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THE COVER

The cover painting shows a biologist suspended among the treetops of a tropical rain forest (see "The Canopy of the Tropical Rain Forest," by Donald R. Perry, page 138). He is supported in a parachute harness by a system of ropes rigged 30 meters above the ground. The canopy region of the rain forest, extending from 10 meters above the forest floor to the top of the tallest trees, is biologically its richest zone. In the canopy live a vast number of species that are entirely independent of the ground, among them a host of insects and epiphytic plants. It is also the site of the complex interactions of plants and animals through which the trees and vines of the rain forest are pollinated and their seeds dispersed. The system of ropes, developed by the author in the Costa Rican rain forest, allows free movement through the canopy, once almost inaccessible to investigators, opening its intricate natural history to observation.

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LETTERS

Sirs:

"The Microbial Origin of Fossil Fuels," by Guy Ourisson, Pierre Albrecht and Michel Rohmer [SCIENTIFIC AMERICAN, August], suggests that the new information it provides is further evidence for the biological origin of oil and coal. In fact the opposite is true—the findings described in the article weaken that case.

The article shows that none of these fuels is free from substantial alteration and contamination by bacteria. The authors do not suggest the bacteria provided the bulk of the unoxidized carbon compounds that led to the deposition of oil and coal; instead the usual assumption is made that photosynthesis by plants was the source of the carbon.

It has been proposed that the bulk of the earth's deposits of hydrocarbons originated through abiotic processes, that they represent a "primordial substance to which bio-products have been added" (Sir Robert Robinson, 1964). The bulk chemical composition of most natural hydrocarbons, their distribution on the earth and the modern view of cosmochemistry and planetary formation have all been presented as favoring this point of view.

The discovery of very specific biomolecules in most natural hydrocarbons tipped the balance away from this abiotic theory and toward the biological-origin theory. It was assumed that these molecules derived from the same source as the bulk of the deposits. The possibility that the molecules represented nothing more than biological contamination seems to have been rejected.

The recent article adds important new information: a class of biomolecules in natural hydrocarbons has been shown to derive from bacterial alteration of the bulk source material. Consequently their presence does not weigh against the abiotic theory. All the other identified biomolecules may also be due to bacterial processing and therefore do not give evidence that the bulk source material was of biological origin.

The new findings also lead to other considerations. A widespread early bacterial flora may have arisen when hydrocarbon outgassing of the earth provided a source of chemical energy in the surface layers of the crust where oxygen was abundant owing to the photodissociation of water and the loss of the hydrogen to space. Methane-oxidizing bacteria (and possibly also oxidizers of hydrogen, carbon monoxide and hydrogen sulfide) may have been able to thrive in the crustal rocks. In the course of evolution, photosynthesis, with all its complexity, may well have been preceded as a source of energy by hydrocarbon outgassing. The flora the outgassing sustained gave oil and coal its distinctive biological imprint.

THOMAS GOLD

Center for Radiophysics
and Space Research
Cornell University
Ithaca, N.Y.

Sirs:

Of course, our work cannot *prove* that the abiotic hypothesis for the origin of the bulk of oil and coal is wrong. As far as I know, however, every one of the molecules isolated by us and by others from petroleums, coals or, after proper degradation, from kerogens could have originated in microbes, plants or animals. I know of no compelling evidence to the contrary, and I believe at least *one* obviously abiotic structure must be identified before one can follow Professor Gold's argument.

I know such evidence will be hard to get, in particular since we and others have demonstrated that original molecular structures can be blurred by isomerizations, et cetera, in the sediment. But the discussion demands such evidence, elusive as it may be.

GUY OURISSON

Centre National de la Recherche
Scientifique
Strasbourg, France

Sirs:

Possessing a thorough knowledge both of Oriental languages and of the societies in which they are used, I was interested in the description given by Joseph D. Becker in his article "Multilingual Word Processing" [SCIENTIFIC AMERICAN, July].

Mr. Becker has correctly defined some of the complexities of the Chinese and Japanese scripts, and he advocates Romaji conversion—the use of Roman letters to spell Japanese words—and its equivalent in Chinese as means of man/machine interface for word processing. The procedure appears on the surface to be effective.

It is my opinion, however, that Mr. Becker has failed to appreciate fully the consequences of his statement that most documents prepared in Japan are handwritten before they are typed. The result is that when Romaji conversion is used, the word-processing task does not begin when the operator starts entering characters. Rather, it begins when the operator examines the handwritten page prepared by the document originator. The operator must first understand what is written, mentally convert the written image into sounds, convert those sounds into Romaji characters and then enter those characters using the QWERTY or other type of keyboard. Mr. Becker states that this can be done at speeds about equal to those of a skilled typist using English in an American office.

If the American secretary occasionally makes a typing error, it usually does not destroy the sense of what is being communicated. This, however, is not the case with Romaji conversion, as can be seen from a close look at processing of the word *kurumade,* illustrated in the article. In the illustration things appear to proceed in an orderly fashion, but if the processing speed is in the range of 100 words per minute, the chance for minor typing errors is great. Assume that the operator makes a small error such as substituting *a* for *e* at the end of the word. The letter group no longer refers to traveling by car but rather states that something actually is a car. Consider a further example in which the operator inserts a space between the letter group *kuru* and the letter group *made.* In this case the machine would select a kanji, or character, based on *kuru* rather than *kuruma,* and the meaning would be changed completely.

For the Chinese language, the author uses the word *beijing* to make his point for Romaji conversion. This is one of the simplest cases in Chinese and is therefore misleading as an illustration. Consider the Romaji form *heji,* for example, which has several intonations, each with a grammatically acceptable but quite different meaning. Which case the document originator intended may not be apparent to an operator. Again, typographical errors can change meaning dramatically: striking *l* lnstead of *j* changes the sense from that of a joint attack to a joining of forces.

Many other examples reveal the shortcomings of Romaji conversion. Equally important is the dependence of this and other keyboard-based techniques on programmed grammar. Machines will obey grammar rules faithfully, and up to a point this is good. But people are not so dependable, and jargon abounds in almost every specialized field. The machine with a knowledge of proper grammar can be paralyzed by jargon.

It is my judgment that the ultimate device for processing Chinese and Japanese languages will employ input techniques that avoid the potential for message distortion and that will readily accommodate jargon. Such techniques are currently under study in Beijing.

J. F. LIU

Liu International Corporation
St. Paul, Minn.

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HOW BMW BUILT A PERFORMANCE CAR FOR A GRIDLOCK SOCIETY.

Every morning you set forth onto the open road together with 106,867,107 other cars (not to mention trucks and buses).

Yet pitifully few performance sedans seem to have taken this into account.

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Even more unique is the fact that this is achieved by a luxury sedan whose creature comforts leave little to be desired. And whose assembly occasioned this from AutoWeek, "It's solid and finished extremely well.... Paint so thick you can sink into it. Seams lined up straight and true."

In sum, the BMW 528e is an inspired example of BMW's belief that technology is most appropriately used in the service of performance—even at less than highway speeds. And a natural outgrowth of a racing heritage that began when there was often more traffic on the racecourses than on the surrounding roads.

You're invited to test drive the 528e at your BMW dealer. We suggest you allow yourself plenty of time in case there's traffic.

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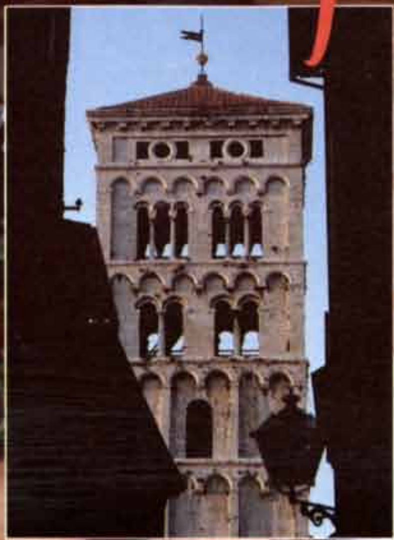
A HERITAGE OF

The Ho

Each holiday season, our family celebrates a heritage of wine and food that is centuries old. It extends far beyond our 80 years in California's beautiful Sonoma Valley to Farneta, Italy. This small, 12th century village near Lucca, is the birthplace of my grandfather, Samuele.

My wife Vicki and I recently discovered the great beauty of Lucca's art and architecture, and while exploring the dozens of markets and restaurants we rediscovered the absolute naturalness with which wine and food should be enjoyed together. Though this ancient city has renewed itself over the years, it has done so without destruction of the past, preserving the history and culture of the town.

It is this same continuity of heritage that is the heart of our family winery. Since my grandfather founded Sebastiani Vineyards in 1904, wine styles have changed with changing tastes. But as we have grown and come to produce wines of even greater elegance and complexity, our original vision



Sam and Vicki Sebastiani shopping and sharing the holidays with friends in the ancient Italian city of Lucca.

For your free Holiday menu, write: Sebastiani Vineyards, Dept. 10 P.O. Box AA, Sonoma, CA 95476

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From my family to your family . . . Buon Natale!

Sam J. Sebastiani

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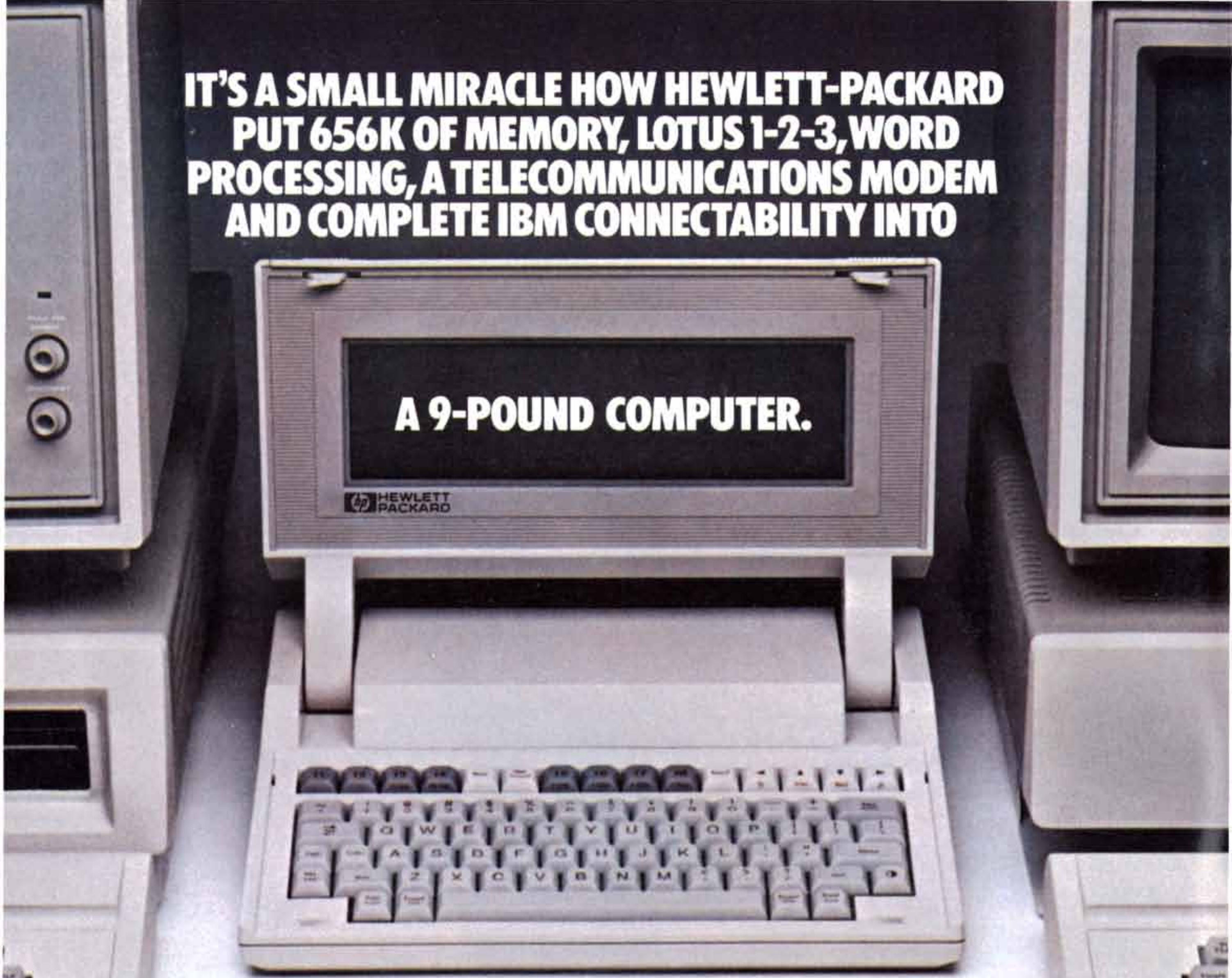

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

NOVEMBER, 1934: "Scanning disk or cathode-ray tube? This seems to be the burning question in television experimental work today. The scanning disk is being marvelously improved; the cathode-ray tube is proving to have many 'bugs' difficult to overcome. Still the public has not been offered a real opportunity to 'play around' with television. When will they have this chance, and what form will the equipment take?"

"A forerunner of what may be tomorrow's home entertainment was demonstrated in the laboratories of the Peck Television Corporation in New York, when scenes from current newsreels flashed across a television screen. William Hoyt Peck, president and chief engineer of the company, has devised a new type of film scanner, built entirely without gears and using two automobile headlight bulbs as its only sources of light to actuate the photoelectric cells for both the sight and the sound channels. Sixty-line images were seen during the demonstration. Although a great amount of detail is not expected in pictures using this number of lines, observers were able to see the swing of baseball bats even in long shots of the diamond, to watch the motion of hockey sticks as players skimmed over the field of ice, to read the numbers on racing horses and to recognize Samuel Insull, Premier Mussolini and Eddie Cantor."

"Synthetic vitamin C can now be manufactured on a commercial scale. Discovered some months ago, the process for this (the first chemical synthesis of any vitamin) has been so elaborated and improved upon that actual production of vitamin C on a large scale has been achieved. Announcement of this discovery was made by Albert Szent-György, distinguished Hungarian scientist, to a meeting of the British Association for the Advancement of Science."

"Henry Ford once stated that flying was now 90 percent pilot and 10 percent airplane and that until these figures were reversed it could have but a limited scope. This view is reinforced by the fact that more than 50 percent of accidents in private flying are charged to errors on the part of the pilot. The Air Commerce Bureau believes it is now possible to produce airplanes which will bring flying much closer to 90 percent airplane and 10 percent pilot. A first step in its safety program has already been taken by calling for bids on the production of 25 airplanes for the use of the Department of Commerce, to meet specifications which demand unusually safe and easy operation. The Bureau is in hopes that this competition will bring forth an airplane which can be handled successfully by a pilot trained in a fraction of the time now required."

"A new electric motor-driven ice cream freezer which fits into the freezing or ice-cube compartment of an automatic refrigerator has just been announced. Ever since the introduction of the automatic refrigerator there has been a demand in the homes for such an idea, and various manufacturers have spent a great deal of time and money endeavoring to perfect such a device."

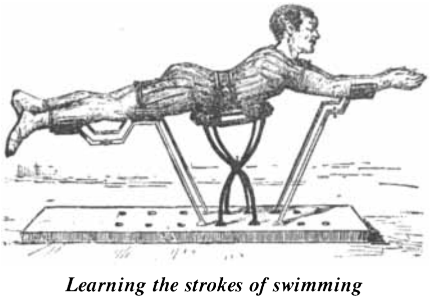
SCIENTIFIC AMERICAN

NOVEMBER, 1884: "The microscope has revealed the existence of innumerable animalcules in the least drop of water taken from any spot whatever on the surface of the ocean, and, in the very place where it was believed that there could be nothing but inert matter, the presence of life has been discovered in its completest development. It is the same with the atmosphere. The microscope shows us to-day a whole world suspended, unbeknown to us, amid the dust that is continuously floating about. We find in the least volume of air collected near the earth infinitely small animalcules, which live, feed, develop and reproduce themselves, and germs of fermentation and putrefaction—those noxious organisms in which Mr. Pasteur has found the cause of so many maladies that afflict humanity."

"The hundred-and-one methods of endeavoring to obtain artistic results in coloring photographs without the possession of artistic skill seem to depend on similar principles; and putting aside the general fact that a colored photograph is almost of necessity very imperfect, fairly satisfactory results may be obtained, by the method termed canvasine. The photograph supplies the outlines, and the impression is not obliterated by the introduction of color, as paints are so prepared that they amalgamate with the chemicals used in producing the photograph, and sink into, and become incorporated with, the paper. The system consists of laying on coats of color and wiping them off before more than a tint has become absorbed. The only art the student has to acquire is the art of patiently laying on successive washes of color and wiping them away until the tint that has sunk in is a soft, natural coloring."

"The average price of regular wheat for the year 1883 was $\$1.01\frac{3}{4}$ per bushel. The average price for the last eighteen years was $\$1.04\frac{1}{2}$. The average price for the last two months has been about 75 cents. How much has this reduction of more than 25 per cent. benefited the consumer? Is a loaf of bread any bigger, or any better, or any cheaper than it was a year ago? Some of the first-class bakeries have added two ounces to the weight of each loaf, some of the bakeries have added one ounce, and some just give the same sized loaf as before, claiming that the difference is too little to allow of their making any change. A barrel of flour will make 320 thirteen-ounce loaves, 297 fourteen-ounce, 277 fifteen-ounce, 260 sixteen-ounce, or 231 eighteen-ounce. A reduction of 60 to 70 cents per barrel will allow the baker to add one ounce to his loaves and still have the same profit. Last year the common bread, retailed at five cents per loaf, and sold wholesale at four cents, was made in fourteen-ounce loaves."

"Natation is locomotion in water. To go, to come, to evolute in water, is a gift of nature to some animals. Does man enjoy the same privilege? It has been said so, but observation does not confirm the assertion. Swimming has to be learned; it is an art. The methodical teaching of natation comprises two orders of exercises: (1) the elementary motions out of water, and (2) the evolutions in water. The importance of the first of these has struck all those who have seriously occupied themselves with the question. An apparatus due to the inventive genius of Messrs. Petit and Dumoutier seems to permit of exercising out of water without fear of fatigue and oppression. This apparatus consists of a strong plank that receives a support for the body, and two for the arms and two for the legs. The fore-arms rest upon two pivoted uprights that allow the arms to describe an entire circle. The legs rest upon two other uprights that are doubly jointed, and that not only allow these organs to execute the three phases of the motion assigned to them, but also cause these phases to be executed in an absolutely correct manner."



Learning the strokes of swimming

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THE AUTHORS

LEON M. LEDERMAN ("The Value of Fundamental Science") is director of the Fermi National Accelerator Laboratory (Fermilab) in Batavia, Ill., and professor of physics at Columbia University. He is a graduate of the City College of New York, where he received his B.S. in 1943, and Columbia, which granted him an A.M. in 1948 and a Ph.D. in 1951. He has taught at Columbia since 1951, and from 1962 until 1979, when he took up his post at Fermilab, he was director of Columbia's Nevis Laboratories. From 1948 until 1978 he was actively engaged in high-energy-physics research at Nevis, the Lawrence Berkeley Laboratory, the Brookhaven National Laboratory, the European laboratory for particle physics (CERN) in Geneva and Fermilab. Among his many research achievements are the discovery of the long-lived neutral *K* meson, the upsilon particle and the bottom quark. Referring to physics in recent decades, Lederman writes: "This is the age of quarks and leptons, a synthesis in the making of data from all the world's laboratories over the past 3,000 years."

HARM J. HABING AND GERRY NEUGEBAUER ("The Infrared Sky") write as representatives of the *Infrared Astronomical Satellite* (*IRAS*) Science Working Group, of which they are joint chairmen; they emphasize that the discoveries reported in their article were made by a great many investigators, most of them members of the Working Group. Habing is professor of astrophysics at the University of Leiden. He was educated at the University of Groningen and spent several years at the University of Colorado at Boulder and the University of California at Berkeley. Neugebauer is professor of physics at the California Institute of Technology and is director of the Mount Wilson and Las Campanas Observatories. A graduate of Cornell University and Caltech, he took part in the first infrared survey of the sky at a wavelength of two micrometers and has done infrared radiometric research on unmanned space missions beginning with the 1962 *Mariner 2* probe of Venus.

MICHAEL S. BROWN AND JOSEPH L. GOLDSTEIN ("How LDL Receptors Influence Cholesterol and Atherosclerosis") are both professors of medicine and genetics at the University of Texas Health Science Center at Dallas, where Brown is also director of the Center for Genetic Disease and Goldstein is chairman of the department of molecular genetics. Brown got his M.D. from the University of Pennsylvania School of Medicine in 1966. He did his internship and residency at the Massachusetts General Hospital in Boston, then began several years of research at the National Institute of Arthritis and Metabolic Diseases and the National Heart Institute's laboratory of biochemistry. In 1971 Brown joined the University of Texas faculty. Goldstein is a 1966 graduate of the University of Texas Southwestern Medical School. He completed his medical training at the Massachusetts General Hospital and spent four years doing research on molecular genetics, first in the National Heart Institute's laboratory of biochemical genetics and then at the division of medical genetics at the University of Washington School of Medicine in Seattle. He moved to the University of Texas in 1972. The two published their first paper together in 1973; since then their collaboration has brought them many awards, including, in 1981, the New York Academy of Sciences Award in Biological and Medical Sciences.

SAMUEL A. MATZ ("Modern Baking Technology") is an expert on food technology who works as a consultant to food and pharmaceutical companies on nutrition, product development and regulatory matters. He studied at Evansville University, Kansas State University and the University of California at Davis, where he earned a Ph.D. in agricultural chemistry in 1958. He has held numerous technical and managerial positions, most recently that of vice-president for research, development and regulatory affairs at Ovaltine Products, Inc., a beverage-mix and snack-food division of the Swiss company Sandoz, A.G. Matz holds 12 U.S. patents on food products and has published eight books, including *Bakery Technology and Engineering.*

DONALD R. PERRY ("The Canopy of the Tropical Rain Forest") is a pollination biologist with a long-standing interest in the biology of tropical treetop communities. His B.A. and M.S. degrees are from California State University at Northridge, and he received his Ph.D. from the University of California at Los Angeles in 1983. He is an avid photographer of tropical life and writes: "The medium will be an invaluable source of information for future researchers, particularly if these ecosystems become extinct." Perry is currently working on a heavily illustrated popular volume on the rain-forest canopy, to be published by Simon and Schuster.

