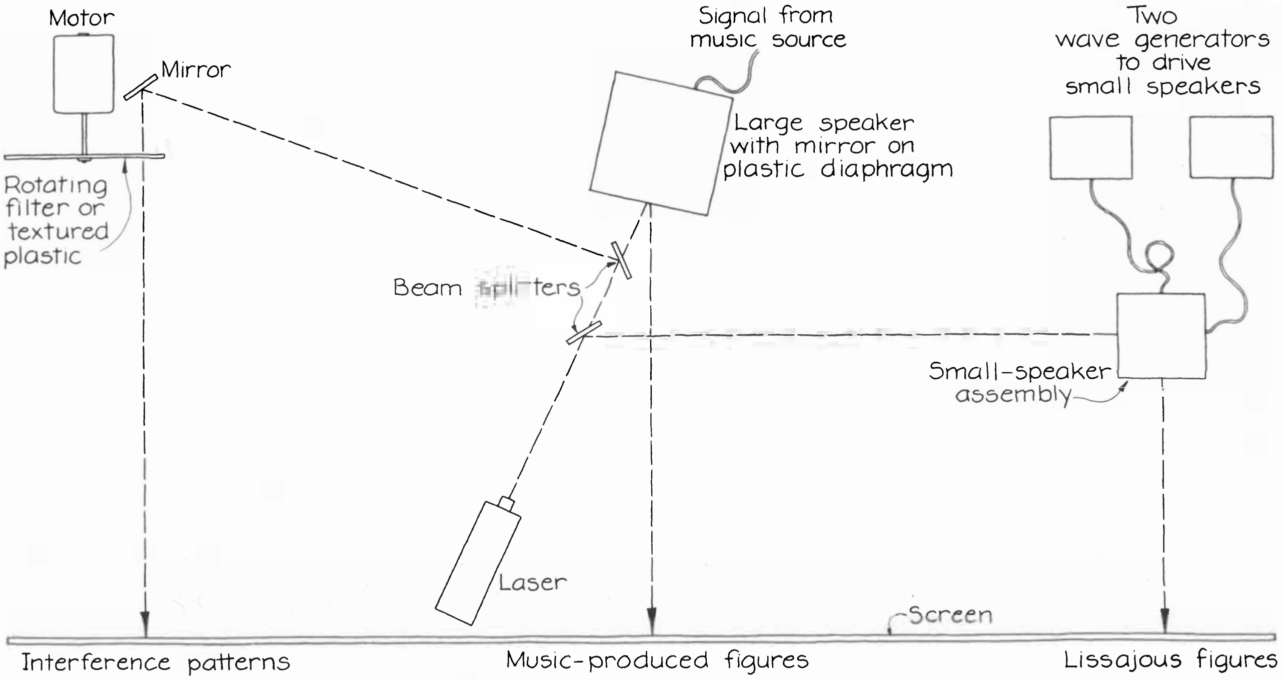
The pattern from crossed Ronchi filters

Textured plastic in the beam



The "Christmas-tree ball" display

A 48-segment grating combined with textured plastic

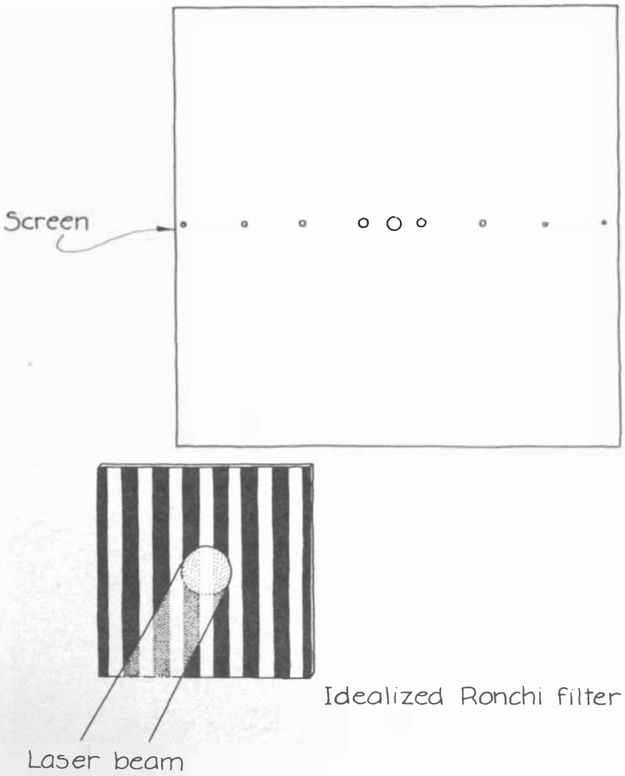


An arrangement of the optics for a laser-light show

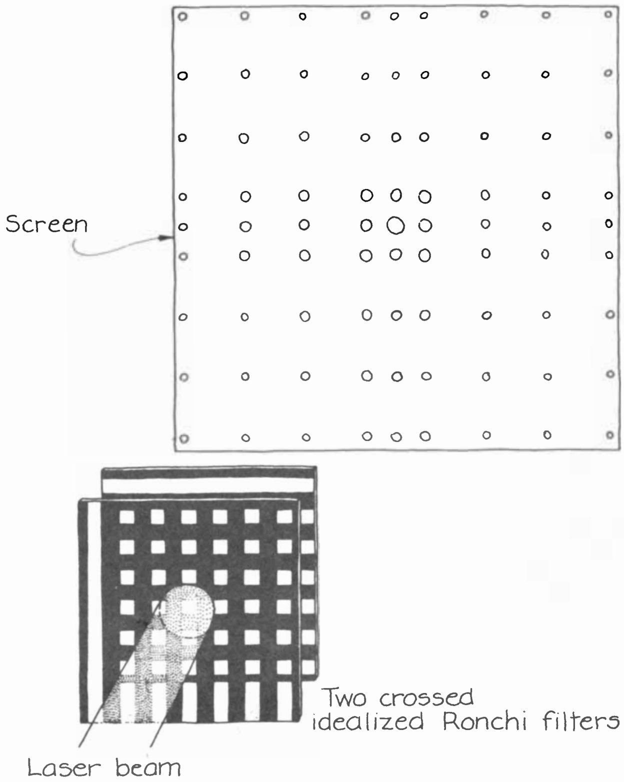
are noticeably dimmer. At least one type of filter from Lumens appears to be a normal Ronchi filter.

If two Ronchi filters are placed in a laser beam so that their "lines" are at right angles to one another, each filter produces its own diffraction pattern. The result is a composite of the two patterns, with one bright central spot and eight slightly dimmer spots lying in a rectangular array around it. Noticeably dimmer spots lie farther from the center. One of the Lumens filters appears to be of this type.

Crossing more Ronchi filters, each at a different angle with respect to the previous ones, creates an increasingly complex diffraction pattern. In each case a bright central spot is surrounded by an array of slightly dimmer secondary spots. The display is also filled with no-



The interference pattern from a Ronchi filter



The pattern from two Ronchi filters crossed at right angles

AT LAST, A CAR THAT'S SLOW FROM "F" TO "E" IS FAST FROM 0 TO 50.

It's not surprising that Renault Le Car will take you a long way on a gallon of gas. What is surprising is how quickly it will do it.

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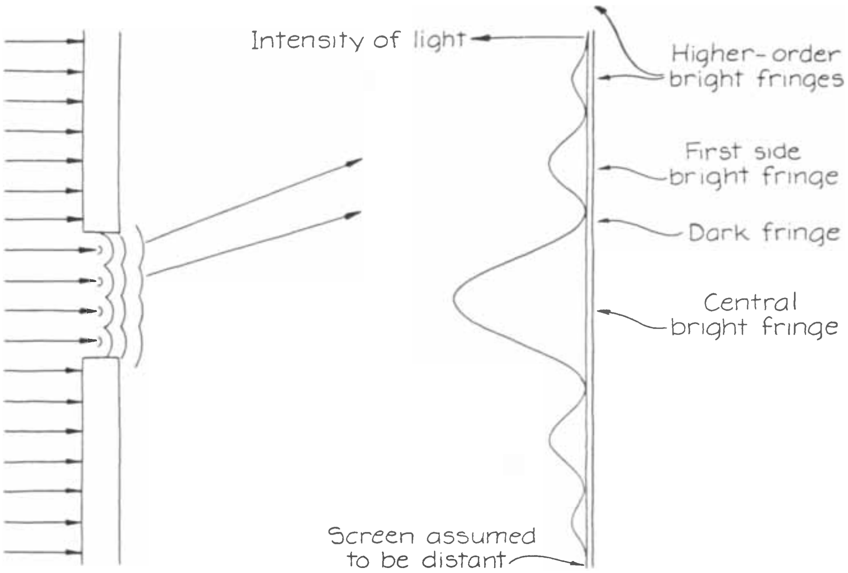
ticeably dimmer spots from higher orders of interference.