W. T. TSANG ("The C^3 Laser") is a member of the Semiconductor Electronics Research Department at AT&T Bell Laboratories in Murray Hill, N.J. A native of China, he went to the Georgia Institute of Technology as an undergraduate and received a master's (1973) and a doctorate (1976) in electrical engineering from the University of California at Berkeley. He joined Bell Laboratories in 1976; since then he has investigated semiconductor injection lasers and molecular-beam epitaxy of III-V compounds and has developed a number of electronic and photonic devices. In 1982 Tsang was awarded the Adolph Lomb Medal of the Optical Society of America.

MIKHAIL I. GLADKIH, NINELJ L. KORNIETZ and OLGA SOFFER ("Mammoth-Bone Dwellings on the Russian Plain") have worked together on excavations of Upper Paleolithic sites in the U.S.S.R., Kornietz as a paleontologist and her colleagues as archaeologists. Gladkih, currently associate professor of archaeology at Kiev State University, was granted his doctorate by the Institute of Archaeology (Leningrad division) in 1973; he specializes in the analysis and typology of stone tools. Kornietz is head of the department of paleontology at the Institute of Zoology in Kiev. She earned her doctorate in 1962 for an investigation of the extinction of mammoths in the Ukraine, and she has excavated sites containing the remains of animals throughout the central Russian plain. Soffer teaches archaeology at the University of Wisconsin at Milwaukee. She was educated at Hunter College and at the City University of New York, where in February she received her Ph.D. Her dissertation, on cultural change among Upper Paleolithic peoples of the central Russian plain, was the product of 19 months of field work in the U.S.S.R. during the years 1977 to 1983.

ROBERT MARK and WILLIAM W. CLARK ("Gothic Structural Experimentation") are respectively professor of civil engineering and architecture at Princeton University and associate professor of art at Queens College of the City University of New York. Mark studied civil engineering as an undergraduate at the City College of New York; after his graduation in 1952 he worked as a stress analyst in the nuclear-power division of Combustion Engineering, Inc. He joined the Princeton faculty in 1957 as a research engineer and since then has applied techniques of engineering analysis to historic structures ranging from the churches of Christopher Wren to the public buildings of imperial Rome. Clark earned his doctorate from Columbia University in 1970. His recent work has focused on the development of the Gothic style and its relation to the earlier Romanesque of England and northern France.

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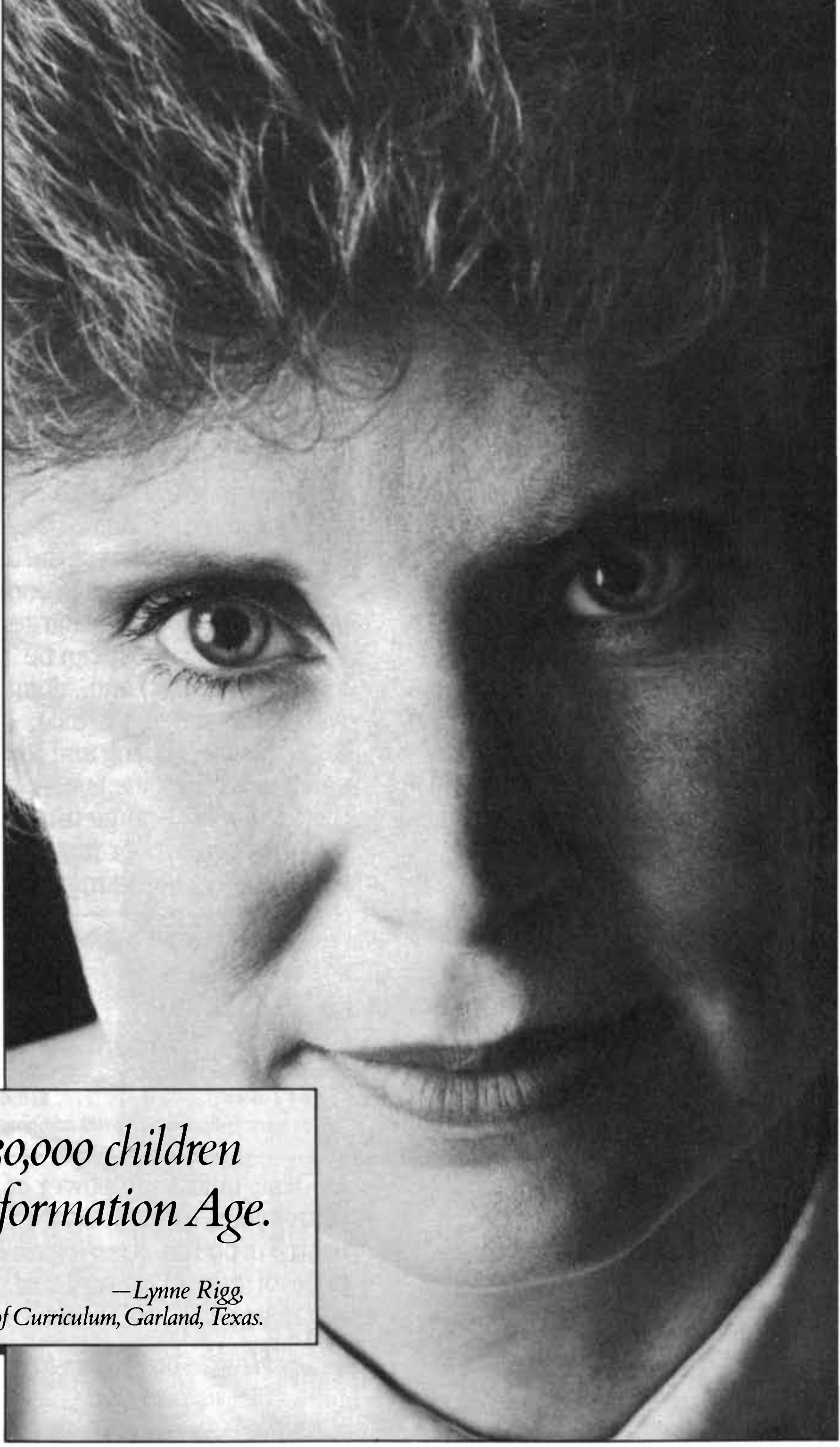

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COMPUTER RECREATIONS

Yin and yang: recursion and iteration, the Tower of Hanoi and the Chinese rings

by A. K. Dewdney

Good puzzles provide an excellent way to log in to the realm of abstract thought inhabited by mathematicians and other theorists. The best puzzles embody themes from this realm; the significance of such themes extends considerably beyond the puzzles themselves.

Two classic puzzles, the Tower of Hanoi and the Chinese rings, suggest two pairs of contrasting themes: recursion and iteration, unity and diversity. Apart from such serious considerations, the puzzles are fun and also provide the neophyte with a satisfying sense of confusion, hallmark of his or her slow entry into the realm of abstract thought.

The tower puzzle consists of three vertical pegs set in a board. A number of disks, graded in size, are initially stacked on one of the pegs so that the smallest disk is uppermost. The disks are manipulated according to these simple rules:

1. Move one disk at a time from one peg to another.

2. No disk may be placed on top of a smaller disk.

The smallest disk must be moved first since it is the only one that is initially accessible [*see illustration below*]. On the next turn there are two moves for the smallest disk (both pointless) and one move for the second-smallest disk. It goes onto the unoccupied peg since it cannot be placed on top of the smallest disk (rule 2). On the third turn it is not quite so obvious what to do: should the second disk be returned to the initial peg or should the first disk be moved again—and if so, onto what peg?

From this point on one is faced with a long succession of moves and with many opportunities for wrong choices. Even if all the right choices are made, $2^n - 1$ moves are needed (as we shall see below) to relocate a tower of n disks, one at a time, onto another peg. The surprisingly long time required to solve a puzzle made up of even a moderate number of disks is well illustrated by the following tale quoted from W. W. Rouse Ball's classic puzzle book, *Mathematical Recreations and Essays:*

"In the great temple of Benares... beneath the dome which marks the centre of the world, rests a brass plate in which are fixed three diamond needles, each a cubit high and as thick as the body of a bee. On one of these needles, at the creation, God placed sixty-four discs of pure gold, the largest disc resting on the brass plate, and the others getting smaller and smaller up to the top one. This is the Tower of Bramah. Day and night unceasingly the priests transfer the discs from one diamond needle to another according to the fixed and immutable laws of Bramah, which require that the priest on duty must not move more than one disc at a time and that he must place this disc on a needle so that there is no smaller disc below it. When the sixty-four discs shall have been thus transferred from the needle on which at the creation God placed them to one of the other needles, tower, temple, and Brahmins alike will crumble into dust, and with a thunderclap the world will vanish."

That the world has not yet vanished attests to the extreme length of time it takes to solve the puzzle: even if the priests move one disk every second, it would take more than 500 billion years to relocate the initial tower of 64 disks!

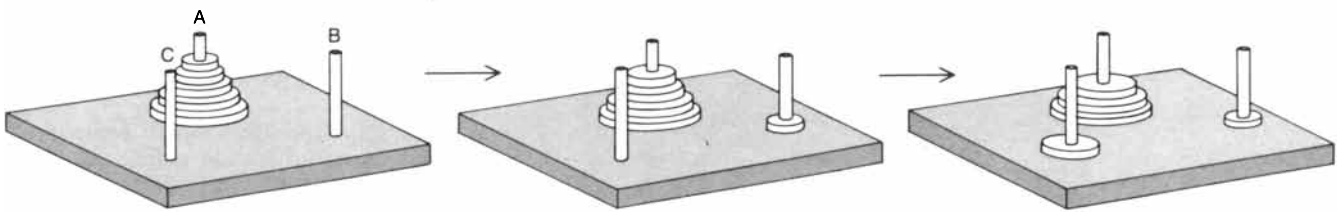
At this point (and at no risk to the universe) the reader can involve himself or herself more directly by picking up five playing cards, for example the ace through five of hearts, and visualizing three spots on a table. Stack the cards on one of the spots, in order, so that the ace is on top. It is now possible to attempt a solution to the five-disk tower puzzle by moving one card at a time between two spots—but never place a card on one of lower value. Can you complete the relocation of the five-card tower before the end of the world? According to the formula $2^5 - 1$, the transfer should be possible in 31 moves.

How does one solve a puzzle such as this? Why is it that some people seem to find it easy to solve puzzles while others must struggle? My answer to the second question suggests an answer to the first one: I am convinced that everyone uses mathematical thinking at almost every moment of conscious existence. Both our conclusions about why Uncle Harry did not show up for the wedding and our plan for packing bags into the trunk of the car are logically derived from certain premises. Such deductions can be very sophisticated, a fact leading me to believe that almost anyone capable of such intuitive prowess could become a good analytic thinker. The trick is to bring the intuitive analytic abilities to the level of conscious awareness so that they can be utilized in a formal way.

For example, after one has played with the five-disk tower puzzle for a while, it will almost certainly be noticed that smaller towers tend to appear from time to time. One encounters two-disk towers fairly often, sometimes three-disk towers and perhaps even a four-disk tower. All of this may happen even while one has no clear idea of a solution. One is merely playing.

Soon enough, however, a key idea presents itself for conscious inspection: "If one can make a two-disk tower or a three-disk tower (let alone a tower of four disks), why not a five-disk tower?" Spotting certain regularities in the way these smaller towers are formed, one is led, more or less quickly, to the pattern of moves yielding a five-disk tower on one of the other pegs.

A similar idea occurs throughout mathematics and computer science as a problem-solving technique. Stated as a principle, it might go something like



The first two moves in the Tower of Hanoi puzzle

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this: "If I can solve the problem in a somewhat smaller instance than the one I am faced with, perhaps I can use such a solution in the larger instance." This is the notion of recursion—the inclusion in a procedure of the procedure itself.

The idea of recursion, applied to the tower puzzle, is quite explicit. If we can solve a tower puzzle for $n - 1$ disks, then we can surely solve one for n disks. The essential clue for developing an n-disk solution from an $(n - 1)$-disk solution comes from the solution of the two-disk version. Suppose two disks—the top, or first, disk and the bottom, or second, disk—are to be moved to another peg. Call the peg they currently occupy the source peg, call the peg they will finally occupy the target peg and call the remaining peg the spare peg. If we move the first disk to the spare peg and the second disk to the target peg, then on the third move the first disk is placed on the target peg, completing the solution. These three moves become the basis for a three-part recursive solution of the puzzle in which the first disk is mentally replaced with an entire tower consisting of $n - 1$ disks and the second disk is replaced with the nth (and largest) disk. The three stages can be presented in this manner:

1. Transfer the tower of $n - 1$ disks from the source peg to the spare peg.
2. Move the nth disk from the source peg to the target peg.
3. Transfer the $(n - 1)$-disk tower again, this time from the spare peg to the target peg.

This three-part recipe merely imitates our solution of the two-disk puzzle. Assuming, of course, that we can solve the $(n - 1)$-disk puzzle, we use the solution sequence of moves to transfer the tower of $n - 1$ disks from the source peg to the spare peg. In the next stage the nth disk has been relieved of its burden and we can move it to the target peg. In the third stage we reapply our solution in the case of $n - 1$ disks to transfer them from the spare peg to the target peg.

How do we solve the tower puzzle when it consists of $(n - 1)$-disks? The answer is staring us in the face: Repeat the same procedure, but this time replace the term $n - 1$ in stages 1 and 3 by $n - 2$, and so on. Eventually we arrive at a point where stages 1 and 3 require the transfer of a single disk.

This solution process, with its mercilessly propagating branches and subbranches, is very confusing for a human to use, but it does make clear why the solution has nearly 2^n steps: each time the procedure is used it repeats itself twice more. Even if humans find it difficult to implement such a solution process, computers do not.

The illustration on this page gives part of the solution for a five-disk tower. Three stages are shown as procedures within a larger procedure called TOWER $(n, X \rightarrow Y)$. This procedure uses three elements of information: n, the number of disks to be moved; X, the source peg, and Y, the target peg.

As the terminology suggests, the essential framework of a recursive program for the tower puzzle can be written algorithmically as follows:

TOWER (n, *source* → *target*):
 TOWER ($n - 1$, source → spare)
 MOVE (n, source → target)
 TOWER ($n - 1$, spare → target)

Suppose we wish to move five disks from peg A (the source) to peg B (the target). If we replace n by 5, source by A, target by B and spare by C, then the above procedure becomes

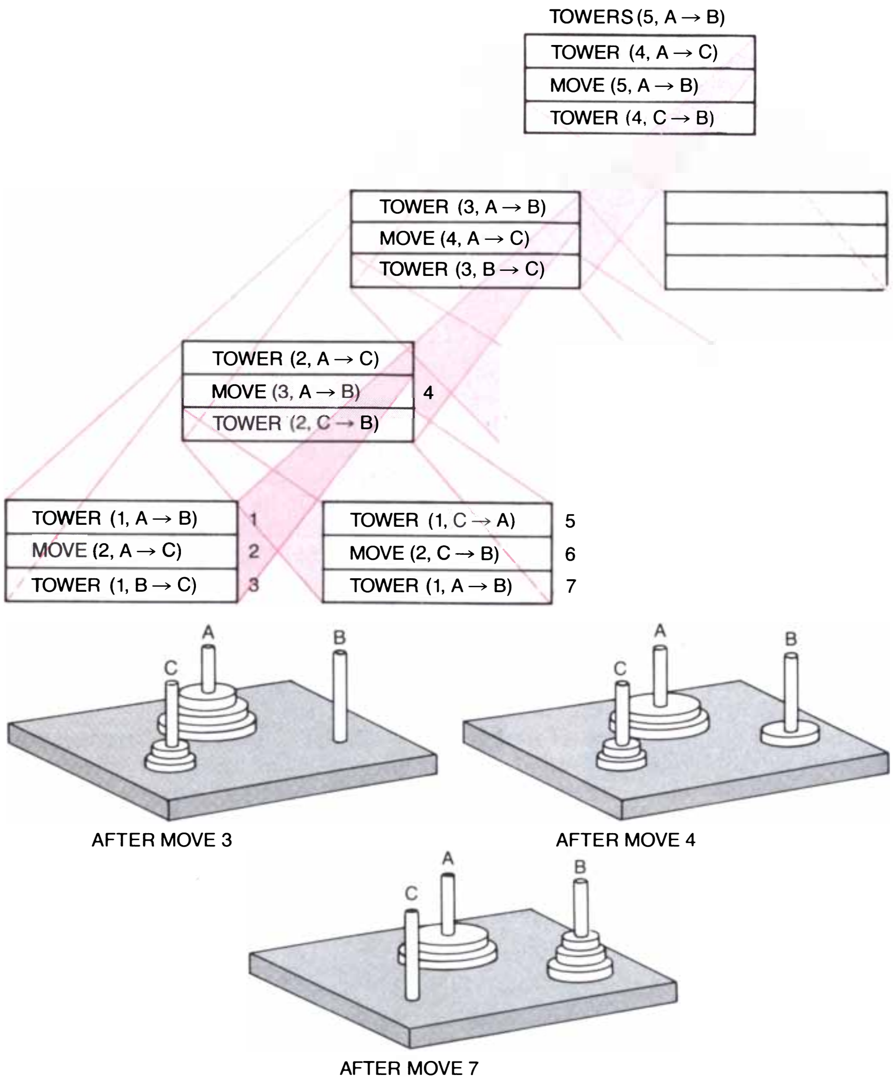
TOWER (5, A → B):
 TOWER (4, $A \rightarrow C$)
 MOVE (5, $A \rightarrow B$)
 TOWER (4, $C \rightarrow B$)

In other words, the program must first succeed in moving the first four disks from peg A to peg C. It records the fact that when this procedure is complete, it must next execute MOVE (5, $A \rightarrow B$), that is, move the fifth and largest disk from peg A to peg B. It also records yet another execution of the procedure TOWER, this time to move the first four disks from peg C to peg B.

Each invocation of the TOWER procedure results in three more procedures being invoked: TOWER, then MOVE and then TOWER again. The MOVE procedure cannot be executed until the first TOWER procedure has been completed. This means that the actual order in which the computer does things is to execute TOWER four successive times, working its way down the left side of the diagram until it encounters

 TOWER (1, $A \rightarrow B$)
 MOVE (2, $A \rightarrow C$)
 TOWER (1, $B \rightarrow C$)

An actual program would contain an additional instruction telling the computer that when only one disk is the object of TOWER, it is moved directly without any further recursions: specifi-



Recursive solution of the Tower of Hanoi puzzle

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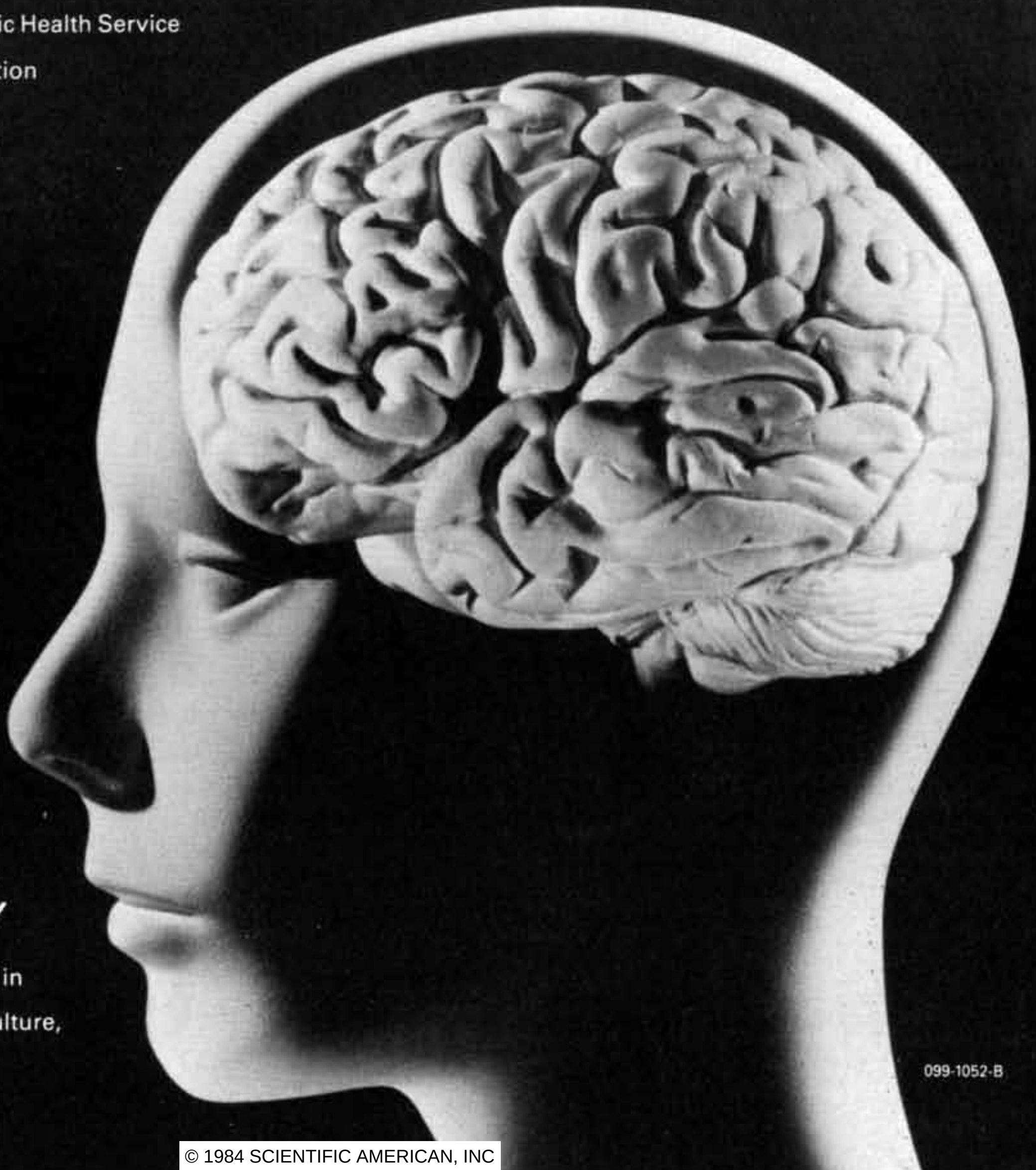

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cally, the first disk is moved from peg *A* to peg *B*. The MOVE procedure then causes the second disk to be moved from peg *A* to peg *C*. Finally, the computer moves the first disk again, now from peg *B* to peg *C*, completing the third move.