The Christmas-ball filter from Lumens appears to be essentially three or four crossed Ronchi filters, some of which have different spacings between the lines. The filter is not merely the result of gluing together three or four normal Ronchi gratings, each with its lines oriented at an angle to the preceding set of lines. The people at Lumens have hit on a method of putting the crossed Ronchi filters on a single surface by appropriately shaping the raised areas of the surface. When I examined the filter under a microscope, I saw a linear arrangement of hexagonal bumps. The arrangement of parallel rows of bumps acts as one Ronchi filter. A line perpendicular to the rows can be designated as axis No. 1. Another filter (axis No. 2) is due to the distance from one of the hexagonal surfaces across the gap to another hexagonal surface. This axis is at an angle to the first one. Another filter (with axis No. 3) lies tilted at the same angle but in the opposite sense. A fourth Ronchi filter may be the result of the periodic structure along each row of bumps.

The Lumens workers are experimenting with filters that produce concentric squares or circles. They have also begun marking their products with a new method of indicating copyright. Within each filter is a hologram that identifies the company and the copyright. Even if the filter is cut into small sections, the copyright information is still contained in each section because the holographic image can be reconstructed from each section. The hologram in the filter does not interfere with the filter's main purpose of acting as a diffraction grating.

More beautiful decorations can be created by placing two filters in a laser beam. For example, I directed my laser beam through both the Christmas-ball filter and a normal Ronchi filter. (The order of the filters does not matter.) The result is a Christmas-ball interference pattern for each of the three brightest spots cast by the normal Ronchi filter. When I substitute the orthogonally crossed Ronchi filters for the single Ronchi filter, the display is even more complex but is less appealing because of the confusion of dots. The optical illusion of a curved three-dimensional surface is lost in the confusion. Another interesting pattern appears when the beam is expanded with a lens and then directed through both the pie-shaped grating and the Christmas-ball one. By rotating the first grating one generates an illusion that swarms of red fireflies are moving on the screen.

During a laser-light show you could move the filters around in the beam of light in order to change the display on the screen. The motion can be accomplished automatically by mounting the filters on a shaft turned by a low-speed motor. The beauty is enhanced further if the speed of the motor (and the direction in which it turns) is controlled by adjusting the voltage with a Variac. With such a control you can vary the rate at which the display changes to coincide with the tempo of the music.



The diffraction pattern cast by a narrow slit

You can make simple and complex Ronchi filters and many other types of filter by photographing large geometric designs. For example, you could draw a series of black stripes on a large sheet of white paper. Put the sheet on the floor and illuminate it with two floodlights whose beams intersect the sheet from opposite sides at an angle of 45 degrees. Photograph the sheet with a 35-millimeter camera aimed downward and triggered with a cable release. If you use slide film, the resulting slide can act as the filter.

Many types of optical-transform filter are described in *Laser Art & Optical Transforms*, by T. Kallard. He points out that drawing the geometric pattern with ink results in stripes that have "soft borders" because of the slight running of the ink. A gradual change in the transmission of light near the borders causes a loss of the greater orders in the interference pattern. If you want the higher-order spots in the display, the borders should have abrupt transitions in transmission. Kallard recommends that you use black tape of the kind sold in art-supply stores. Lay the tape to form whatever pattern you want.

A different kind of interference pattern can be obtained by inserting patterned glass or plastic in the laser beam. I have tried various types of the plastic that is used to cover the recess in which fluorescent lamps are mounted in an office ceiling. All these plastic covers have patterns, but not all the patterns are pleasing in the laser beam. The cover that works best has a surface that looks as though it was sculptured with a putty knife. Other surfaces have hexagonal or semispherical bumps. The surfaces are less interesting when they are merely inserted in the beam, but they yield highly interesting designs when they are slid to and fro across the beam so that the interference pattern constantly changes. Combining the pieces of plastic with one of the diffraction filters can give rise to stunning interference patterns. If either object is mounted on a rotating shaft, the varying pattern can be kaleidoscopic.

A ruffled piece of plastic generates an interference pattern because the light rays are refracted as they pass through the plastic. The different rays in the laser beam pass through different surfaces, each of which is tilted in a slightly different way. The rays therefore travel different lengths inside the plastic and emerge through surfaces of different tilt. The result is that although the rays were initially parallel to one another (or nearly so, depending on the divergence of the laser), they are no longer parallel after they pass through the plastic. The overlapping rays interfere with one another at the screen to create bright and dark lines.

The same effects can be achieved by applying airplane glue or Duco cement to a plate of clear plastic or glass. I distort the glue as it dries, ensuring not only that the surface is rough but also that the glue dries with several small bubbles. The rough surface gives rise to a complicated interference pattern on the screen. The bubbles generate simpler but more pleasing interference patterns consisting of closely spaced dark and bright fringes in a geometric pattern. During a laser show I move a bubble in and out of the beam in order to give motion to the interference pattern on the screen. To achieve any of these interference effects I first have to adjust the distance between the optical components and the screen until images of a suitable size appear on the screen.

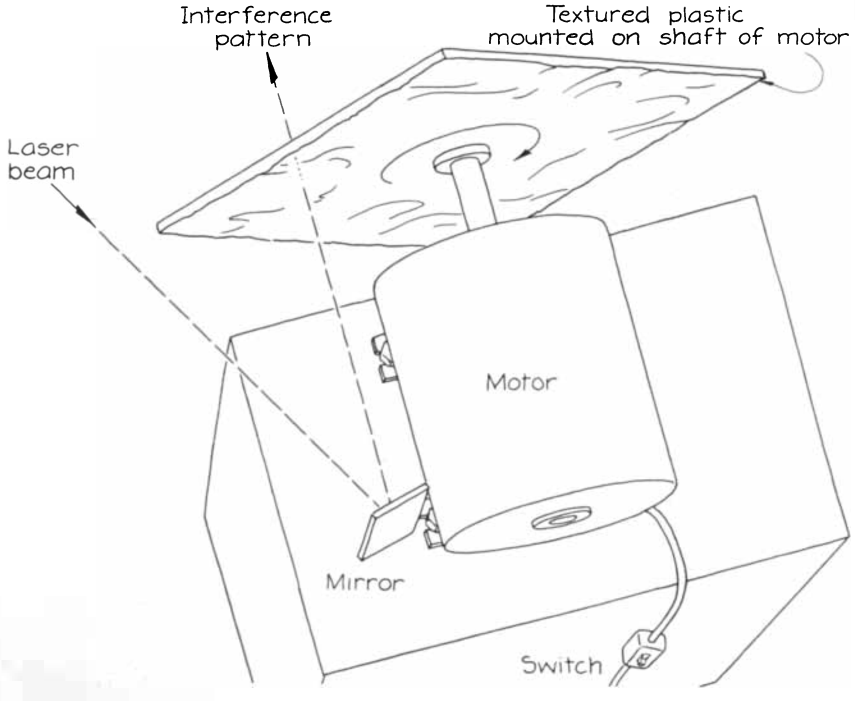
A completely different set of laser images can be created by using loudspeakers into which an audio signal is fed and from which the laser beam is reflected. Ray Laning, a former student of mine, built such a system with two small speakers (the type commonly found in an automobile radio) driven by two audio oscillators. The idea is to have one speaker deflect the laser beam horizontally as the other one deflects it vertically. The combined deflection can create on the screen the complicated patterns called Lissajous figures.

The reflection of the laser beam was achieved by means of a small mirror that Laning mounted on the inside of each speaker. The center of the cone of a speaker is a slightly curved region that oscillates when an audio signal is fed to the speaker. There Laning glued a small piece of Styrofoam that he had shaped to match the slight curvature in the region. The outer surface of the Styrofoam was flat so that he could glue one end of a small, lightweight mirror to it. The other end of the mirror was glued to a portion of the cone about midway between the central region and the rim. Laning used a glue that was somewhat elastic and therefore would not crack or break during the oscillation.