At this point the computer has also completed the first TOWER procedure in the next-to-bottom box in the illustration on page 20. Naturally it then executes MOVE (3, $A \rightarrow B$), immediately moving the third disk from peg *A* to peg *B*. Next the instruction TOWER (2, $C \rightarrow B$) is expanded into the three moves carried out in the box at the bottom of the illustration.

The seven moves thus carried out also complete the execution of the first invocation of TOWER on the second level of the diagram, and the computer continues to follow the same pattern, sometimes racing down to a low-level box and sometimes backtracking to a higher level. Eventually it succeeds in working its way through the entire diagram and the puzzle has been solved.

Recursion often seems magical because all the bookkeeping needed to remember "where one is" has been carried out by the computer; people are not much good at such large memory tasks. Fortunately a technique requiring little memory is available. Four years ago a simple pattern of moves was found by Peter Buneman of the University of Pennsylvania and Leon Levy of AT&T Bell Laboratories. Buneman and Levy suggest a simple alternation between two kinds of move:

1. Move the smallest disk from its present peg to the next peg in clockwise order.
2. Move any disk but the smallest.

The second step is not as arbitrary as it seems: there is always only one legal move to make under this restriction—until the puzzle is suddenly solved.

Recently I made an eight-disk tower puzzle out of wood and let a friend play with it for a while. He got nowhere and left the room momentarily. Hurriedly, I explained the Buneman-Levy solution to his eight-year-old daughter, who had been looking on with fascination. When my friend returned, he gaped at the sight of his daughter calmly and without hesitation transferring disks from peg to peg. She completed the solution in a few minutes. "That's some kid you have there," I said.

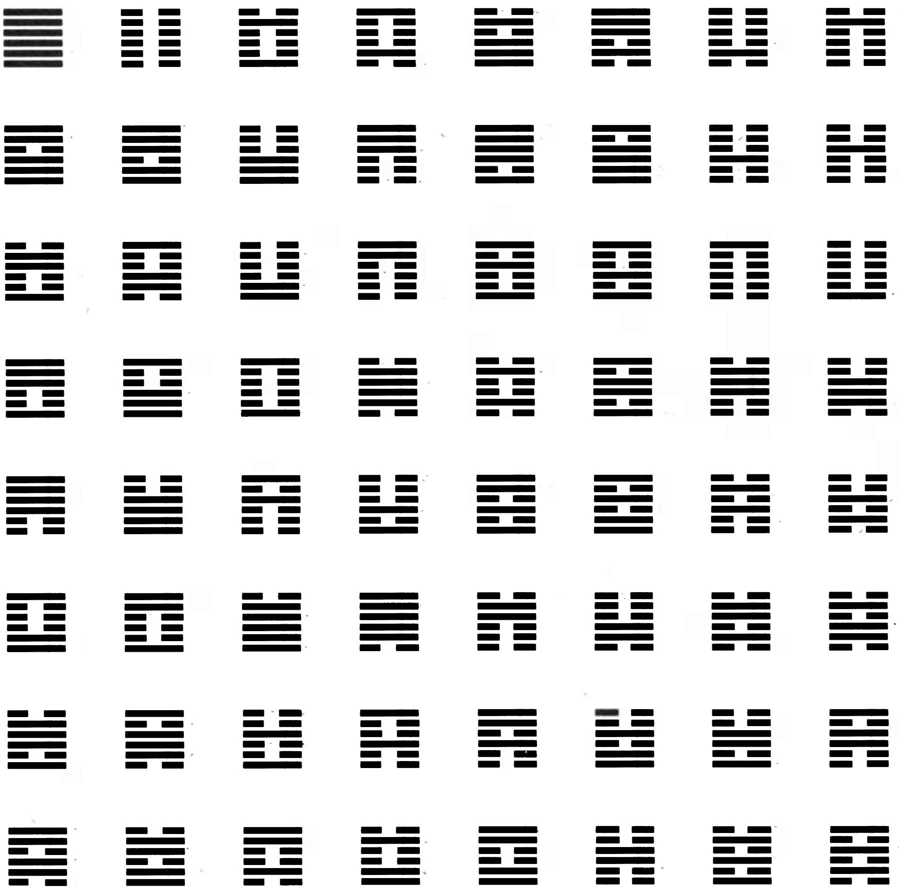
The point of the Buneman-Levy solution is that recursion is not really needed for solving the tower puzzle; a simple iterative solution suffices. An iterative program is one that carries out a repetitive task by means of a simple loop rather than through a succession of recursions. Although recursive programs have the special charms of brevity and elegance, they require large amounts of storage. For example, it is obvious from the illustration of the recursive solution of the tower puzzle that much memory is needed to save all the incomplete executions of TOWER. The kind of iterative program based on the Buneman-Levy solution algorithm requires almost no memory at all. Rarely, however, can one replace a recursive program by an iterative one in this manner.

Recursion and iteration form one of the many polarities of computing, a kind of yin and yang in the approach to repetitive processing. The yin and yang symbols represented the complementary duality central to major philosophical traditions of prerevolutionary China. The two principles form the basis of the *I Ching* ("Book of Changes"). Yin and yang are like the binary numbers 0 and 1, which are fundamental to digital computing. In the *I Ching* yin is represented by a broken horizontal line (– –) and yang by an unbroken one (—). Together these symbols are grouped into sets of six, making up 64 hexagrams [*see illustration on this page*]. Properly interpreted, each hexagram represents a special choice. The believer draws yarrow straws to determine which hexagram is relevant to his or her life. The arrangement shown is ascribed to King Wen, who ruled in 1150 B.C. (The reasons for this ordering of hexagrams are obscured by time. I would be indebted to any reader who can provide the key to this mysterious arrangement.)

Having mentioned binary numbers, I am reminded of yet another way to solve the Tower of Hanoi puzzle. If one numbers the disks 1, 2, 3,... up to *n* in the usual manner from smallest to largest, it turns out that each move in the puzzle's solution is indicated by a binary number. For example, to solve the five-disk puzzle here for illustrative purposes, we would list the five-bit binary numbers in the usual order of counting. The first nine five-bit binary numbers are

0 0 0 0 0	
0 0 0 0 1	(1)
0 0 0 1 0	(2)
0 0 0 1 1	(1)
0 0 1 0 0	(3)
0 0 1 0 1	(1)
0 0 1 1 0	(2)
0 0 1 1 1	(1)
0 1 0 0 0	(4)

Each binary number that has a predecessor in the sequence also has exactly one bit that has just changed from a 0 to a 1. The position of this bit (counting from the right) is given by the decimal number written beside the binary one. These numbers are also the numbers of the first seven disks moved; the correspondence holds throughout the standard solution sequence. Armed only with any one binary number in the sequence, Timothy R. S. Walsh of my de-



King Wen's arrangement of the 64 hexagrams of the I Ching

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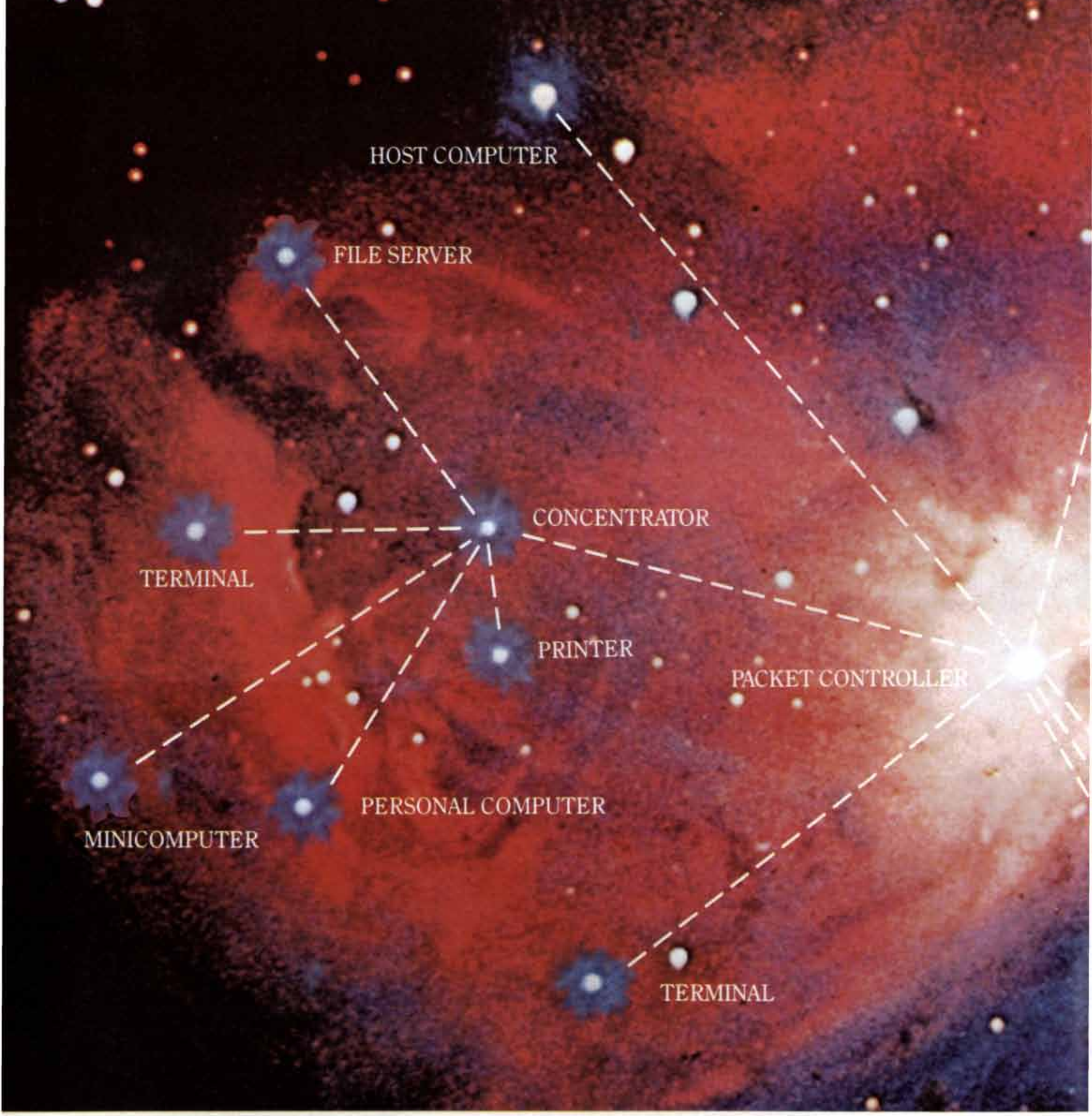

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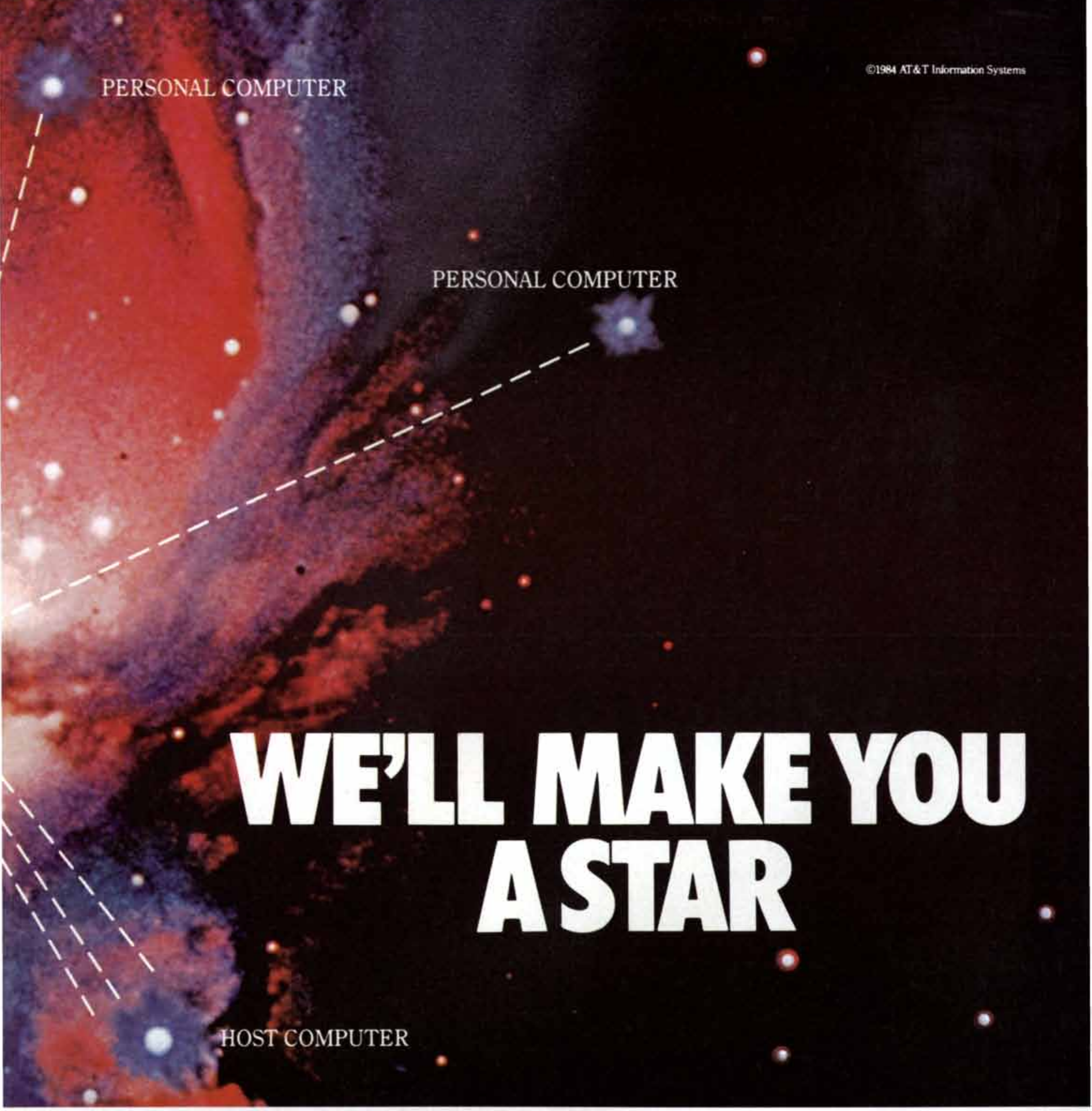

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partment at the University of Western Ontario can reconstruct by computer the exact appearance of the tower puzzle at that stage. Unfortunately his algorithm is too long to include here.

Mention of yin and yang serves to introduce the Chinese rings [*see illustration on this page*]. This puzzle consists of a long wire loop set in a handle with a series of rings encircling the loop. Each ring is linked loosely by a metal post to a wood platform below the loop. The post connecting each ring to the platform passes through the ring behind (closer to the handle), preventing its removal from the loop.

The goal is to remove all the rings. As in the tower puzzle, newcomers will discover much scope for wrong moves. The illustration shows the first two moves in the five-ring puzzle. To remove a ring from the loop, slide the loop back, if possible, to the post of the ring just ahead of the ring to be removed. The latter ring can then be pivoted upward so that the swinging portion clears the end of the loop. By sliding the loop forward again the ring can now be tilted sideways and dropped through the loop. In solving the puzzle it is often necessary to put rings back on the loop; in such cases the reverse procedure is followed.

Attempts to solve the rings puzzle reveal the same general problem posed by the tower puzzle: configurations appear in which various numbers of consecutive rings have been removed from the loop, once again leading one to believe all the rings can somehow be removed. It comes as no surprise, then, to learn that the rings puzzle can be solved by the same kind of recursive algorithm. Indeed, there is also a simple iterative procedure for solving the rings, considerably more transparent than the iterative solution of the tower puzzle. It would be a pity to reveal the simple technique here and deny readers the pleasure of having their own "Aha!" experience. I can give almost no hints without giving the answer away, but the solution can be stated in one or two sentences and requires no notation at all. I shall discuss the best solutions early in the new year.

Of somewhat greater surprise is the near identity of the two puzzles, which suggests another contrast common in computing and mathematics: two problems that on the surface appear to be quite different turn out on closer inspection to be essentially the same!

The link between the two puzzles is provided by two binary codes and an algorithm that translates one into the other. Just as we represent the moves of the tower puzzle by consecutive binary numbers, so we introduce a new binary code to represent the rings puzzle: a 1 represents a ring on the loop and a 0 symbolizes a ring off the loop. The five-ring puzzle can then be represented by a five-digit sequence of 0's and 1's, the leftmost digit standing for the ring next to the handle. Written as a sequence of such numbers, the first four configurations of the rings puzzle are as follows:

1 1 1 1 1 (all rings on)
1 1 1 1 0 (first ring off)
1 1 0 1 0 (first and third rings off)
1 1 0 1 1 (third ring off)

On the next two moves the second ring and then the first ring are removed. Following that, the fifth ring is removed. Then the first three rings are put back on the loop in preparation for taking off the fourth ring. In all, 21 moves suffice to remove all five rings. The last four configurations are listed thus:

0 0 0 1 0 (second ring on)
0 0 0 1 1 (first and second rings on)
0 0 0 0 1 (first ring on)
0 0 0 0 0 (no rings on)

Without turning the page, readers might enjoy supplying the 14 missing code numbers by solving the rings puzzle in this form and following two simple rules that represent the constraint adjacent rings place on each other:

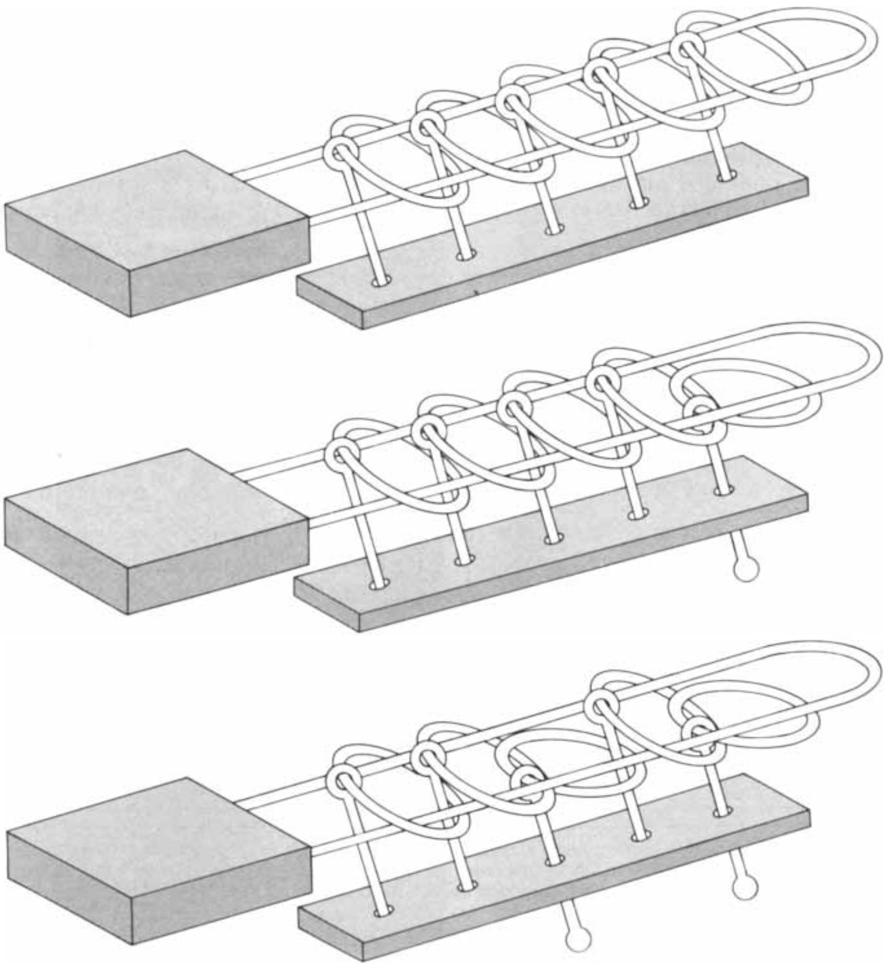
1. The rightmost digit can be changed (from 0 to 1 or from 1 to 0) at any time.

2. The only other digit that can be changed is the one immediately to the left of the rightmost 1.

At first glance there seems to be no obvious relation between the sequence of 22 binary code numbers implied above and the binary counting sequence arising from the tower puzzle. Actually there is a relation. It involves the Gray code, named after the engineer Frank Gray, who invented it during the 1930's at AT&T Bell Laboratories to provide an error-correcting technique for electronic communications. The code is explained in the illustration on the next page. In the same illustration are shown the first 22 binary numbers and beside them their corresponding Gray codes.

Examination of the Gray-code numbers in the illustration reveals a remarkable coincidence. In reverse order the Gray-code numbers are just the successive ring positions in a solution of the Chinese-rings puzzle!

These, then, are the 21 positions forming a solution to the five-ring puzzle. But the five-disk tower puzzle requires 31 moves for its completion. One would think that if the two puzzles are in some sense identical, they would have the same number of moves in their solution. The discrepancy is removed, however,



The first two moves in the Chinese-rings puzzle

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when we examine the Gray-code numbers beyond the 21st. Each of these represents a possible configuration in the rings puzzle, and the very last (corresponding to the binary number 11111) is 10000, the configuration in which only the last ring is on the loop. This implies that if you want someone to work harder at the rings puzzle, present it with all rings but the last one removed. Here the number of moves to solve the n-ring puzzle is $2^n - 1$, precisely as in the n-disk puzzle.

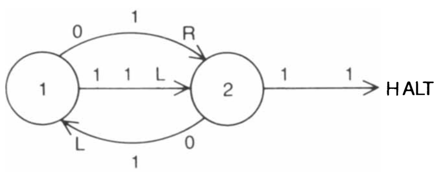
A very informative book on the Chinese rings has recently been written by Sydney N. Afriat, professor of economics and mathematics at the University of Ottawa. Called *The Ring of Linked Rings,* it is published by Gerald Duckworth & Co. Ltd., The Old Piano Factory, 43 Gloucester Crescent, London NW1, England. I am indebted to Afriat for the idea of tying the Chinese-rings puzzle to the yin and yang notion of duality. Although he suspects a Chinese origin for the Chinese-rings puzzle, he is aware of definite references only as far back as 1550. Afriat's book also describes the "Gros code," a 19th-century anticipation of the Gray code by the French mathematician Louis A. Gros, who published a treatise on the puzzle in 1872. The French, incidentally, call this puzzle Le Baguenodier and the English call it The Tiring Irons.

There are many other facets to both puzzles that I do not have the space to explore here. For example, Leroy J. Dickey of the department of pure mathematics at the University of Waterloo in Ontario reminded me that solving the Chinese-rings puzzle is also equivalent to traversing the edges of an n-dimensional hypercube.

It might be observed that the n-disk tower puzzle can be solved in $2^n - 1$ moves if three pegs are used, whereas the use of $n + 1$ pegs shortens the number of necessary moves to a considerably smaller number, $2n - 1$. What happens between three pegs and $n + 1$ pegs? How does the minimum number of moves in a solution change as one changes the number of available pegs? It would be interesting to pursue such questions in a later column. Even as I write this there are people puzzling over the four-peg problem, as well as over what Martin Gardner calls a "fiendish version of the Tower," a Japanese puzzle that has been marketed under the name PANEX.

PANEX can be obtained (along with enough perplexity to while away any number of rainy afternoons) by writing to Tricks Limited, 71 Shinozakicho, 7-chome, Edogawa-ku, Tokyo 133, Japan.

The three busy-beaver puzzles posed in the August column were solved by Martin J. Maney of Palatine, Ill. His two-state busy beaver is shown below. Starting with a blank tape, it produces four 1's before halting.



Maney's solutions are best summarized in words. A Turing machine that erases a single 1 from an otherwise blank tape uses two 1's as markers. At each stage it shuttles from one 1 to the other, checking just beyond each to see whether the 1 to be erased lies there. If it does, the machine erases all three 1's and halts. If it does not, the machine moves that marker one square outward and shuttles back to the other marker. The multiple 1's tape cleaner works similarly, except that it can never halt. How could it when some as yet unexplored region of the tape may contain a 1? Two-state busy beavers were found by Peter J. Marineau of Troy, N.Y., and Dave Kaplan of Deer Park, N.Y. Marineau also solved the tape-cleaner problem, describing his movable 1's as "brooms" that sweep the tape.

Raphael M. Robinson of Berkeley, Calif., wrote a Turing-machine simulation program for his IBM PC. As he watched Uwe Schult's conjectured busy beaver writing out its 501 1's, Robinson noticed that before halting it produced a recurring and ever lengthening pattern of alternating 0's and 1's. Starting with a blank tape, the successive lengths of this pattern were 0, 6, 13, 28, 48, 78, 121, 190, 289, 442 and 667. The last pattern contained 501 1's. It occurred to Robinson to investigate the behavior of Schult's machine, beginning not with a blank tape but with one of the alternating patterns. Starting on a pattern of length 9 (containing five 1's), the machine halted after 12,870,233 steps, having produced a new pattern containing 4,911 1's. This required three times the space and 25 times the number of steps performed by Schult's machine when started on a blank tape. That such a modest change in the input tape should produce such extravagant behavior disturbed Robinson. "It seems to me," writes Robinson, "that these results throw serious doubts on Schult's space and time restrictions."

Apparently Bruno Weimann of the University of Bonn was not the first to discover a four-state busy beaver. Allen H. Brady, now at the University of Nevada at Reno, discovered his own a decade before Weimann. At the time Brady was at Oregon State University. The school mascot is the beaver, and the computer in Brady's research was at nearby Beaverton. Brady shares Robinson's skepticism. "I know from solving the four-state problem that the five-state problem is far from decided. The crux of the matter is deciding that each alleged runaway machine will in fact never halt.... As the machines become more complex this decision will become more and more difficult, eventually encompassing very profound unsolved mathematical problems.... The blank tape halting problems of individual machines at some point become essentially individual mathematical theorems."

	BINARY CODE	GRAY CODE		BINARY CODE	GRAY CODE
0	0 0 0 0 0	0 0 0 0 0	11	0 1 0 1 1	0 1 1 1 0
1	0 0 0 0 1	0 0 0 0 1	12	0 1 1 0 0	0 1 0 1 0
2	0 0 0 1 0	0 0 0 1 1	13	0 1 1 0 1	0 1 0 1 1
3	0 0 0 1 1	0 0 0 1 0	14	0 1 1 1 0	0 1 0 0 1
4	0 0 1 0 0	0 0 1 1 0	15	0 1 1 1 1	0 1 0 0 0
5	0 0 1 0 1	0 0 1 1 1	16	1 0 0 0 0	1 1 0 0 0
6	0 0 1 1 0	0 0 1 0 1	17	1 0 0 0 1	1 1 0 0 1
7	0 0 1 1 1	0 0 1 0 0	18	1 0 0 1 0	1 1 0 1 1
8	0 1 0 0 0	0 1 1 0 0	19	1 0 0 1 1	1 1 0 1 0
9	0 1 0 0 1	0 1 1 0 1	20	1 0 1 0 0	1 1 1 1 0
10	0 1 0 1 0	0 1 1 1 1	21	1 0 1 0 1	1 1 1 1 1

Each five-digit Gray-code number is obtained from its corresponding binary number by a simple rule: numbering the digits in left-to-right order, the first Gray-code digit is always the same as the first binary digit. Thereafter each Gray digit is a 1 if the corresponding binary digit differs from its successor; otherwise it is a 0.

Gray codes for the first 22 binary numbers

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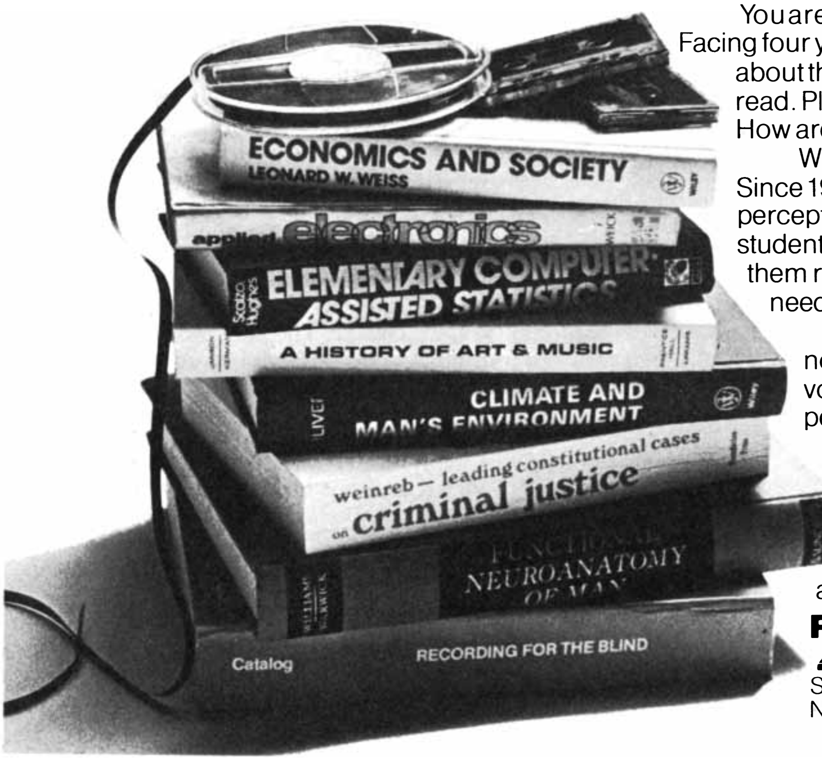

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BOOKS

The comforts of being ill in Japan, explosive volcanism, virus wars, an avian map of smells

by Philip Morrison

ILLNESS AND CULTURE IN CONTEMPORARY JAPAN: AN ANTHROPOLOGICAL VIEW, by Emiko Ohnuki-Tierney. Cambridge University Press ($37.50; paperbound, $9.95). "In the United States, where the sovereignty of the individual is sacred," a hospital patient typically "becomes a number on a wristband, is clothed in a nondescript sterile gown, regardless of sex, fed institutional food, and almost completely isolated from the rest of society." In Japan, where the individual role is much less central, where a uniform is commonplace for every level of school, there are no johnnies. Hospital patients sport the best personal nightwear; indeed, such clothing is a welcome gift from friends. Family members, or attendants engaged for the purpose, will attend to the frequent laundering and feed the patient well on favorite delicacies, even though the hospital stands ready to provide three daily meals. Visitation and gifts are an obligation accepted by friends, who may reasonably expect gifts in return on recovery. Doctors will weigh medical decisions against customary social and personal needs. How could one deny any sick person the small agreeable comforts of a choice of food and clothing, at the price of minor inconvenience, or even of slight risk?

Cultures at large write the script for the ill. In the U.S. a patient is symbolically something of an undesirable. Metaphorically if not factually infectious, he or she is set apart, placed for a while without appeal under the firm authority of a powerful institution; even the prized individualism enjoined on every productive citizen is swiftly taken away. In Japan every person—whose very birth certificate is not individually issued but is part of a family registry—remains in illness bound to a strong social network, within which the medical institution takes its assigned place. It would be naive to reduce these differences wholly to economics or epidemiology; rather, they are customary consequences of a balance struck between matter-of-fact claims and a social milieu that imposes its own symbolic structure on secular practices, a symbolism no less compelling than the symbolism of religion.

This eye-opening book for the general reader outlines from such a structuralist viewpoint the culture of health in today's Japan. Dr. Ohnuki-Tierney is an experienced and reflective ethnographer, a professor of anthropology on the faculty of the University of Wisconsin at Madison and a native of Japan. The readable and personal text is based specifically on her careful field work four or five years ago in the Kobe-Osaka-Kyoto region, among "middle-class" urban Japanese. Although the book is not systematically comparative, most readers will find illuminating comparisons implicit throughout; they bear on everyday life no less than on the formal institutions of health care.

Three systems of care are intertwined in Japan. There is a revitalized and modernized traditional system called *kanpō,* "the method of the Han"; it is derived from ancient Chinese medicine, first brought to Japan 1,500 years back. The second is the therapeutic side of the two major Japanese religions.(More than half of the people of Japan belong to more than one religious organization.) Shrines and temples alike house a public pantheon of supernatural beings tightly specialized for healing and protective functions. The third system is the much newer biomedicine, the term used by Ohnuki-Tierney for the broadly causal modern cosmopolitan scheme. That scheme derives from Renaissance learning; it began to win wide adherence within Japanese medicine just 200 years ago after covert circulation of a translation from the Dutch version of a well-known German copperplate anatomical atlas.

Only a glimpse can be offered of the intricate weave here teased apart. What comes clear is that the Japanese are not, or at least not only, those loyal corporate "workaholics" seen by our anxious media. There is wide everyday anxiety about infection by "Japanese germs," which are by no means only real microorganisms. Plenty of dirty things and dirty people are always out there; hence indoor slippers, gauze masks, hot towels, white gloves and no fondness for the secondhand, even for used books. (The author admits to a shrewd hunch that cultural germs "lurk abundantly" in Western backyards as well, perhaps differently expressed.) The state of personal health is a steady topic of conversation, particularly "my very own illness," a phrase for some condition carried throughout life, a recognized inborn weakness, ready any time to put one down for a while. Eighty percent of housewives queried felt they were suffering from such a commonplace trouble. The conditions identified included shoulder stiffness, constipation, low blood pressure and a few more.

Enter *kanpō* in its thriving up-to-date form. Its elaborate recipes directed toward such broadly defined symptoms are now available in every drugstore, made up into easy-to-use pills and bright-colored solutions by the big companies, and marketed vigorously with insistent television commercials. Your own chronic weaknesses can gain help from just the right mix; if a skilled—and expensive—doctor of the art is not consulted, perhaps a careful questionnaire will allow a trained pharmacist to offer the needed choice. One such Customer's Card is shown here: its columns invite detailed entry of self-perceived symptoms over a wide range, from food preferences through the frequency and qualities of stool to a choice among seven diagnostic states of the abdomen. This is no folk medicine, looking for the sign recited in some old saw, but rather a learned and intricate response to one personal instance of what just about everyone suffers.

A similar remarkable specificity marks the supernatural aid available for votive participation, generally implying donations of money. In the foothills outside busy Osaka there is a famous shrine, rather surgical in its orientation. Among its crowd of diverse manifestations a few small structures house a minor deity specializing in the "treatment of ringing ears and excessive discharge of ear wax"; votive pebbles and painted prayer boards are piled high there. Even such archaic institutions are open to change. The Smallpox Deity is now engaged with contagion in general, and the Deity of Coughing, once much besought in the face of epidemic influenza, attends the more chronic asthmas. It is almost always the explicit physical body and not the psychological domain that dominates Japanese healing.

Both of these old medical systems fit closely everyone's prudent anxieties and daily self-appraisal of a somewhat threatened health; therein lies their strength. Recall that *kanpō* includes along with the herbal doses the dramatic counterirritant and pain-relieving procedures of acupuncture and moxi-

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bustion. (One unexpectedly learns that these classical therapies by needle and burning tinder have traditionally been administered in Japan by blind paramedical specialists.) The strength of the old systems within postindustrial Japan has lately profited no little from well-publicized chronic side effects of certain popular biomedical drugs. The resurgence of confidence and pride in today's Japan encourages these peculiarly national structures even as their variety and ubiquity are exploited by commercialization. The complex needs these systems fulfill transcend healing altogether, whatever the therapeutic statistics may turn out to be. Estimates of pain-killing endorphins flowing freely under the well-placed needle or of hormonal effects of one or another bitter alkaloid within those subtly composed ginseng mixes are of secondary interest. For in human society medicine is a many-sided art; it has been noted that a woman's memorial apology to an aborted fetus draws, without direct appeal, a Japanese husband's attention to her sufferings.

The newer biomedicine is very far from neglected. Hospital beds per capita in Japan exceed those in the U.S. by 50 percent (the figures date from a decade ago); the mean duration of hospitalization in Japan is "by far the longest in the world," three times the Scandinavian stay and fivefold the American. These lengthy stays carry official sanction for "peace and quiet," the most cherished therapy in popular Japanese medicine. Someone else back at the company will cover for the missing worker; true, the hardworking woman indispensable to her family may not enjoy so generous a time of rest.

The systems interpenetrate surprisingly. During pregnancy Japanese women have by custom wrapped a 12-foot cotton sash around their abdomens. Such a sash is usually obtained from a religious precinct noted for its efficacy in childbirth; the sash is to be burned, or sometimes returned, after use. Now, in the Japanese calendar the days of the lunar month are named in rotation for the 12 zodiacal animals. That sash is expected to be donned for the first time, publicly confirming pregnancy, on the day of the dog during the woman's fourth month; a magical meaning was once plain, for the dog is associated with easy delivery. In the author's survey 139 out of 149 women coming to a modern obstetric clinic in a biomedical hospital used the sash. The conscientious senior physician who was head of the clinic and director of the hospital sat at his desk every day of the dog, and as his patients came in each presented her sash so that he could write across it, in bright red with one stroke of his brush, the elegant character for happiness. A photograph displays his fine calligraphy. Then the head nurse showed each woman how to tie the sash. Dr. S. agrees with most of his patients on the sheer utility of the sash, warding off chill and offering comfort and support much better because of its daily adjustability than any girdle or corset could. An apt syncretism is always at home in Japan.

Ohnuki-Tierney makes a good first case for the structures of metaphor that she finds in Japanese health systems: a basic duality, the outside impure and dangerous, the inside held clean and safe within social bounds. Most of all one grasps Japanese personal energy and internal sense of obligation. Against the illness that every sensitive person expects to carry lifelong, against the bearable ordinary weaknesses of the body, one is obliged to act, to exploit the help so diversely provided, even to the "urban magic" of charm and amulet. But a patient faced with the uncontrollable, say the dreaded cancer, is regularly kept uninformed. This is usual current practice, shared by ordinary people and doctors alike; in disaster the network, no longer able to help, simply conceals inexorable fate. On the other hand, as everyone knows, suicide is culturally sanctioned, even given aesthetic meaning within Japanese tradition. Such a dramatic end does not surrender the dignity of a human being; it enables the individual to manipulate even death into what is a cultural, if not a personal, triumph.

What seems most general is that any causal system of health, necessarily statistical if it is biologically founded, stands in direct conflict with the uniqueness of individual human fate. A perfected but still probabilistic biomedicinal prognosis, even one free from human error—far beyond our present finite science—would leave a sufferer with a poor outcome no choice but to seek some active support from the culture, magic or no. As long as Jenner's quasi-magical vaccine cannot be matched by every therapeutic action against the unavoidable deficiencies of an aging organism, or finally against death itself, just so long will people attend to some irrational force.

Hōsō-shin, the Smallpox Deity, might have to enlarge his specialty once again, but he will not lack for votaries. Although the specific synthesis here is undilutedly Japanese, its components are everywhere. In the medicine of any country it will be a long time before it is science that informs the subsoil of the mind.

EXPLOSIVE VOLCANISM: INCEPTION, EVOLUTION, AND HAZARDS, a report of the Geophysics Study Committee, National Research Council. National Academy Press ($24.50). The source of energy is clear: the internal heat deep in Mother Earth. Volcanism is the localized convective delivery of some of that energy up to the surface by molten rock, a process that concentrates energy flux wonderfully within small areas of the essentially solid mantle and crust. Nine-tenths of the melt that reaches the surface each year flows out almost unnoticed under the sea or on remote islands. Even where anxiously watched and regularly televised in their ominous beauty, the glowing island lavas move slowly, almost benign if inexorable, as they issue from Pele's famous Hawaiian kitchen. But the tenth of the flow we worry about erupts with explosive violence from a thousand vents along the coastal arcs and inland rifts of colliding plate boundaries.

A dozen related papers by American experts address the phenomenon in the uneasy context provided by the notorious caprices of Mount St. Helens. A brief summary and a set of specific recommendations for further research and improved organization make up the joint work of the Geophysics Study Committee; the final paper is an interesting comparative study of the public relations of the volcanologists on hand during volcanic crises in the 1970's on two Caribbean islands. The book is overall, however, an up-to-date account at research level of the where, how, why and when of explosive volcanism, as far as we can say today. (The absence of an index is a genuine blemish that might easily have been avoided.)