The mount and the mirror had to be light in weight because the additional weight Laning was adding would damp or eliminate the normal oscillations of the cone. When an audio signal was fed into the speaker, the oscillations of the cone forced the mirror to pivot (more or less) around the point where it was glued to the Styrofoam. To increase the amplitude of the oscillations Laning cut symmetrical slits into the cone so that they radiated from the central region out to the edge. The slits allowed more play in the oscillations of the speaker so that when the system was in use in the laser show, it gave larger deflections of the laser beam on the screen.

After Laning had mounted mirrors in both speakers he fastened them to a wood mount in such a way that the plane of each speaker opening formed an angle of about 45 degrees with the horizontal. When the speakers were excited by an audio signal, the bottom mirror oscillated horizontally (that is, around a vertical axis) and the top mirror vertically (around a horizontal axis). A laser beam directed at the bottom mirror was reflected up to the top mirror, which then reflected it to the screen. The alignment of the beam, the mirrors and the final image on the screen took a fair amount of patience.

After alignment the image on the screen was a single spot of light. Laning then connected an audio oscillator to each speaker. Each oscillator produced a sinusoidal electrical signal that caused its speaker to oscillate, thereby moving the mirror in the laser beam. When the bottom mirror was oscillated, the beam was deflected horizontally and therefore moved back and forth across the top mirror and horizontally across the screen. The oscillations of the top mirror in turn caused a vertical oscillation of the beam. The beam was deflected vertically and horizontally simultaneously and moved across the screen accordingly.