Three papers of unusual freshness offer a first-order physical account of the chain of events that culminates when a mountain blows its top. Begin at a depth of a couple of hundred kilometers, temperature and pressure high. Some volume of mantle must get hot enough to melt in part. That is normally the result of heat convection, either through the plastic flow of hot solid rock under ambient pressure or through conduction from such a hot mass to a cooler but more fusible neighbor. The excess heat comes from the decompression of the initial hard-worked material; heat from radioactive material diffused into a new place seems an unlikely, if possible, origin. Then the balloon ascends; that is, the hot lower-density melt very slowly rises. All the materials are complex mixes; fusion is partial, and surface magma always contains a large proportion of solid crystals. The problem for the rising matter is to displace the roof rock above it down toward the bottom. That displacement might proceed as it does for a balloon, by a flow around the rising mass; conduction may melt a fluid wall layer, or roof rock may fall in solid chunks right down through the rising mass. Given plenty of heat, layers of the expanded melt can enter and fracture the solid layer. Many fluid-filled cracks

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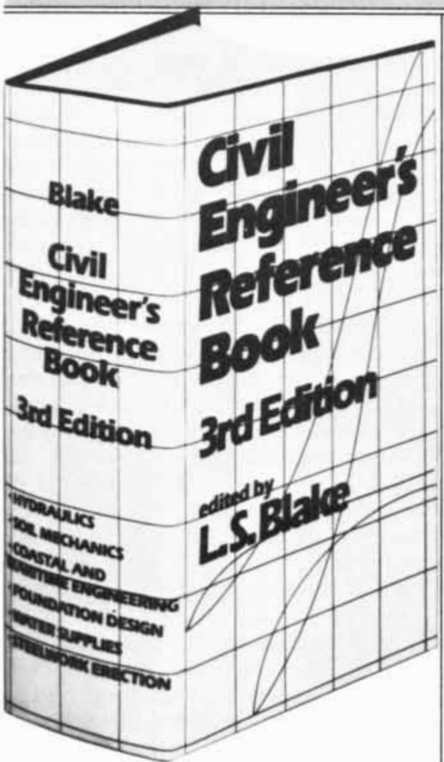

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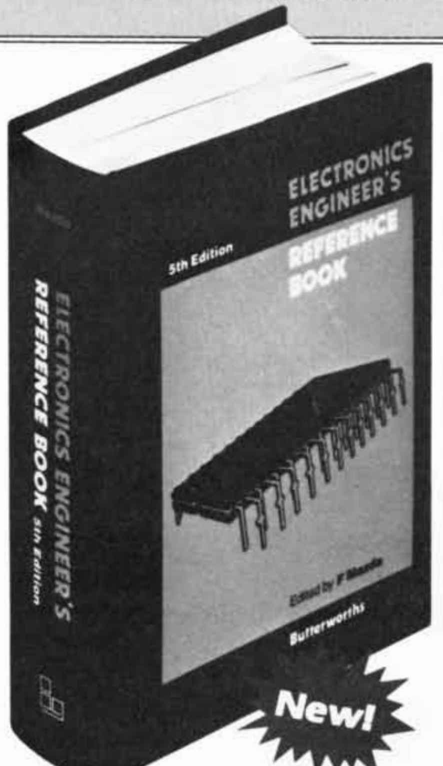

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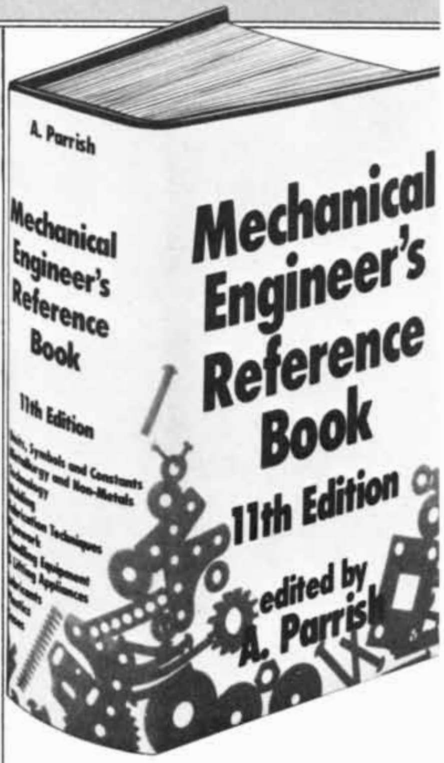

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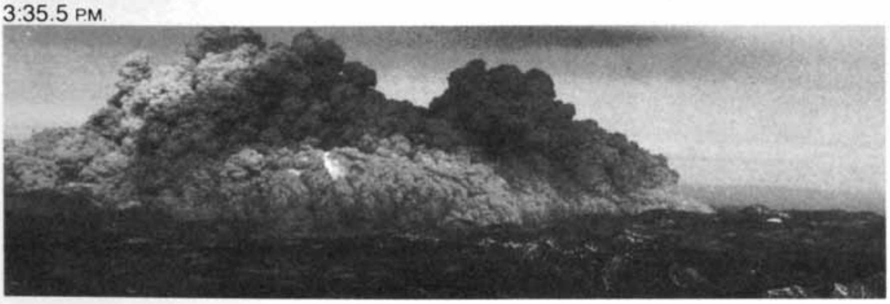

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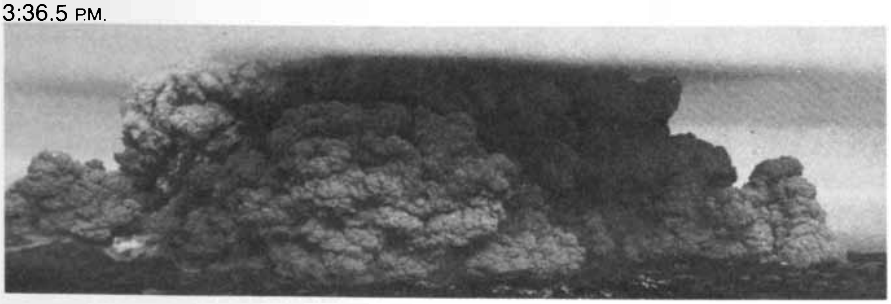

Gas and ash burst from Mount St. Helens during a 1980 eruption, seen from 32 miles away

propagate upward: a swarm of dikes. All these processes can be described semiquantitatively, and the dynamic choices can be laid out.

The classical division of igneous rocks of the surface into granites and basalts remains a sound generalization. The granites are usually found as intrusive masses, laid down below the surface and exposed only long after cooling; the basalts dominate the extrusive layers flooding over the land. The explanation here, by Bruce D. Marsh of Johns Hopkins, is quite persuasive. It rests on considering the time of cooling of a rock mass and the crystallinity of the mix as a function of temperature. Granite becomes too crystal-locked to flow eruptively once it cools below a rather high temperature; it will usually solidify at depth. It is much more likely that a basalt mass can be extruded before it cools, to erupt as lava. A related account can be given of the rising of a deep basalt mass, which heats its increasingly silicic environment, modifying it and often releasing a less dense magma, able to penetrate and rise beyond the original basalt bubble. In such a way the basalt supplies the energy for the cookery that generates the large bodies of silicic magma near the surface, the substance of the giant ash flows that are the most conspicuous relics of explosive volcanism.

High-speed gas flow is the mark of explosion. Since magma temperatures are far from high enough to turn much rock into gas, some volatile substance must be at hand. Water—copious near the surface—and perhaps carbon dioxide brought from the depths are the chief actors. Again the material is no simple stuff: it is a heat-rich heavy pseudogas, the volatiles from the outgassed melt carrying along a fine load of hot lava particulates. An ingenious physics paper by Susan Werner Kieffer of the U.S. Geological Survey treats the rock-laden gas flow expected. Where the surface is reached through long narrow conduits, friction limits the pressure. Where instead there are shallow surface craters, the jets decompress by lateral expansion. In either case most such jets should emerge as nearly vertical plumes, and they do. (Quite different results apply to the umbrella plumes seen from the volcanoes of airless Io.) Only when the pseudogas can suddenly reach the atmosphere does the outflow obtain high overpressure, allowing a wide variety of flow forms, some with shocks. Radiation is yet to be treated; there is no account of those terrible glowing avalanches.

The last of the papers that address dynamical questions is an awesome experimental study by Kenneth H. Wohletz and Robert G. McQueen at Los Alamos. Their model volcanoes are powered by up to 100 kilograms of the

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explosively melting but gas-free mix of aluminum and iron oxide powders called thermite. This stands in well for molten magma. Over a variety of setups, water is introduced to offer the needed volatile load. The efficiency of conversion from chemical energy into kinetic can compete with any engine. If little water is present, the products are recognizably like the prototype seaside volcano of Stromboli, a long-lasting spray of centimeter-size fragments of the fused mix. Drown the mix in water and the melt is passively quenched into chunks. The right amount—water about a third of the magma stand-in—and violent blasts spread dust afar, with shocks and even incandescence. Yet this work is only a beginning toward quantitative models. The photographs are striking, particularly since the model eruptions appear against a scene of high cliffs of real volcanic ash laid down around the Jemez Mountains by the explosion that left a grand caldera there a few million years ago.

Three more papers examine the complicated geologic and geochemical issues that seek the reasons behind the plain connection between explosive volcanism and plate collision. The answer is not yet neat, particularly for the northwestern U.S., where plate collision has been a complex affair, including both extensive compressive stresses and tensional ones. The Cascades appear as direct consequences of ocean-floor subduction, but the rest of the west has seen plenty of varied volcanism in the recent past. Ocean-floor material carried under the continent plays a major role; the chemical and isotopic patterns of the output are by no means simple and uniform. It is hard to avoid the conclusion that the drifting continents are yachts with deep, hidden keels: a couple of hundred kilometers of varied material drifts along below them. A second kind of volcanism, that of the kimberlite pipes, is discussed in a comparative opening chapter by Professor Arthur L. Boettcher of U.C.L.A.; their nature remains conjectural, since no witness has ever seen one in the act.

The remaining papers are more field-oriented. They review explosive activity at Kilauea, not invariably gentle, at St. Helens and in the past of Yellowstone Park. A broad survey looks at volcanism around the world, and another one derives and annotates maps of the volcanic past of the Western states during the past 16 million years; the maps are included with the volume. The chronicle of Yellowstone is remarkable; it draws on many years of field work and on seismic soundings of the entire region. Three large calderas are to be found in and near the park; the ash outpourings of the oldest one bulk at 100 times the volume of Krakatau. Careful study of the layered deposit makes plain that three long repetitive cycles of ash flows included climactic events at this scale that took place "certainly within hours or days, not decades or centuries." The deposits are uniform, without even slight erosion, reworking by streams or entry of extraneous material. In due confirmation, the matching ash can be found from California to Mississippi and Saskatchewan.

Will this region erupt again? Pretty surely it will. The patterns of the past suggest a rough cyclicity, not only in the Cascades but also across the Snake River plains to Wyoming, and in a diagonal belt from below Yuma to Raton. The time scale is some five millions of years, not mere human lifetimes. Each cycle includes episodes at individual vents by the thousand. Historical experience is a single uneventful frame from a disaster film on a grand scale. These results will surely bear on eventual estimates of what the thermonuclear volcanism of human design might do at its unprecedentedly swift rate, and at its chosen locations, from its position on the low end of the scale of Pluto's yields.

MODERN APPROACHES TO VACCINES: MOLECULAR AND CHEMICAL BASIS OF VIRUS VIRULENCE AND IMMUNOGENICITY, edited by Robert M. Chanock and Richard A. Lerner. Cold Spring Harbor Laboratory ($57). An abstract figure built of circular arrays of a few thousand graduated black spots adorns the cover of this symposium report. It represents one step toward an ideal, a high-resolution X-ray-diffraction photograph of a crystal of poliovirus. A set of a hundred such photographs should soon supply the data for a full three-dimensional model of the virus particle at atomic resolution. The tiny polio virion is known so far as a nearly featureless icosahedral array about 300 angstroms across, built of a few repeated proteins that enclose one short single strand of parasitic RNA. This is a high-tech new result: big single crystals of the virus (that is, the better part of a millimeter across) are available because we can now concentrate large amounts of the virus, as a contaminated by-product of vaccine manufacture. So subtly ordered a crystal is X-ray sensitive, but careful cooling allowed a few photographs to be made using the latest scanning techniques. Already we can spell out the entire message 7,500 nucleotides long that the tiny capsule holds. One day a map of the relations between changes in that virulent message and the protein structure is to be expected that should allow fully "rational design" of safe, potent, tailored synthetic vaccines using chosen portions of the virion that are incapable of neural infection.

To be sure, right now the war against virus infection is going well. The clever epidemiologists armed with plenty of an old vaccine have ended smallpox worldwide for good. But humans, even affluent ones, still properly fear influenza, herpes simplex and hepatitis, and our livestock suffer seriously from foot-and-mouth disease. Moreover, our present winning tactics are not free of important risk: occasional casualties of the influenza vaccine cut short the most recent campaign against a forecast epidemic. The volume presents current staff work on a variety of new tactical plans based on the latest intelligence about the old enemy.

Defense of big complicated animals against fast-replicating virus hordes has always been based on intelligence. With viruses, forewarned is definitely forearmed. That was true long before our species arose; the mammalian immune system marshals its many weapons best once it gains secure information about a specific intrusive protein coat. That measles or smallpox will not strike any individual twice is ancient human experience. Deliberate infection with crusts taken from smallpox lesions was practiced on that logical ground thousands of years ago. It was always risky, and two centuries ago Edward Jenner—his image adorns the back cover—introduced the less heroic tactic he had learned from the lore of the dairy farmers. He inoculated not with smallpox itself but with another symptomatically related virus known to share with smallpox immunogenicity but not virulence.

A century later the drama of rabies vaccine found Louis Pasteur extending Jenner's selective introduction by nurturing rabies virus through many generations within a strange host; the aim was to select against virulence and then chemically kill or at least damage the still-unknown particles. Later tactics came to include the use of passive immunity, the transfer of antibody proteins from organisms already informed, often chosen only statistically by using a pool of serum proteins. Most of our victories, those over measles, mumps, polio, rubella and a few more, followed these lines. Such procedures do not much depend on molecular biology. Rather, they share the oldest genetic insights of the plant breeder: select among natural strains to suit your purpose and try to cultivate well the variety you choose.

This volume contains, along with a summary by the senior editor, about 66 succinct papers presented in 1983 before a large expert audience. They sample new ways of virus war, ways that incorporate the extensive intelligence we now have about the molecular course of infection and response. No longer is the infectious virion viewed only as an organism; now we see it phys-

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ically as a protected message tape, its program for virulence and its vulnerable protein armor alike open to elaborate modification to prepare effective, safer, cheaper, more general vaccines.

Plainly one can seek vaccines that transfer only some of the key proteins, without any viral nucleic acids at all. They cannot infect, but if well chosen they can induce a powerful production of antibodies. The measles-virus envelope, some of its protein in fact glycoprotein that bears carbohydrate side chains, surprised the strategists. They broke out two components from the virus coat. One component was known to be subject to control by specific circulating antibodies made by the host. The other was responsible for fusion between cell surfaces and between virion and red blood cells. Introduced as a vaccine, the virus-coat fragments did not provide long-lasting immunity; indeed, some vaccinated individuals developed an atypical form of measles. The antibodies induced were not able to prevent pathological fusion of cells; the procedures used in protein separation had damaged the fusion portion in such a way that it did not induce adequate immunity. The vaccine conferred satisfactory circulating immunity against the one component, and so that virus was neutralized well enough in vitro. But in the patient's blood virus infection still produced a damaging amount of cell fusion. Not much is foolproof in a complicated biological enterprise, as any gardener knows. The moral is explicitly drawn: the goal should be "a balanced immune response directed against all protective antigenic sites of the virus," as during natural infections.

One major epidemiological concern is the natural variability of certain infectious viruses, for instance influenza, harbored in its many animal hosts. The sudden random appearance of a new strain that combines acute virulence in humans with a modified coat distinct from that of previous strains for which vaccines have been made ready in quantity is a clear hazard. That intrinsic genetic adaptability of flu may yet imply its own defeat. Flu virus has eight RNA segments known to reassort independently during infection of a single host cell by two different virus particles. If a strain can be engineered to take its six internal genes from a safely and stably attenuated laboratory strain but the two surface proteins from some dangerous newcomer, a new live vaccine might be generated in one swift step without tedious serial passages through chick embryo. A handful of papers here report that international progress toward this rather elegant goal is not close at hand.

Somewhat better success has been achieved with viral hepatitis; a major disease worldwide, the virus is hard to grow even in specialized primate tissue cultures, and control tests of attenuated vaccines may require live marmosets or chimpanzees. Within the past couple of years a vaccine has been prepared along classical lines for the A type. For the infectious, B type it has been possible to separate a single decisive antigen from rare blood plasma among chronic human carriers, using modern biochemical means. These methods are so taxing and costly that the new strategies appear very attractive. They require the insertion of the coding nucleic acid from the virus into yeast or bacterial cells to produce the antigen in good yield. It is secreted as tiny spheroidal protein particles, shown here in an electron micrograph, indistinguishable from those found in the serum of human carriers. The particles confer long-lasting protective antibody production in test monkeys. Full-scale use of this engineered vaccine is just ahead, a kind of biocryptological breakthrough. Hepatitis may turn out to be both the last disease to be confronted by the old tactics and the first to be controlled by the new. The news from the viral front continues good; even newly recognized AIDS can expect a classical vaccine attack, now being mobilized. We await late reports from the taxing campaigns against bacterial and protozoal infection.

BIRD NAVIGATION: THE SOLUTION OF A MYSTERY? by R. Robin Baker. Holmes & Meier Publishers, Inc. ($32.50; paperbound, $24.50). A Manchester zoologist, Dr. Baker is forthright: a mystery two centuries old has been solved. "I now feel, almost for the first time, that bird navigation, whether by pigeons or long-distance migrants, is no longer enigmatic." His small book, richly illustrated and tightly documented, supports his conclusion with a logical account of the gradual growth of experimental evidence mainly during the past 40 years.

Pigeons home by the use of a landscape map. The best-mapped part is their home area, and distant regions are step by step pieced together somewhat spottily to the limits of experience, up to 1,000 kilometers or more. The map is crudely metric, good enough to allow rough bearings and vector distances to be taken from it, but it does not contain any universal grid of bird latitudes and longitudes independent of experience. The map is visual, recording topographic landmarks large and small, but it is more than that: it includes a landscape of smells, and it may also have an acoustic supplement mapping the large-scale infrasound sources of the natural environment, in a frequency band below human hearing. With this triple map there goes a multiple set of compasses. They include a magnetic compass, a time-corrected sun compass, able under overcast skies to switch from the solar disk to sky polarization patterns, and perhaps a clever Doppler compass to judge the direction of infrasound sources. At night many birds, particularly the migrants, can extend their celestial direction finding to make use of star patterns, and very likely of the moon. Even first-time migrants can use the direction clues, of course, to go outside the boundaries of their maps toward the new seasonal goal, perhaps using staging areas along the way. Eventually they too come to own a mosaic map of an elongated route connecting a few distant but familiar areas.

The substance of the book is also a kind of mosaic map, pieced together from the hints and ambiguities and ultimately decisive experimental tests of all those inferences. This review will not summarize the intricate tale; it seems more representative simply to outline a few individual experiments within the mosaic, ambitious, ingenious and startling as they may be.

A map of smells? Raise two batches of pigeons in airy, open aviaries. Give the birds access to two glass-walled corridors through which air is blown. For one group, add olive oil to the air when the wind is from the south. (The experiment was carried out by the group of Professor Floriano Papi at Pisa.) When the wind is from the north, add turpentine. The other birds get the treatment in reverse. Carry the birds off to a distant release point east of the loft to test their homing. There a drop of olive oil is applied to the bill of half of the birds, turpentine to the other half. Birds with olive oil on the bill flew off to the south if in the home loft they had received the oil on north winds, and to the north if they had received it on south winds. The turpentined bills showed the same effect. "The pigeon landscape has olfactory landmarks."

A magnetic compass? The proposal is a century old. There is a library of elaborating experiments. One example will give the flavor; it implies additional results representative of many puzzling discrepancies of the past, now largely understood. Charles Walcott and R. P. Green fitted their homing pigeons with small cap and collar coils fed by a shoulder battery. The magnetic field direction through the bird's head could be set to be north-up or south-up. On sunny days the birds oriented well toward home whatever the direction of the disturbing field they bore. But on overcast days the birds with distinct field directions set off for home in opposite directions.

Two conclusions can be drawn, confirmed in many experiments. First of all, the birds have several optional compasses. They tend to use only a fraction of what they redundantly know. The

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magnetic compass ranks below the sun clues in their hierarchy of information; if they can use sun direction, they will. Second, magnetic field polarity is sensed by the pigeon. This result is a little strange; there is strong evidence that in other species at least the magnetic clue used is not field polarity but the inclination of the lines of force with respect to vertical. It may be that the strong fields at the pigeon's head dazzled its sensing system abnormally. Our mariner's compass, of course, is a polarity-sensing device; it points north, even in Australia. A dip, or inclination, compass would indicate the nearer geomagnetic pole, and it becomes ambiguous on the magnetic equator.

Dip compasses have been in great vogue since it was shown that tiny biogenic magnetite (that is, lodestone) crystals are the instruments by which certain bacteria can sense the vertical. Such particles have been found in a variety of animals, so far without clear demonstration of function. A pioneering investigator, Walcott, now at Cornell, has undertaken with his partner a histological search for the magnetoreceptor that must lie hidden in a pigeon's head. They made a magnetometer study a few years ago using a pigeon head that had been magnetized in a strong field. That appeared to succeed, but the result has not been confirmable in 80 subsequent pigeons. Now they are looking with the microscope at stained serial sections of the head, slice by microtome slice from the beak backward. Thus far three sites seem consistently to contain iron; the heroic experiment is so direct that it stands out in this long list of ingenious subterfuges of inquiry.

The mosaic fits quite well, if with many gaps and some pieces awry. Baker reports some new experiments of his own using human subjects, suggesting a human magnetoreceptor. The properties found are so subtle—an effect of magnetic storms, of polyester clothing, perhaps electrostatic, and of the orientation along which the subject slept the previous night—that the careful experiments themselves are rendered fragile to unexpectedly subtle artifacts unknown and uncontrolled. It will probably take more time to winkle out unconscious truth from human subjects than it has from mute pigeons.

This is a delightful and well-argued book, packed with ordered diagrams and data, not always easy to read out. The index of subjects is complemented by an exhaustive list of references neatly turned into a useful index of authors. The author closes by saying there are no major loose ends, but one suspects that the ends we hold in our hand nonetheless lead into a larger and still more challenging maze among birds and humankind.

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The Value of Fundamental Science

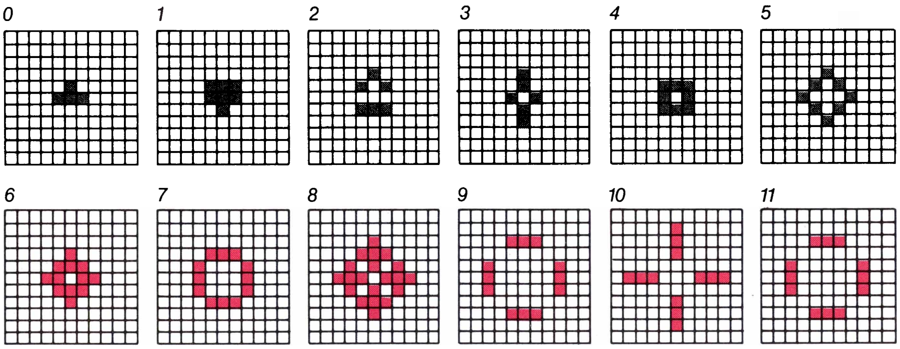
Its cost to the taxpayer is only about 5 percent of the cost of applied research and development. Yet it contributes deeply to technology, the education of scientists and the general enrichment of our culture

by Leon M. Lederman

One takes up fundamental science out of a sense of pure excitement, out of joy at enhancing human culture, out of awe at the heritage handed down by generations of masters and out of a need to publish first and become famous. When the cost of pursuing this enterprise is high, it is fair to ask why society should support it.