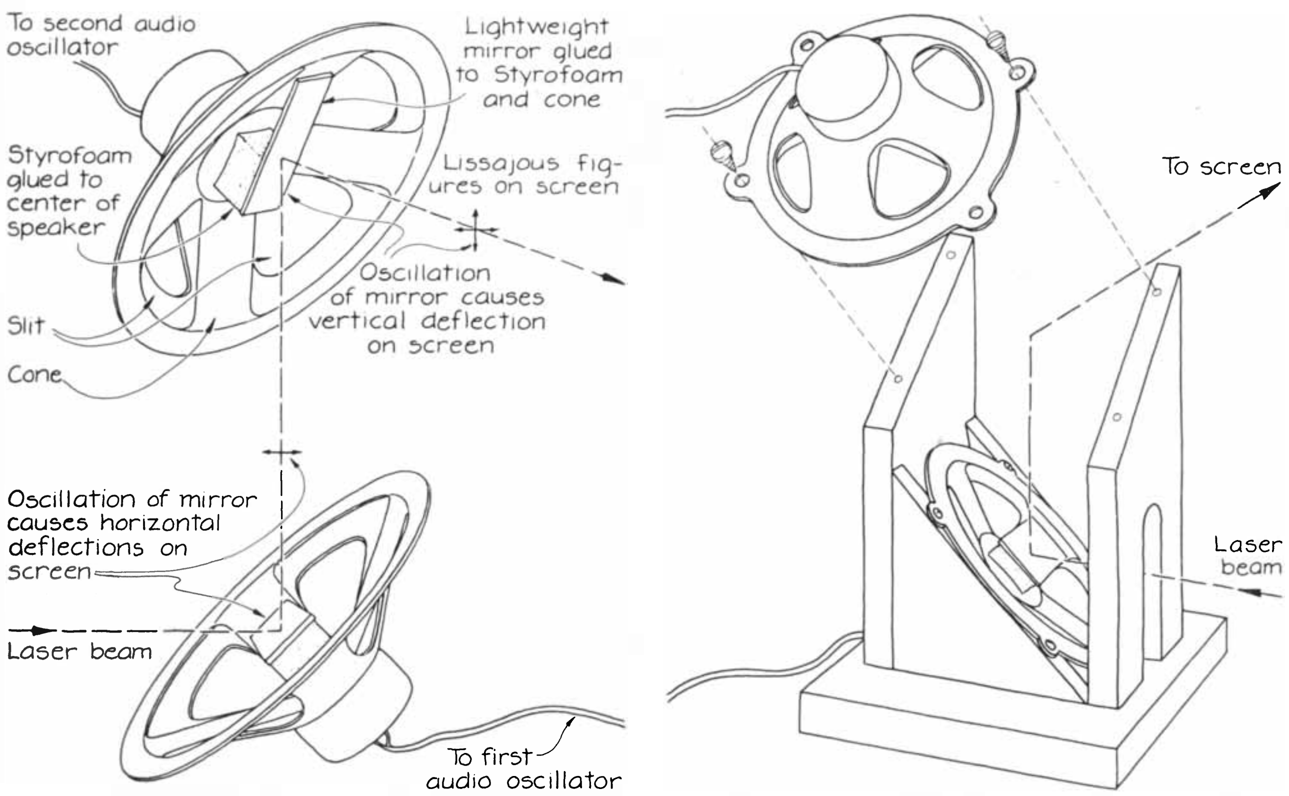


An arrangement for rotating textured plastic in the laser beam

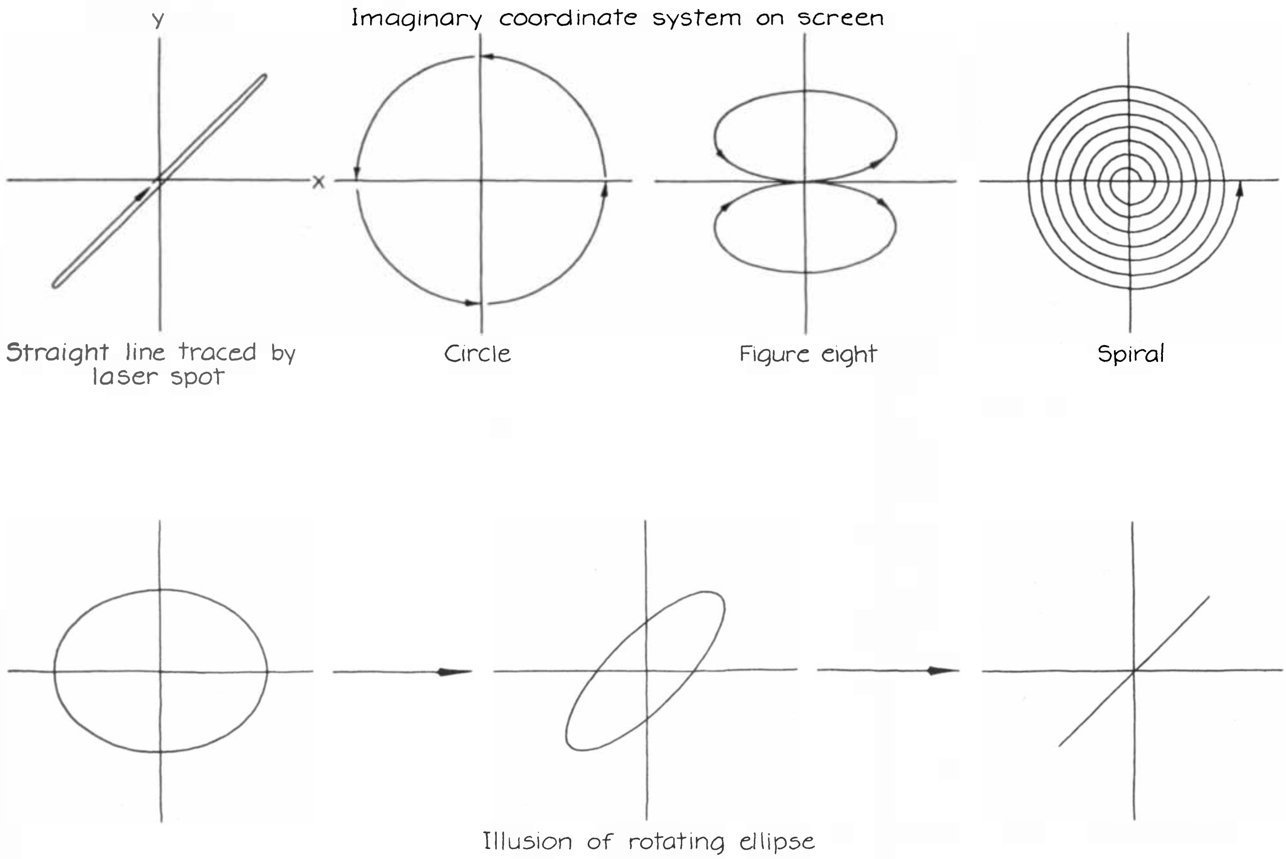
Two mirrors and two audio oscillators were put in the system so that the frequency and amplitude of the two deflections could be controlled independently. For example, suppose the mirrors were oscillated at the same frequency. Several patterns could appear on the screen according to the phase relation of the oscillations. Consider an *x-y* coordinate system superposed on the screen. The center of the coordinate system is the position of the undeflected beam. If the bottom mirror begins to deflect the beam to the right as the top mirror begins to deflect it upward, the beam moves across the screen to the upper right. If the amplitudes of the two deflections are equal, the beam traces on the screen a straight line that forms an angle of 45 degrees with the horizontal. After the deflection is complete the beam retraces the line back through the origin of the coordinate system and continues it to the lower left. As the oscillations continue, the beam traces the same slanted line repeatedly. The pattern of a straight line is not particularly interesting, but it is an example of a simple Lissajous figure. It develops when the oscillations are at the same frequency, have the same amplitude and are in phase (meaning that both signals increase at the same time).

Suppose instead the horizontal deflection of the beam is at a maximum to the right when the vertical deflection is just beginning to send the beam upward. The oscillations are said to be 90 degrees out of phase. As the beam is brought back horizontally it is also being sent upward. When the maximum vertical deflection is reached, the horizontal deflection is zero. What you see on the screen is part of another kind of Lissajous figure; the spot of light traces out a part of a circle, moving from the far right to the uppermost part of the circle. As the oscillations continue, the circle is eventually completed and the tracing begins to repeat the circle. If the oscillations of the mirrors are of low frequency, you can see the spot of light actually trace out the circle. At the frequencies we employed in the light shows the circle was generated so quickly that our persistence of vision gave us the illusion that a completed circle was always on the screen.

Laning could control the amplitude of oscillation of each mirror by adjusting the amplitude controls on the audio os-



***How to set up loudspeakers to generate Lissajous figures* (left)*; the mounting of small speakers* (right)**



Some of the Lissajous figures that can be made with the small-speaker system

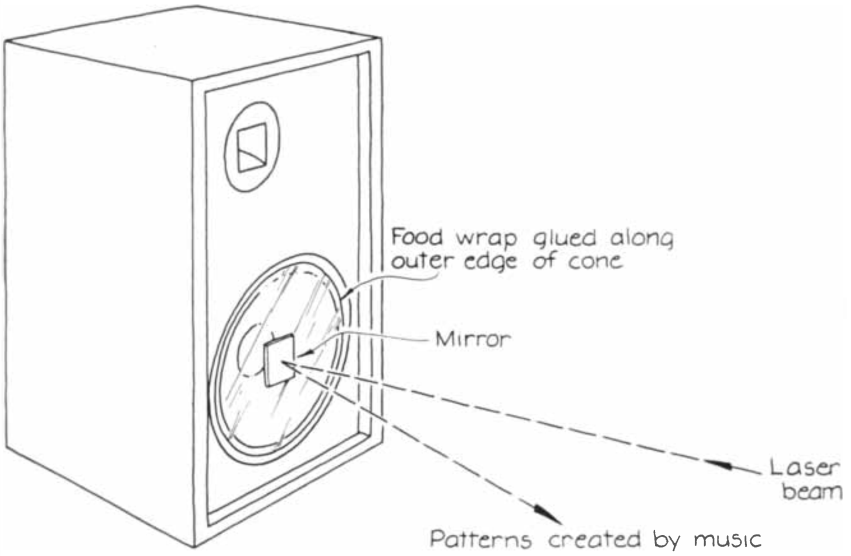
cillators. When he made the amplitude of the horizontal oscillation greater than that of the vertical oscillation, the pattern we saw on the screen was an ellipse with a horizontal long axis. Similarly, he could create an ellipse having its long axis vertical.