The answer is that the support of fundamental science—mathematics, astronomy, the physical and the biological sciences—yields profoundly significant benefits. They can be classified roughly according to the time it takes for them to be transferred to society. The most important benefits are cultural; the cultural benefits also require the longest and most complicated maturation process. Direct benefits, in which the object of scientific inquiry is put to some practical use, typically require about 30 years to be realized. For example, nuclear magnetic resonance (NMR) was discovered in the 1940's, and its commercialization as an imaging device in medicine began in the 1970's. The most rapidly realized social benefits are usually indirect, such as technological spin-off. They arise when some solution to a problem in a fundamental discipline is perceived to have application in an unrelated field. For example, an apparatus designed for the collection and concentration of extremely dim light emitted by elementary particles passing through a medium has been applied to the collection of solar energy. There is a great deal of controversy among economists over the correct procedure for measuring the influence of fundamental science on the economy, but there is no question that such measures are beginning to be quantified. I shall examine each of these benefits in turn.

Many of my colleagues are astonishingly shy about raising the cultural issue in full view of policymakers. Part of the reason is that the issues are philosophical and hence cannot possibly hold or compete for attention in times of crisis. It is also hard to establish the fraction of the gross national product that can be identified with the cultural value of science. Within the scientific community, however, most people acknowledge that the most important aspect of science is the cultural one. The need is universal—to give a coherent account of the world and our place in it—and for this purpose our society has cast its lot with the rational explanation of na-



PATTERNS OF PRISMATIC GROWTH on the surface of the tent-olive shell (*bottom illustration on opposite page*) are strikingly similar to the patterns generated by simple rules for the evolution of a one-dimensional cellular automaton (*top illustration on opposite page*). Similar V-shaped patterns are also seen on the surface of a stream, and Stephen Wolfram of the Institute for Advanced Study in Princeton has suggested that the study of one-dimensional cellular automata may contribute to the study of turbulence, the chaotic flow of a gas or a liquid. The history of this intellectual development epitomizes the way an abstract exercise in fundamental science can lead unexpectedly to the understanding of some feature of the natural world. The study of one-dimensional cellular automata was stimulated by an extraordinary recreational interest among scientists, mathematicians and computer buffs in the game of "life" (see "Mathematical Games," by Martin Gardner; SCIENTIFIC AMERICAN, October, 1970). The appeal of the game exemplifies the appeal of abstract problems: the rules of life are easy to understand, yet the intricacy and beauty of the patterns to which they give rise reward close attention by the finest minds. Young people are attracted to the problem, and the newest and most interesting patterns are shared by a large community. In the game one follows the evolution of certain "life forms," such as the one shown in frame 0 of the illustration above. The coloring of each cell, or square, in any frame depends only on the coloring of the eight surrounding cells in the preceding frame. Since every stage in the game of life is a two-dimensional pattern, Wolfram suggested that further progress in the study of such patterns could be made by initially limiting study to cells arranged in a line. In the one-dimensional cellular automaton shown each stage in the evolution is a row of colored cells; the rows evolve from top to bottom. The color of each cell depends solely on the colors of the three nearest cells in the row immediately above. If work on cellular automata does lead to a better understanding of turbulence, that understanding would be invaluable for the study of phenomena such as the weather, ocean waves, the design of airfoils, the flow of oil in a pipeline and the dynamics of matter inside the sun.

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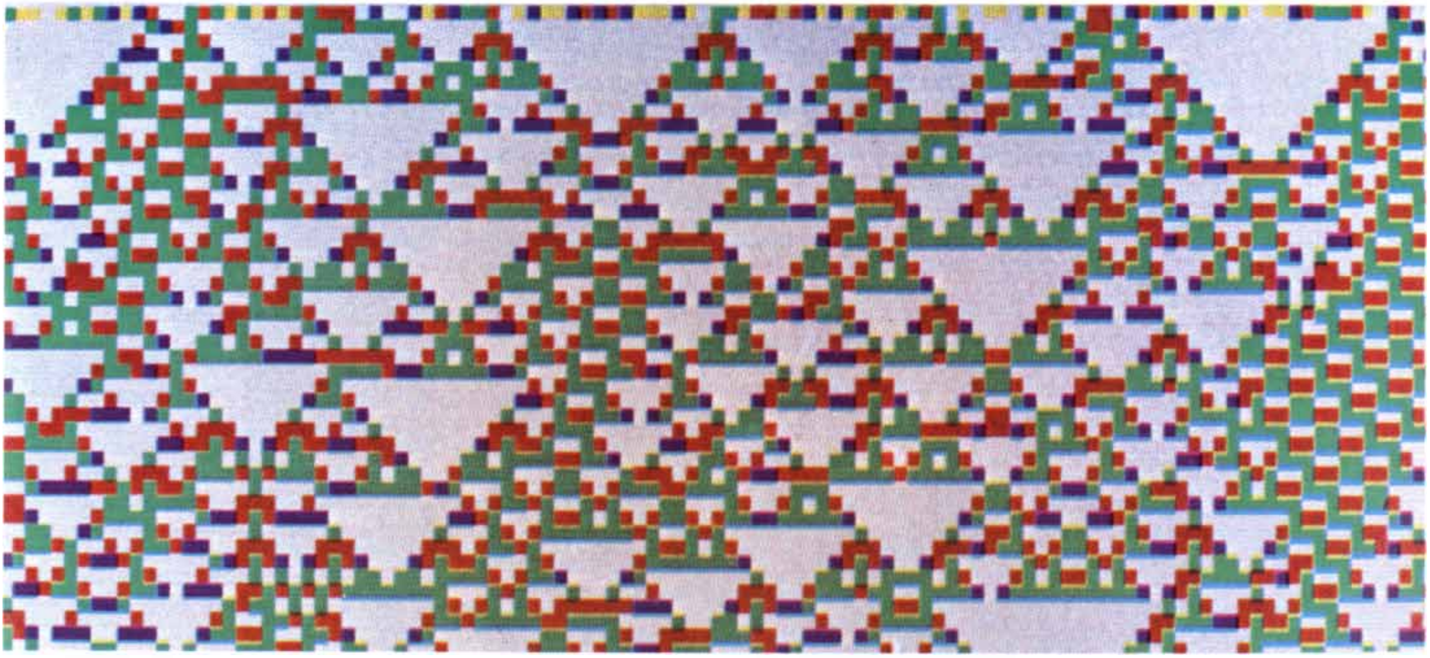
ture. That choice is demanding, for insofar as it shows the inadequacy of formerly held beliefs, it requires great confidence in the ultimate benefits of rationality.

One of the most important of these benefits is derived immediately from the activity of scientific investigation. The study of apparently remote and exotic regions of inner and outer space is an example of the kind of rational behavior our society is committed to. We want to do as well as we reasonably can in these matters. Furthermore, we keep discovering surprising connections: organic molecules are found in space; beams of neutrinos emerging from particle accelerators could change our ideas about the evolution of the universe. Such connections emphasize the unifying idea, common to many cultures but put forward most clearly by the ancient Greek philosophers, that there is a single and economical law of nature, valid throughout the universe for all time. The quest for such a unified scientific law has been undertaken and advanced by all nations and all creeds. Indeed, the idea of the unity of science has been a major force in developing the unity of humanity, which is much on the minds of those who struggle for mutual international understanding in these perilous times.

It follows that society must care about science in the same way as it must care about its other creative intellectual activities, such as art, music and literature. Science, like art, manifests its deep cultural influence when its basic principles or its way of viewing the world is appropriated and applied to a larger social context. The concept of the earth as an elaborate spaceship, which expresses a humility about the planet, an appreciation of our place on it and a concern about protecting the environment, could not have been invented before Copernicus demoted the earth from its position at the center of the universe more than four centuries ago. The scientific outlook contributes deeply to general intellectual enlightenment and has done so for centuries. Keith Thomas, writing in his book *Religion and the Decline of Magic* about the repeal of the witchcraft laws in England in 1736, recalls Richard Bentley's comment on the key



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role played in this advance by the development of natural philosophy: "What then has lessen'd in England your stories of sorceries? Not the growing sect of free thinkers but the growth of Philosophy and Medicine. No thanks to Atheists but to... the Boyles and Newtons."

There are two important cultural effects of fundamental science within the sciences themselves, which add significantly to the quality of the more practical contributions that science can hope to make to society. One is the cultural appeal of science, which has attracted some of the best minds to scientific work. Whereas the guarantee of a cheap and clean source of energy may be a crucial scientific problem for the scientists of today, the bright high school student is more often drawn to science by such topics as the puzzle of antimatter or the big-bang theory of creation.

The second cultural effect of fundamental science within science is maintaining the esprit of the scientific community. The success of fundamental science sets standards throughout science, and it provides a shared body of knowledge that can be discussed and contributed to by workers in a wide variety of special fields. A good example of the cultural drive is the history of the development of one of the quintessential technological developments of the 20th century, the transistor. The direct technological goal of the work that led to the discovery of the transistor in 1947 was to fabricate active, solid-state circuit elements. Fundamental to the success of the effort, however, was Alan H. Wilson's prior application of quantum mechanics to the explanation of the electronic band structure of semiconductors. Walter H. Brattain of the Bell Telephone Laboratories writes: "The transistor came about because fundamental knowledge had developed to a stage where human minds could understand phenomena that had been observed for a long time. In the case of a device with such important consequences to technology, it is noteworthy that a breakthrough came from work dedicated to the understanding of fundamental physical phenomena, rather than [from] the cut-and-try method of producing a useful device."

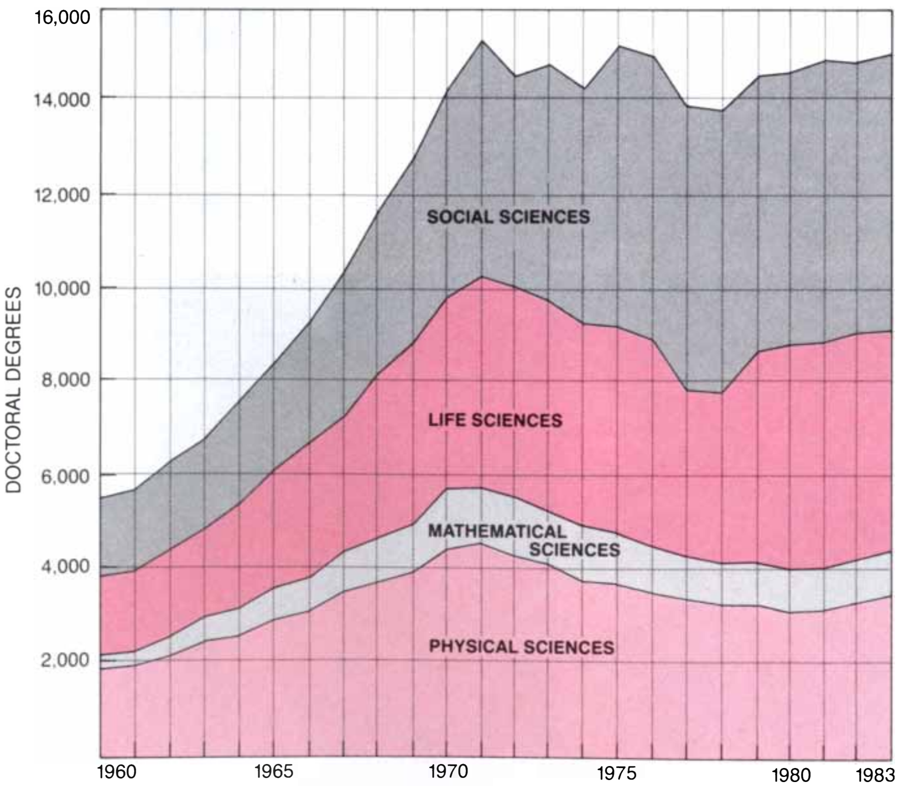
The transistor is a straightforward historical example of a direct benefit of fundamental science. But what of the future? To extrapolate from the recondite topics of current fundamental scientific investigation to a technological spin-off is to indulge in grandiose speculation. Responsible colleagues shirk the task almost as a tradition. Ernest Rutherford is reported to have said: "Anyone who expects a source of power from the transformation of these atoms is talking moonshine." The irony is that Rutherford's statement was made five years before the demonstration of fission. If one is to be guided by history, one is challenged to propose applications of science at least as remarkable as many of our current technological miracles would appear to be to an 18th-century savant. As a vehicle for discussion I shall lean heavily on my own discipline, the study of high-energy particle physics, which would seem to be as remote from useful application as one can get.

One potential benefit of high-energy particle physics is presumably the economical generation of useful energy. The amount of energy released by an ordinary chemical reaction such as the burning of coal or oil has often been compared unfavorably with the energy released by a nuclear reaction such as fusion: fusion releases roughly four million times as much energy as burning does per unit mass of fuel. Nevertheless, according to Einstein's basic formulation of the equivalence of mass and energy, fusion liberates only 1/500th the total energy locked up in any mass at rest. One of the most exciting implications of recent developments in particle physics is that there may exist natural processes that could liberate virtually all the energy in such a rest mass.

For example, in 1973 T. D. Lee and Gian Carlo Wick of Columbia University pointed out that the rest mass of the nucleons (neutrons and protons) bound together in an atomic nucleus would suddenly fall to a small fraction of its normal value if the nucleus were squeezed past a threshold of extraordinarily high density. The result would be the radiation of almost a billion electron volts of energy per nucleon.

One rather speculative way such conditions could be brought about is to make heavy nuclei such as the nuclei of uranium collide at high velocities; the collisions might temporarily raise the density of nuclear matter past the critical point at which the reaction proceeds. If any given mass of matter could be organized in such a way that all its constituent nucleons were to undergo the reaction, the energy needs of the world projected for the year 2000 could be met with a few tons of water.

Another reaction that could transform almost all mass into energy is the decay of the proton. Proton decay is predicted by the so-called grand unified theories, which seek to account for the strong, the weak and the electromagnetic force; if such theories are correct, ordinary matter is unstable. The expected decay rate is so slow, however, that not more than a few protons in 10,000 tons of matter can disintegrate in a year. No



NUMBER OF DOCTORAL DEGREES awarded annually in a science is a good index of the health of the discipline. The graph shows that the number of new Ph.D.'s has been roughly constant during the past decade in the social sciences and in the life sciences; it has declined in the mathematical and physical sciences from a high reached in the early 1970's. A slow growth indicates a discipline in a state of well-being; the author argues that the current low level of new Ph.D.'s may have serious consequences. The data are from *Science Indicators 1982*.

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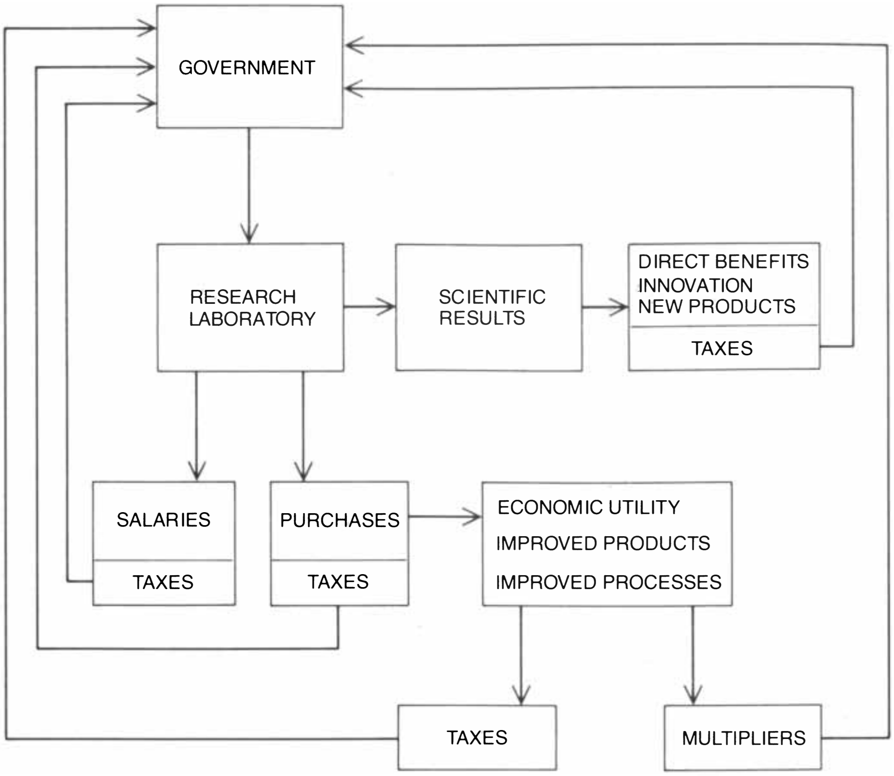
clear observation of proton decay has yet been made.

The interesting question for generating energy is whether, if the proton does decay, the rate of the decay can be changed by altering the environment. In principle the answer is yes. Proton decay should be frequent when the temperature of matter is about 10^{29} degrees Celsius. According to cosmologists who apply grand unified theories to the study of the early universe, the universe was at least that hot until about 10^{-32} second after the start of the big bang. Although collisions in high-energy particle accelerators can simulate conditions about 10^{-13} second after the start of the big bang, attaining the critical temperature for proton decay is still a distant goal.

This one limitation does not rule out the possibility that other microscopic changes in the environment could bring about a higher rate of proton decay. A few years ago, for example, several physicists and cosmologists raised the possibility that the reaction could be catalyzed by the presence of a magnetic monopole, an unusual particle predicted by grand unified theories. According to calculations done recently by Curtis Callan of Princeton University, the effects of a monopole extend over a much larger volume than had previously been thought. If a proton were to drift into this volume, the monopole would suck the proton into its interior, whereupon the proton would decay. The catch is that the detection of a magnetic monopole has never been confirmed. In grand unified theory the magnetic monopole is so heavy that most monopoles on the earth may have already sunk into the core; high concentrations of monopoles might also be found in the superdense matter of a neutron star. Hence if magnetic monopoles actually exist, the chief problem for a practical scheme to extract energy from proton decay might well be the difficulty of mining the catalytic monopoles.



RESEARCH LABORATORY, like any other institution supported by public funds, spends its money on salaries and purchases; with appropriate multipliers such expenses are taxed, and so a portion of the supporting funds are returned to the treasury. If work at the laboratory gives rise to a product or to information from which a product develops, new sources of repayment are generated. For example, the study of nuclear magnetic resonance (NMR) in the 1940's has led to medical imaging devices that are expected to generate several hundred million dollars in taxes in the late 1980's. Indirect return results from the collaboration between the laboratory and industry: the needs of the laboratory often change the capacity of industry to produce certain goods and services. Such changes can yield higher profits and hence increased taxes. The effects of the collaboration can also be propagated throughout the economy: increased employment and demand for new raw materials both result in taxes. For example, the need for superconducting magnets in accelerators at the Fermi National Accelerator Laboratory (Fermilab) and at the Brookhaven National Laboratory has led to improvements in the superconducting wire and cable available from industry. The new industrial capability can contribute in turn to the construction of larger and cheaper superconducting magnets for NMR imaging, the study of fusion, levitated rail transport and the like. The flow chart was adapted from a study of the economic utility of CERN, the European laboratory for particle physics.

A third process that derives energy from mass is the interaction of matter with antimatter. It is well known that if matter and antimatter are brought in contact, they annihilate each other; the mass of matter and antimatter is converted almost entirely into energy. Antiparticles kept in isolation from ordinary matter by, say, a strong magnetic field therefore constitute a kind of storage battery, a compact way to store large amounts of energy that can be released at a controlled rate. In 1977 a memorandum published by the Jet Propulsion Laboratory of the California Institute of Technology discussed the applications of such a device for space travel.

The trouble is that antiparticles are difficult to generate and store. At the Fermi National Accelerator Laboratory (Fermilab) my colleagues are designing a machine that will generate antiprotons by smashing a beam of protons into a stationary target made up of tungsten. The antiprotons will be collected and stored in a magnetic ring; they will then be accelerated and allowed to collide with a beam of protons traveling in the opposite direction in order to study physical systems at extremely high energy. Although our design will yield large numbers of antiprotons, a practical device for storing energy would require a beam of antiprotons at least a million times as intense as our own.

In 1956 Luis W. Alvarez and his coworkers at the University of California at Berkeley unexpectedly discovered a mechanism whereby fusion reactions can proceed at low temperatures and so release a large amount of energy. They observed several unusual tracks made by elementary particles in a bubble chamber filled with hydrogen. The tracks were caused by the formation of a molecule made up of one proton, or nucleus of hydrogen, and one nucleus of deuterium, which is a heavy isotope of hydrogen whose nucleus includes a proton and a neutron. The two nuclei were bound together by a negatively charged muon, which played the role in the binding of the molecule ordinarily played by the electron; the resulting molecule had a single negative charge.

The most important property of the new molecule is its size. Because the muon is 200 times heavier than the electron, the hydrogen and deuterium nuclei are 200 times closer to each other in the new molecule than they are when the binding is effected by an electron. The proximity of the nuclei enables them to fuse together at ordinary terrestrial temperatures to form the nucleus of helium 3, a helium isotope; the reaction yields about five million electron volts (MeV) of energy. Furthermore, the muon is ejected and is free to catalyze another fusion reaction.