Laning could also control the frequencies of the oscillations by adjusting the frequency controls on the audio oscillators. Suppose he gave equal amplitudes to the oscillation of each mirror but made one mirror oscillate twice as often as the other. Suppose further the higher frequency is on the horizontal oscillation and the two sets of oscillations are in phase. Consider the beam as being initially at the origin of the coordinate system. It begins to move both to the right and upward, but because of the difference in frequencies it has reached only half of its maximum vertical deflection by the time it has reached its full horizontal deflection. It continues to move upward but now has begun to move back to the left. By the time its horizontal deflection has again been reduced to zero it is at its maximum vertical deflection. The path it has traced out is part of a figure eight in its proper vertical orientation. The rest of the figure eight is traced out as the oscillations continue. If the mirrors are oscillating fast enough, persistence of vision gives the illusion of a bright red figure eight on the screen. Similarly, a horizontal figure eight can be created by giving the vertical deflection of the beam twice the frequency of the horizontal deflection.

Laning had no way to control the relative phases of the two oscillations. Indeed, the relative phases varied in an unknown way every time he reset the frequencies on the audio oscillators. During the show he therefore varied the frequencies and amplitudes on the audio oscillators until a pleasing pattern appeared on the screen. He could create not only straight lines, circles and figure eights but also more elaborate Lissajous figures. At some adjustments he could create a pattern that slowly changed from a straight line to an ellipse and back again. The changing pattern gave the illusion of a three-dimensional circle revolving slowly on the screen. Sometimes we saw the full circle as if it were slightly tilted out of the plane of the screen. At other times we saw the circle edge on, seemingly perpendicular to the screen.

Laning fiddled with the controls during a show so that he could switch from one illusion to another. When he hit on a circle, he sometimes quickly changed the amplitude on both audio oscillators. We then saw a pattern that rapidly and smoothly switched from a large circle to a small one and back again. I had the impression I was peering into the open end of a large pipe. At slower oscillations, when the persistence of vision was not as dominant, the spot of laser light seemed to map out a spiral that constantly came and went on the screen. Laning could pace the illusion to match the beat of the music.

A direct response of the laser display to the music can be achieved by using a speaker driven by an audio signal from the source of the music for the show. Yoel ran an audio line from my cassette player, which provided the music, to one of his old stereophonic speakers that he had modified. Over the opening of the woofer cone he stretched a sheet of plastic food wrap and glued it to the rim. (This procedure is easier if the cone is pointed upward.) He worked with common white glue because it was sufficient-



A modified speaker

ly strong and stretched the plastic tighter as it dried. During the drying he left a few heavy books on the rim. When the glue was dry, he glued a lightweight mirror directly in the center of the plastic.

When the audio signals from Yoel's cassette player excited the speaker, the pressure variations in the air trapped between the cone and the plastic caused the plastic and the mirror to oscillate. Yoel then caused a laser beam to reflect from the mirror onto the screen. The constantly changing patterns were therefore in response to the music entering the speaker and were not pure Lissajous figures, but the display was pleasing because it was in time with the music the audience was hearing. The main response was to the low frequencies in the music because of the relatively large volume of air that had to be moved in the cone.

Both of these speaker systems require lightweight mirrors, which can be obtained from scientific supply houses. Most mirrors, however, do not reflect very well. If your laser is high-powered, losing some of the light to absorption by the mirror will not matter much. There might still be enough light on the screen for the audience to see. Another problem is that many common mirrors do not give a clean reflection and so add divergence to the laser beam. We bought a mirror of high quality from the Newport Research Corporation (18235 Mount Baldy Circle, Fountain Valley, Calif. 92708) and then had a glass cutter slice it into pieces small enough to be mounted on the speakers.

For the deflection system of Laning's design one could replace both the speakers and the mirrors with galvanometer mounts salvaged from surplus galvanometers. These mounts have a much faster and cleaner response than the speakers and therefore give cleaner patterns on the screen. Commercial laser shows that include drawing or writing with laser beams on a screen use galvanometers. With any design one must be careful not to feed too much signal to the system. In setting up our systems we on several occasions blew off mirrors.

I have mentioned only a few of the laser-art techniques that can be applied in a light show. In another column I shall describe how to make the laser beam visible as it passes over the audience. I shall also describe a variety of other techniques by which to cast interference patterns on the screen. As a final note let me remind you that laser light is dangerous. If you direct a beam toward a screen, you must be careful that no one in the audience can possibly stand up to intercept the beam. You must also take care that the light scattered from the screen is not dangerously bright. Strict Federal regulations apply to the use of lasers in public shows.

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