Alvarez described his observations in

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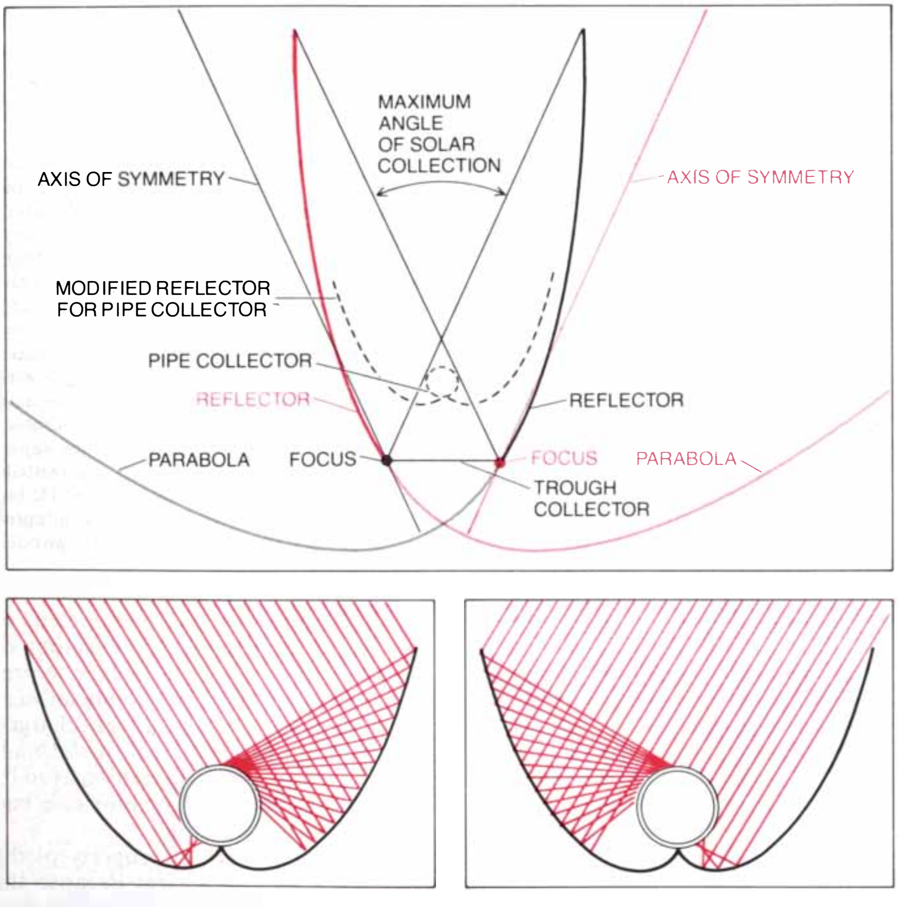
1972: "We had a short but exhilarating experience when we thought we had solved all of the fuel problems of mankind for the rest of time. A few hasty calculations indicated that in liquid HD [hydrogen and deuterium] a single negative muon would catalyze enough fusion reactions before it decayed to supply the energy to operate the accelerator to produce more muons, with energy left over after making the liquid HD from seawater. While everyone else had been trying to solve this problem by heating hydrogen plasmas to millions of degrees, we had stumbled on the solution... involving low temperatures instead."

More careful work showed the initial calculations were in error; it was subsequently found that in the hydrogen bubble chamber only about five fusion reactions could be catalyzed before the muon underwent radioactive decay. Nevertheless, several theorists, including Andrei D. Sakharov, speculated as early as the late 1940's that such a process could catalyze enough fusion reactions to pay for the energy of the accelerator, if only nature would provide a heavy and stable particle that is similar to the electron. Until recently the muon was assumed to be too short-lived, but that assumption has now been called into question.

Last year Steven E. Jones of the Idaho National Engineering Laboratory demonstrated a so-called resonant enhancement of the catalytic properties of the muon in pressurized mixtures of deuterium and tritium, another heavy isotope of hydrogen. As many as 100 fusion reactions were catalyzed by a single muon, and each reaction yielded 17.4 MeV. The energy is far greater than that initially observed by Alvarez; if the number of fusions can be further increased and accelerators are designed to maximize the production of negative muons, a practical, low-temperature fusion reactor may become possible. Could other particles catalyze a fusion reaction?

George Zweig of the California Institute of Technology has speculated deeply about fusion catalysis by heavy particles that bear a fractional electric charge. The process depends on the existence of such particles, and up to now they have proved to be quite elusive. If they could be generated in an accelerator, however, and then introduced into a gas of deuterium molecules, they could bring about the fusion of the deuterium nuclei. The reaction releases between three and four million electron volts of energy; the heavy, fractionally charged particle is then free, like the muon, to catalyze another fusion reaction. Zweig estimates that one mole of such particles, or about a cubic foot of them if they form a gas, could generate energy at a rate of 10^{16} B.t.u. per year.



INDIRECT BENEFIT of technology originally designed for the detection of elementary particles is a stationary device that collects solar energy without having to track the daily motion of the sun. The collector, which is called a compound parabolic concentrator, is based on the geometry of two intersecting parabolas: the gray one and the colored one shown in the top panel. All light rays that enter the collector from a direction parallel to the axis of symmetry of, say, the colored parabola bounce off the surface of the dark-color reflector and meet at the focus in color. Light rays from directions between the direction of the colored axis of symmetry and the vertical are reflected to some point along the trough collector. Similarly, light from directions between the vertical and a direction parallel to the axis of symmetry of the gray parabola is either reflected to the trough collector or directly intercepted by it. Thus all the solar energy entering the collector is concentrated along the trough or, if the shape of the reflector is modified slightly, along a pipe carrying water that can store the energy as heat. The two bottom panels show how solar energy is concentrated along the pipe for two positions of the sun. The device was invented by Roland Winston of the University of Chicago for detecting Čerenkov radiation, a dim blue light given off by certain particles during passage through a medium.

The potential for direct benefit from the work of the past 30 years in high-energy physics is by no means exhausted by proposals for generating energy. Consider the raw census data for particles: hundreds of them have been discovered since the 1950's, but their properties have only begun to be exploited.

The neutrino, for example, interacts so weakly with matter that in a beam of moderate power only about one neutrino in a million would be stopped on its way through the center of the earth. If the intensity of a neutrino beam passing through the earth is increased, its attenuation on the far side of the earth becomes measurable. The possibility of measurable attenuation has led to the proposal that beams of neutrinos be aimed at the interior of the earth from various points on the ground. From the attenuation in the beams brought about by passage through the earth a computer could reconstruct an image of any interior slice of the earth. The procedure is identical in principle with a CAT scan, or computerized axial tomography, of the head, which makes it possible to reconstruct the image of a slice of the brain by measuring its absorption of X rays from various directions. Neutrino beams could also be exploited in the search for oil, ore and similar mineral deposits.

I must emphasize that the direct benefits of current activity in fundamental science that I have discussed so far are extravagant speculations; it is quite possible they will never come to pass. I list them only to suggest that if history is to be the guide, the future applications of science may be far more bizarre than one can imagine. Lest these proposals seem too fantastic, it is worth citing a

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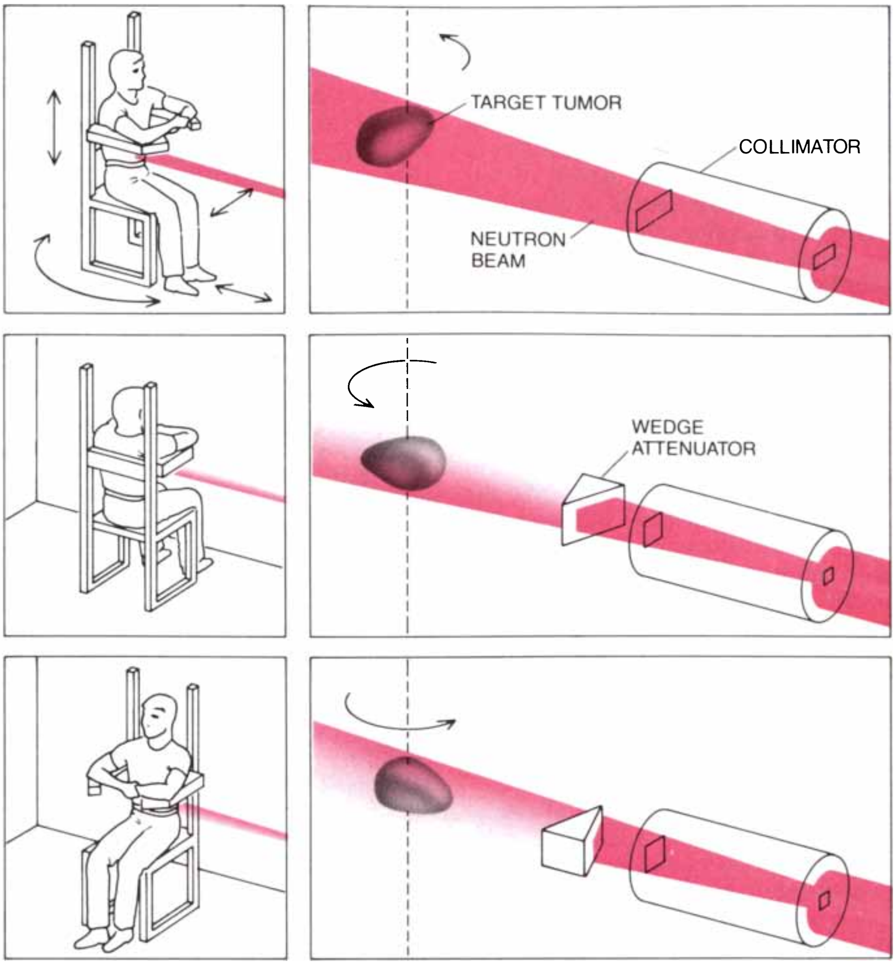
few examples of relatively recent work in fundamental science from which applications have already developed.

I have mentioned that under certain conditions exotic particles can replace the electrons, neutrons or protons in ordinary matter. They can thereby become useful as physical probes and markers. A positively charged muon, for example, can replace the proton in the nucleus of the hydrogen atom to form the so-called muonium atom; the chemistry of the atom and its isotopes has been studied in semiconductors and in insulators. The use of muons as tags to detect distortions of a solid atomic lattice, the presence of impurities or the diffusion of a material over a surface or in a fluid is already well established. It is difficult not to be sanguine about the variety of new and potentially useful properties that may arise among composite systems of exotic particles. The very scale of the phenomena suggests that if applications are found, they will be momentous.

A second direct benefit has developed out of the great interest of the 1940's in the magnetism carried by atomic nuclei. A spinning proton, for example, acts like a tiny magnet, and the spin axes of a collection of protons will align themselves with an external magnetic field. If a radio signal of just the right frequency is applied to the spinning protons, it can cause the spin axes to flip, or reverse direction. The spin reversal absorbs energy from the radio signal; by measuring the frequency of the absorbed energy, fine details of the atom's structure can be determined. The technique is the basis of NMR imaging in medicine, a noninvasive diagnostic tool that has many advantages over other techniques such as X-ray, CAT or ultrasound imaging. Some financial analysts predict that NMR will soon generate sales of $1 to $2 billion per year.



NEUTRON THERAPY is a form of experimental radiation therapy now under investigation at Fermilab. The neutrons are created by bombarding a piece of beryllium with protons ordinarily supplied to the main accelerator for the study of elementary-particle interactions. Here a patient with a pancreatic tumor is seated in a chair whose vertical axis of rotation can be fixed at the center of the tumor volume in the horizontal plane. The treatment room, which is a converted freight elevator, is then lowered until the tumor can be centered vertically on the axis of the fixed beam of neutrons. The size and shape of the neutron beam is controlled by a collimator, which can be rotated within its sleeve or removed and replaced. The intensity of the beam can be varied from point to point in its cross section by inserting a wedge of varying thickness in the path of the beam; the thicker the wedge, the more attenuated the beam. The tumor is first exposed to the neutron beam entering from the patient's front, then from the patient's right side and finally from the patient's left side. The thick part of the wedge is toward the front of the patient in the final two exposures in order to deliver a more uniform dose of radiation to the tumor. The aim is always to maximize the radiation that reaches the lesion and to minimize the radiation that reaches surrounding tissues. A patient in better health would have been treated in a standing position in order to reduce the radiation dosage to the intestines.

It is quite likely that the public cost of fundamental science can be justified by simply comparing it dollar to dollar with the value of the indirect benefits of science, including technological spin-off. The current cost can only be estimated from the national budget. Defined in a rather loose way, the line item designated basic research was allocated about $7 billion in 1984, or slightly less than 1 percent of the total Federal budget. Of this amount I estimate that only about $2 to $3 billion is really supporting fundamental science; the rest is supplied for basic research that has some connection with mission-oriented science. Alvin M. Weinberg of the Institute for Energy Analysis in Oak Ridge and others have suggested that whereas the cost of not so basic research and development must be borne by its beneficiaries, the cost of fundamental science should be treated as overhead for the total research and development effort.

The experimental work required for fundamental science traditionally leads to the invention of novel instruments and techniques that are later found to create goods and services adding to the gross national product. The return to the U.S. Treasury in the form of taxes collected on the new business generated is at least a substantial fraction of the cost of fundamental science. In addition there are the new products themselves, which may contribute to health care, to the quality of life or to the general well-being and security. Only part of the value of such products is quantifiable. The accelerator that destroys a tumor generates profits for the manufacturer, for the doctor and for the hospital. It is more difficult, although statistically possible, to put a cash value on the extended life, provided one chooses not to regard the life as priceless.

A second kind of indirect benefit of fundamental science is the creation of new opportunities for basic experimental investigations in completely different fields. X-ray diffraction, for example, was invented to study the structure of crystals soon after the nature of X rays was explained. The technique was then borrowed by molecular biologists, whereupon it assumed an essential role in the elucidation of the structure of DNA. The continuing technological spin-off from the early investigation of

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DNA is by now quite familiar [see "Industrial Microbiology," SCIENTIFIC AMERICAN; September, 1981].

There is a third kind of indirect benefit that arises from the theoretical work of fundamental science. Much of this work can also be exported to other fundamental disciplines and modified there for home use as needed. For example, solutions found to certain kinds of equations that appear in the so-called electroweak theory of elementary-particle interactions have been applied in the study of the physics and chemistry of polymers. Mathematical methods for the evaluation of certain equations important in the study of elementary particles have been applied to describe the propagation of density waves in the ocean and to follow the likely pattern of percolation of an oil deposit in a region of the earth's crust. Much current research on computers that might one day process information in parallel has been guided by the computing needs of the theory of quantum chromodynamics, which describes interactions of elementary particles that are mediated by the strong force.

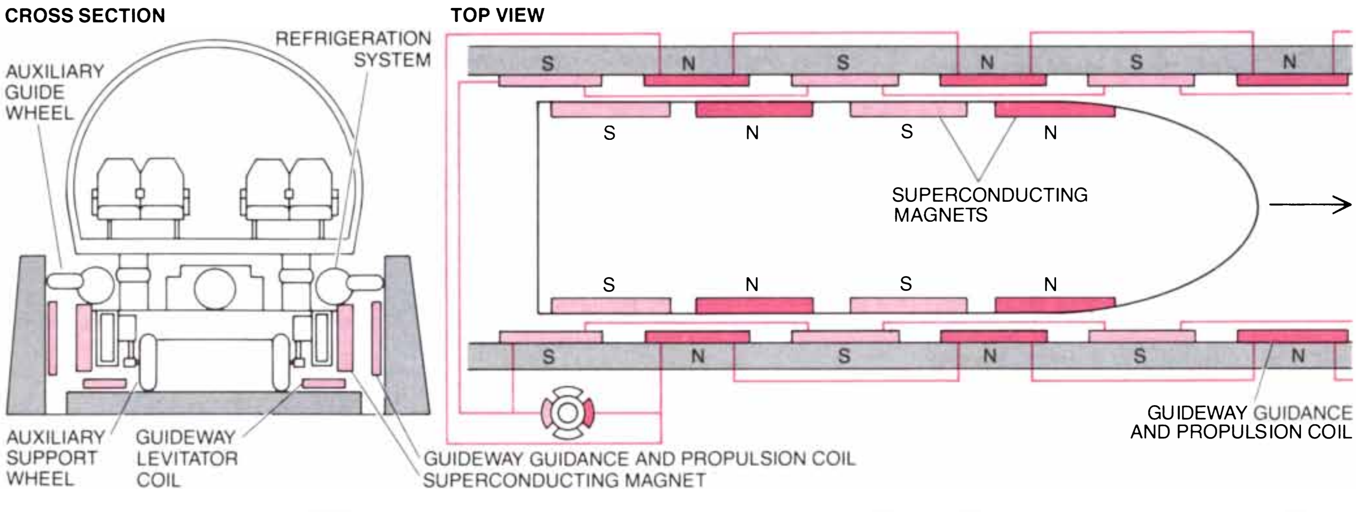
The fourth indirect benefit of fundamental science is the training of scientists. In high-energy physics about 130 people receive doctoral degrees in the U.S. each year. About half of them initially remain within the discipline, but defections are continual; the equilibrium input rate has been set at about 50 per year since 1974. My experience with graduates of the high-energy physics laboratory at Columbia indicates that the other 80 people who receive the Ph.D. in high-energy physics each year are drawn to highly diverse fields, including industrial research, college teaching, Government laboratories not involved in high-energy physics, biophysics, computer science, administration, finance and management or ownership of a business. To this total one should add engineers, technicians and computer programmers who are also trained in fundamental science and then hired away. The flow of talent away from fundamental science has been an important resource in large technological projects at least since World War II.

To indicate the depth and diversity of technological spin-off I shall briefly take a closer look at several aspects of experimental work in high-energy physics that have led to useful devices elsewhere. In this context I must again emphasize that high-energy physics is not unique. Fundamental investigations in chemistry, biology, astronomy and so forth have led to applications of similar variety and interest.

The particle accelerator was initially invented in order to bombard atomic nuclei with energetic projectiles. The outcome of the interaction gives a great deal of information about the structure of the target nuclei. Particle accelerators have been applied in industry to tasks almost totally unrelated to their function in high-energy physics. They are now employed for the inspection of thick steel vessels and pipes, the production of radioisotopes needed in medicine, the sterilization of food, the disinfection of sewage that is to be recycled as fertilizer and the direct treatment of tumors. Accelerators were run extensively to collect the data needed for the design of fission and fusion reactors. One plan for generating power from nuclear fusion calls for accelerated beams of ions that would compress and ignite small pellets of nuclear fuel.

The techniques developed for accelerating beams of electrons have now been applied to create highly energetic pulses of light ions. Such pulses can deliver a few trillion watts of power over a small surface for a short time; they could also be applied in the fusion-energy program to confine the intensely hot fusion reaction. Accelerators are used to implant ions in semiconductor materials during the manufacture of integrated circuits, to add extremely small quantities of rare metal to a melt in the manufacture of alloys, to survey for hydrocarbon deposits in the rock surrounding the shaft of a well and to convert certain plastics, such as those used in the manufacture of baby bottles and shrinkable wrapping, into materials that will not melt in boiling water.

Electron accelerators also give rise to



SUPERCONDUCTING MAGNETS carried on board a Japanese test train induce a strong magnetic field of the same polarity in coils of wire embedded in the bottom of the guideway. The repulsion between the superconducting magnets and the guideway magnets levitates the train, thereby eliminating the friction between wheel and track that accounts for much of the energy loss by an ordinary train (*left*). The train is also propelled magnetically; in effect, the propulsion system is a synchronous electric motor rolled out onto a line. Coils are mounted on both sides of the guideway and connected to a source of electric power in such a way that their magnetic polarity alternates between north and south along the guideway (*right*). The polarity of the superconducting magnets on the train does not change. Each superconducting magnet is pushed forward by the repulsion of the nearest side coil of like polarity and simultaneously pulled forward by the attraction of the next side coil of unlike polarity. The polarity of the side coils is then reversed and the train is given another forward impulse. The train shown schematically in the illustration is the MLU 001, which has been built to 60 percent of full scale and tested at speeds of up to 185 miles per hour at the Miyazaki Test Track in Japan. The application of superconductivity on a scale as large as a full-scale passenger railroad requires large refrigeration systems and piping for the liquid-helium coolant that must be kept at 4.2 degrees Celsius above absolute zero. By far the most extensive liquid-helium refrigeration system in the world has been built at Fermilab to cool 1,000 superconducting magnets installed in a ring four miles around, which control and focus beams of particles. Experience at Fermilab and at other superconducting accelerators should therefore prove useful in large-scale applications of superconductivity.

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synchrotron radiation, the electromagnetic radiation generated by the deflection of charged particles in a magnetic field. In the X-ray and ultraviolet regions of the spectrum its intensity can be up to five orders of magnitude greater than the radiation generated by conventional sources. Its high intensity and broad spectrum make synchrotron radiation useful in a variety of applications. In the manufacture of integrated circuits, for example, synchrotron radiation promises to make possible a hundred- to thousandfold increase in circuit density on each chip produced.

Synchrotron radiation also has potentially important medical and biological uses. In diagnosing cardiovascular disease or studying the structure and function of vasculature, physicians and medical scientists find it useful to be able to view coronary and other small arteries. The high intensity of synchrotron radiation may enable clinicians to examine the smallest of these structures while greatly reducing the risk to the patient.

To do full justice to the stimulation the accelerator has given the national economy one must also cite spin-offs from the spin-offs. The development of the accelerator has led to advances in the generation of ultrahigh vacuums and high-power signals at radio frequencies, in precision-beam optics, in electronic controls and in the understanding of the properties of materials under highly energetic bombardment. The net effect of these applications is to generate economic activity worth many billions of dollars per year.

A major aspect of fundamental work in experimental physics is the detection of the products of the collisions of elementary particles once they are created. Detectors such as Geiger counters, ion chambers and scintillation counters coupled to photomultiplier tubes are familiar elements in many industries that employ accelerators. The manufacture of gamma-ray detectors made out of sodium iodide crystals activated with thallium has become part of a business with sales of $50 million per year.

Digital circuitry originally devised to register the trajectories of particles played a major role in the early development of the computer, and the huge amount of data flowing from the current generation of accelerators continues to stimulate work on novel techniques for data processing and on new computer architectures. Data processing at a rate of 10 billion bytes per second is now standard in high-energy physics, and rates orders of magnitude higher are expected. Indeed, the computing needs of high-energy physicists have been instrumental in the proliferation of small, innovative computer companies. That proliferation has led in turn to a highly competitive industry with significant benefits for the consumer.

The detection of particles has also led to innovative solutions to quite general problems. For example, in order to determine which of several million nuclear events per year are worthy of more detailed examination, automatic systems were devised for recognizing certain patterns of signals from the detector. Such techniques of pattern recognition and signal processing have been adopted by astronomers and biologists.

Some of the most recent work in high-energy physics should increase the reliability and availability of devices that exploit the effects of superconductivity. Physicists built the first large superconducting magnets to serve as components of instruments that detect elementary particles. More recently the technology has been extended to the construction of magnets for use in accelerators, which is a much more difficult undertaking. The magnetic field must be capable of being varied and maintained with great precision throughout the accleration cycle. A superconducting ring of magnets four miles in circumference has now been installed at Fermilab; the scale of the installation, including the cryogenic facility required to cool 1,000 magnets to within about four degrees C. of absolute zero, is unprecedented. It demonstrates the feasibility of building the large-scale refrigeration system, piping system and computer controls required for superconducting operations.

Even larger superconducting installations would stimulate industry to manufacture superconducting components, thereby lowering the unit cost, creating jobs and bringing the considerable potential benefits of superconductivity closer to practical realization. For example, superconducting power lines would transmit electric power without loss. One could then contemplate even greater separation between the objectionable power plant and the consumer. Superconducting magnets have already been installed on board experimental passenger trains in Japan, which allow the train to float above magnets of the same polarity in the roadbed.

It is by no means clear what relation exists between the benefits of fundamental science—cultural, direct and indirect—and its costs. What does appear to be true is that the relation is not strictly proportional: if support falls below some critical level, fundamental science would probably decline sharply. The number of scientists who could remain working actively under such conditions would be reduced. In many subdisciplines the discussion necessary to fruitful advance would wither away for lack of competent, interested participants.

Without knowing the exact nature of the response of science to various levels of public support it is still possible to set criteria that can measure the adequacy of funding. One reliable indicator is the rate at which creative young investigators come to the fore. In the physical sciences that rate has fallen from its highest level of more than 4,500 new Ph.D.'s, achieved in 1971, to its current plateau of about 3,400. In the life sciences the absolute number of new doctorates is increasing, but the rate of growth has slowed almost to zero. The most critical shortfall appears to be in mathematics. Even when mathematics is lumped together with computer science, the number of new Ph.D.'s is dropping rapidly. Such a compression of our fundamental scientific resources is a tragic mistake. Because breakthroughs in science and technology are often made by individual genius, the loss of even one person capable of, say, finding a cure for cancer can be costly indeed.

What is to be done? My survey here provides only a rough guide for a definitive study of the economic and cultural effects of fundamental science. A definitive study could address three main issues. First, it could seek to identify the fields of science that are most remote from application and deserve to be called fundamental; obviously there will be gray areas. Second, it could track the effects of past and ongoing work in fundamental science discipline by discipline. Such a study would make the connections between laboratory and industry explicit, and it would assess the performance of the industrial follow-up, given the potential of the laboratory work. Finally, the study could estimate the contribution made by fundamental science to the education of people needed in technology and the more applied sciences. One of the subtlest questions here is quality: are the best minds, as much lore would have it, retained by fundamental science?

It is the thesis of this article that such a study would clearly indicate that fundamental science pays for itself, and it returns to society both cultural enrichment and the continued resources for enhancing the quality of life. Moreover, given the increased stresses on our natural resources and on the environment that the future appears to hold, an adequate base of fundamental knowledge on which to build a technological response becomes a matter of survival. One can safely assume that for all these reasons the idea of fundamental science as a national trust is both sound and profitable. The goal is then to reproduce some fraction of the opportunities young investigators had in that greatly productive scientific period between 1955 and 1968. If this goal is reached, the public and the policymakers who serve the public cannot lose.

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The Infrared Sky

An orbiting, liquid-helium-cooled telescope has made panoramic images of the infrared sky, recording the glow from cold, solid matter in the solar system, the galaxy and the universe at large

by Harm J. Habing and Gerry Neugebauer

For astronomers the infrared region of the electromagnetic spectrum holds both fascination and frustration. Many astronomical objects—principally those made up of cool, solid matter—radiate most of their energy at infrared wavelengths. Moreover, certain events of special interest—such as the birth of stars and the condensation of planetary systems—can be seen to best advantage through infrared observations. At the earth's surface, however, the atmosphere blocks almost all infrared radiation. Furthermore, building an astronomical instrument sensitive to infrared wavelengths is a considerable technical challenge. Hence long after the sky had been thoroughly surveyed at visible and radio wavelengths, and even after ultraviolet, X-ray and gamma-ray surveys had been made, the infrared sky remained largely unmapped. Only at the shortest infrared wavelengths could the sky be surveyed with high sensitivity.

A comprehensive sky survey covering a broad range of infrared wavelengths has now been completed by instruments aboard the *Infrared Astronomical Satellite* (*IRAS*). The satellite was launched in a joint undertaking by the Netherlands Agency for Aerospace Programs (NIVR), the U.S. National Aeronautics and Space Administration (NASA) and the U.K. Science and Engineering Research Council (SERC). It operated throughout most of 1983, recording images of 98 percent of the celestial sphere. The mission has produced rich rewards: from the data returned by the satellite we have compiled maps of the sky's brightness in four bands of infrared wavelengths and catalogued some 250,000 discrete sources of infrared emission. The magnitude of this number bears emphasizing. In all the history of astronomy before *IRAS* some 500,000 sources had been catalogued.

As a survey instrument *IRAS* was intended primarily to give an overall view of the infrared sky and to identify objects that merit further investigation. Both goals were accomplished. Within the solar system the satellite detected several new comets and a pair of tenuous dust bands above and below the asteroid belt. An extensive band of solid material was found in orbit around a nearby star; the band may represent an early stage in the formation of a planetary system. Elsewhere newborn stars were observed still shrouded in the veil of gas and dust from which they had condensed. The satellite gave a clear and panoramic view of the core of the Milky Way. Other galaxies detected by *IRAS* include some that are more than 50 times brighter at infrared wavelengths than they are in the visible band.

The *IRAS* observations were not the first ones ever made of the infrared sky. Ground-based observations are possible in narrow "windows" in the spectrum where wavelengths of near-infrared radiation, shorter than those sampled by *IRAS*, can penetrate the atmosphere. For far-infrared studies telescopes have been carried aloft by balloons, rockets and high-altitude aircraft, but it is difficult to make a sensitive all-sky survey in the far infrared by these techniques. Such a survey is important in large part because it is unbiased; in an observing program looking only at selected objects, the findings may be skewed by the selection process. A satellite observatory is an ideal platform for a survey.

Atmospheric opacity is not the only problem facing the infrared astronomer. Infrared radiation is emitted copiously by matter at ordinary terrestrial temperatures; for example, the barrel and the optical components of a telescope at room temperature glow brightly in the infrared. The glow tends to overwhelm the infrared signal of interest. In the insulating vacuum of space it was possible to solve this problem by cooling the entire telescope with liquid helium. *IRAS* had by far the largest cryogenic system ever launched into earth orbit. The need to conserve the helium supply had a major influence on the design of the telescope and on the observing program. Ultimately it was the evaporation of the coolant that ended the mission.

Planning for *IRAS* began in 1974. Both NASA and the NIVR had such studies under consideration; it was decided to combine the two programs, and soon thereafter the SERC joined the endeavor. The telescope, the main survey detectors and the cryogenic system were built in the U.S. by NASA. The remaining parts of the spacecraft, including the solar panels for electric power, the on-board computers and systems for controlling and pointing the telescope, were constructed in the Netherlands by the NIVR. The U.K.'s SERC built a ground station at the Rutherford Appleton Laboratory in Chilton, England, to operate the satellite. Project management of activities in the U.S. was at the Jet Propulsion Laboratory of the California Institute of Technology, where the final analysis of most of the data is being done.

The telescope had a "folded" optical path: radiation struck a 57-centimeter

INFRARED VIEW OF THE SKY, showing a 22-by-30-degree area in the constellations Taurus and Perseus, was constructed from data gathered by the *Infrared Astronomical Satellite* (*IRAS*). The image combines measurements of the flux of radiation in three bands of infrared wavelengths: 12-micrometer emissions are blue, 60-micrometer green and 100-micrometer red. Thus the colors indicate the approximate temperature of the emitting matter: blue areas are the warmest and red areas are the coolest. The image records the total flux in square "bins" two minutes of arc on a side. The two largest glowing areas are the nebulas NGC 1499 (at the top of the image) and IC 348. They are aggregations of gas and dust warmed by embedded stars. The white, comma-shaped object below IC 348 is the emission from dust surrounding the Pleiades, a cluster of young, hot stars. To the left of the Pleiades, near the edge of the image, is a region of star formation known as TMC 1; a semicircular cluster of four newborn stars can be seen within it, shrouded in the dust from which they condensed. Alpha Tauri, the brightest star in the region at visible wavelengths, is a faint blue dot three and a half inches below TMC 1.

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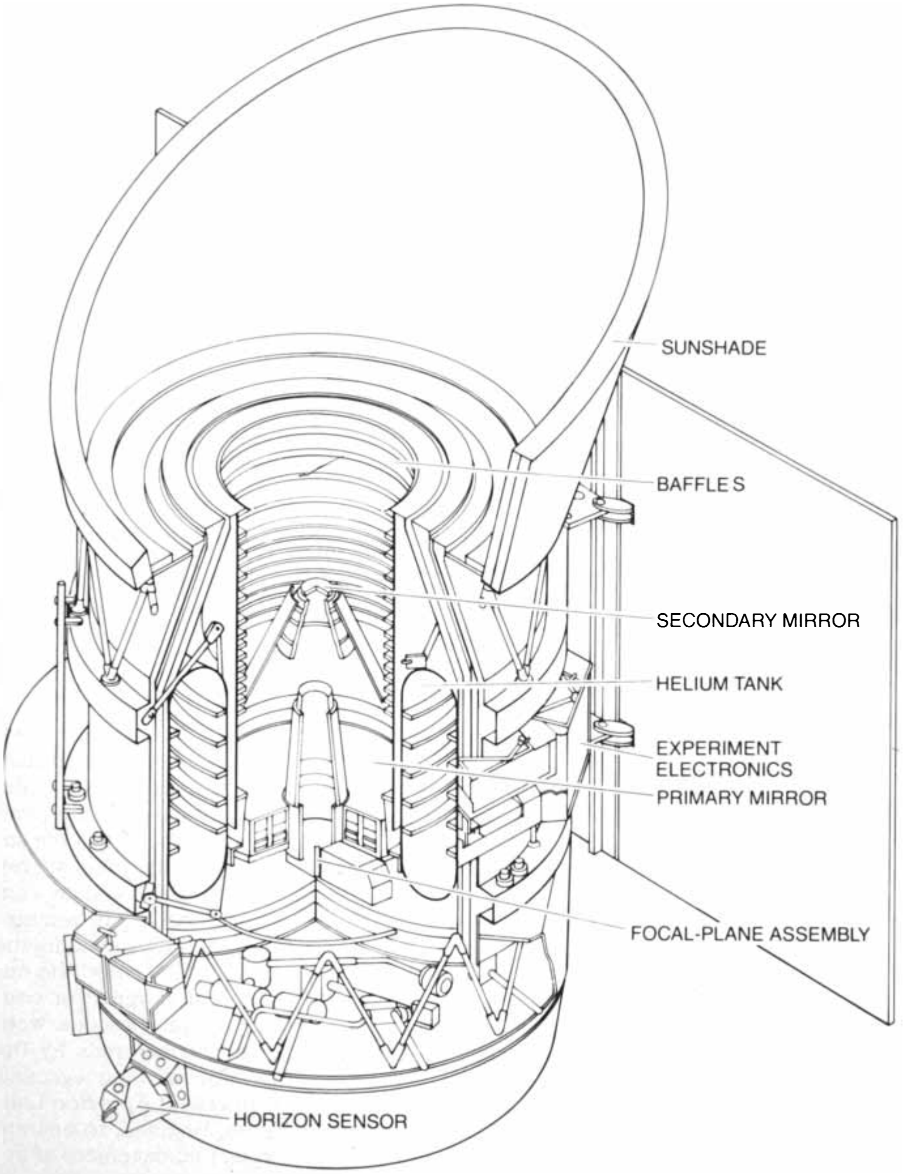
primary mirror, then a small secondary mirror directed it through an opening in the center of the primary. At the focal plane the radiation was focused onto three instruments incorporating semiconductor detectors sensitive to radiation at infrared wavelengths. An insulated vessel filled at launch with 475 liters of liquid helium housed the telescope. The coolant kept the barrel of the telescope and the mirrors at about 10 degrees Kelvin (degrees Celsius above absolute zero). The detectors were even colder: about two degrees K. The coolant was maintained at this temperature, below its boiling point, by allowing it to evaporate slowly.

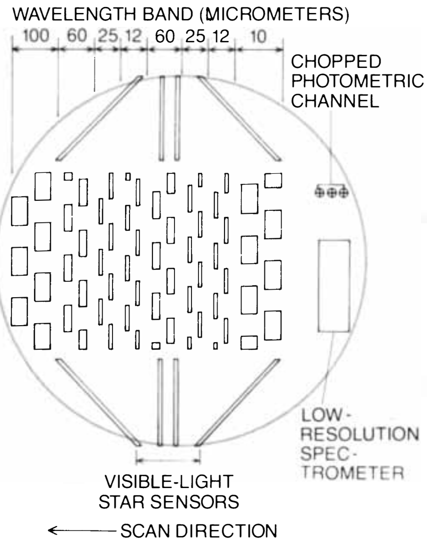
The detectors were photoconductive devices fitted with filters so that they would respond to specified bands of infrared wavelengths. They were extraordinarily sensitive: the telescope could detect a speck of dust at a distance of two or three kilometers. The main survey instrument was an array of 62 detectors that covered the major portion of the infrared spectrum, from eight to 120 micrometers, in four bands centered on wavelengths of 12, 25, 60 and 100 micrometers. (The visible part of the spectrum extends to about .7 micrometer, and radio waves begin at about 1,000 micrometers.) In addition to the main array of detectors two other instruments were mounted at the focal plane: a spectrometer for recording the infrared spectrum of bright sources and a photometer for measuring preselected sources with higher spatial resolution than the survey array could provide.

Each element in the main detector array was swept over a strip of sky about five minutes of arc wide and produced a signal proportional to the total flux of radiation it received in its band of wavelengths. Computer processing done on the ground extracted discrete sources from the continuous data stream and combined multiple sightings of a single source. Because of the nature of the processing, the discrete sources were "pointlike"; given the angular resolution of the *IRAS* sensors, this means smaller than a few arc minutes.

The satellite's orbit, at an altitude of 900 kilometers, was a near-polar one. The plane of the orbit precessed by about one degree of arc per day, just matching the earth's orbital motion around the sun. In this way the spacecraft was kept constantly near the earth's terminator—the boundary between day and night—and therefore pointed roughly 90 degrees away from the sun.

The great sensitivity of the detector elements came at some cost: many spurious signals were generated by dust and debris near the satellite and by the passage of cosmic rays and other energetic particles through the detectors. Astronomical signals were sifted from this background noise by requiring that each recognized source be confirmed by repeated observations over several time scales. A source seen by two detector elements a few seconds apart was said to be seconds-confirmed. A source picked up on two consecutive orbits was then said to be hours-confirmed. Subsequent reexamination of the same area of the sky gave opportunities for weeks- and months-confirmation. By these means





INFRARED ASTRONOMICAL SATELLITE **carried a telescope with a primary mirror 57 centimeters in diameter and an array of electronic detectors sensitive to infrared radiation. In order to eliminate infrared emissions from the instrument itself the telescope was cooled with liquid helium, which kept the barrel and the optical system at about 10 degrees Kelvin and the detectors at two degrees. The main survey detectors mounted at the telescope's focal plane were silicon and germanium devices sensitive to four bands of infrared wavelengths. The detectors were arranged in staggered rows so that as the telescope scanned the sky the image of a source would cross at least two detectors in each band. The chopped photometric channel and the low-resolution spectrometer made additional measurements.**

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the survey achieved high standards of reliability and completeness. Except in those areas of the sky where the density of sources leads to confusion, we calculate that 99.8 percent of the sources catalogued are real and that no more than 2 percent of the real sources bright enough to be detected have been missed.

IRAS was launched on January 25, 1983, from Vandenberg Air Force Base in California. After a few days of preliminary tests the telescope's aperture cover was jettisoned and observations began. Twice a day some 700 million bits of image data were transmitted to the earth. About 60 percent of the observing time was given to the survey; the rest was used for "pointed observations" of selected targets. By August substantially complete coverage of the sky had been achieved, and another layer of scans was begun. By November 22, when the helium supply ran out and the 1telescope was shut down, *IRAS* had covered 95 percent of the sky with at least two hours-confirmed scans.

The findings of the *IRAS* mission bear on all the realms of astronomical interest: the solar system, nearby stars and interstellar space, other regions of the Milky Way, other galaxies and finally quasars and similar extremely distant objects. The data returned by the satellite give the first comprehensive view of what the sky "looks like" at far-infrared wavelengths.

The appearance of the sky depends to some extent on the spatial or angular size of the features being looked at, and it certainly depends on the wavelengths of observation. At the shortest *IRAS* wavelengths the bright pointlike objects are hot stars; one is seeing the long-wavelength tail of the stars' continuum spectrum, which peaks in the visible band. A dense concentration of stars marks the disk of the Milky Way galaxy. At the longer wavelengths the pointlike sources away from the plane of the Milky Way are essentially all external galaxies, whose emissions include a strong component with an effective temperature of from 20 to 60 degrees K. As would be expected, the galaxies detected have a fairly uniform distribution in space. The distribution of both the stars and the galaxies is shown in the lower illustration on the next page.

The *IRAS* observations of stars have also provided a new means of viewing the overall shape and structure of the Milky Way. By picking sources from the point-source catalogue that satisfy specific selection criteria, we can sample different constituents of the galaxy. In particular there is a class of bright infrared sources that can be selected because they radiate strongly at 12 and 25 micrometers and much less at other wavelengths. They are probably hot stars (with temperatures of some thousands of degrees) surrounded by cooler material (at a few hundred degrees).

The distribution of these sources is plotted in the upper illustration on page 53. It shows a clear pattern in which a galactic bulge is superposed on a thin wedge, presumably the disk of the galaxy. Similar bulges are readily perceived in other galaxies, but it has been impossible to see the overall shape of our own galaxy from our position within the disk.

Looking at the emission from extended features rather than from pointlike sources gives a different picture of the sky. At short wavelengths (12 and 25 micrometers) the main contributor to the infrared background is emission from the zodiacal dust, a component of the solar system. The dust is concentrated in the zodiacal, or ecliptic, plane (the plane in which the planets orbit) and in *IRAS* images it shines brightly. The detailed structure of the zodiacal emission is intriguing. The emission is densest in the ecliptic plane, as expected, but there are also two outlying bands about nine degrees above and below the ecliptic.

The material within the ecliptic plane might be generated by the grinding up of asteroids in multiple collisions, but the two halos flanking the plane are more difficult to explain. The fact that the material in the rings appears to orbit a point well above or below the solar poles is surely an illusion; the particles are in orbits that cross the ecliptic at an angle of nine degrees, so that a particle spends some of its time in each band. Two parallel rings are seen rather than a continuous cylinder because each particle spends more time away from the ecliptic than it spends near it. The question is: What could give rise to a well-defined population of dust particles with such a large orbital inclination? One possibility is the disintegration of a comet, perhaps in a collision with an asteroid.

An analysis of the emissions in the four wavelength bands reveals some of the characteristics of the dust particles. They must be comparatively large (perhaps 30 micrometers in diameter) and dark (reflecting only 10 or 20 percent of the radiation falling on them). Considering their proximity to the sun, they are relatively cool: probably about 275 degrees K., or close to room temperature. This fact in turn suggests they may be made up largely of silicates, which radiate at infrared wavelengths more efficiently than other candidate materials and therefore remain cooler. Silicates are the main components of most rocky solar-system bodies.

In the longer-wavelength bands the infrared background has other components. Of particular interest is the pattern observed in the background radiation at 100 micrometers. When the data in this band are spatially filtered to emphasize features that range in size from half a degree to about 10 degrees, the celestial sphere is seen to be covered by wispy clouds termed infrared cirrus.

The nature and the location of the infrared cirrus clouds are not yet definitely established. Some of them may be part of the solar system, but the failure of a preliminary analysis to detect any triangulation effect indicates the clouds are at least 1,000 astronomical units away (1,000 times the distance from the earth to the sun, or 25 times the orbital radius of Pluto); it should be possible to extend the limit to 5,000 astronomical units. The clouds might be as far away as 50,000 or even 100,000 astronomical units and still be gravitationally bound to the sun. At that distance they could be associated with the Oort cloud, a shell of material that is supposed to be the source of most comets.

Most of the infrared cirrus is probably in the interstellar medium, outside the solar system but within the sun's immediate neighborhood. Some of the cirrus features are coincident with clouds of hydrogen gas observed at radio wavelengths; the hydrogen clouds are known to be interstellar, at distances of a few hundred light-years or more (equivalent to several million astronomical units).

If the interstellar interpretation of the clouds is correct, they are made up of gas and dust ejected by dying stars and probably swept up by expanding supernova remnants. From the ratio of emissions at 60 and 100 micrometers the average temperature of the clouds can be calculated; it is between 25 and 50 degrees. That is warm for material at such a great distance from any star, which puts constraints on the possible composition of the dust grains. It is likely that very fine particles of carbon, in the form of graphite, are a major component of the clouds. Graphite particles radiate less efficiently than the silicate particles of the zodiacal dust and therefore stay warmer.

The first really surprising observations made by *IRAS* were of a few fast-moving objects in the solar system, namely comets. Data coming from the satellite were put through a preliminary computer analysis at the Rutherford Appleton Laboratory to detect sources that had moved between two hours-confirming observations. Early identification of such transitory bodies is essential if other observatories are to follow up on the discovery.

The first comet found by *IRAS* came to attention on April 26; it was also discovered by two amateur astronomers and was named comet IRAS-Araki-Alcock. On May 11 it passed within about three million kilometers of the earth, closer than any other comet in the past 200 years. The appearance of the comet's head was quite similar at infrared

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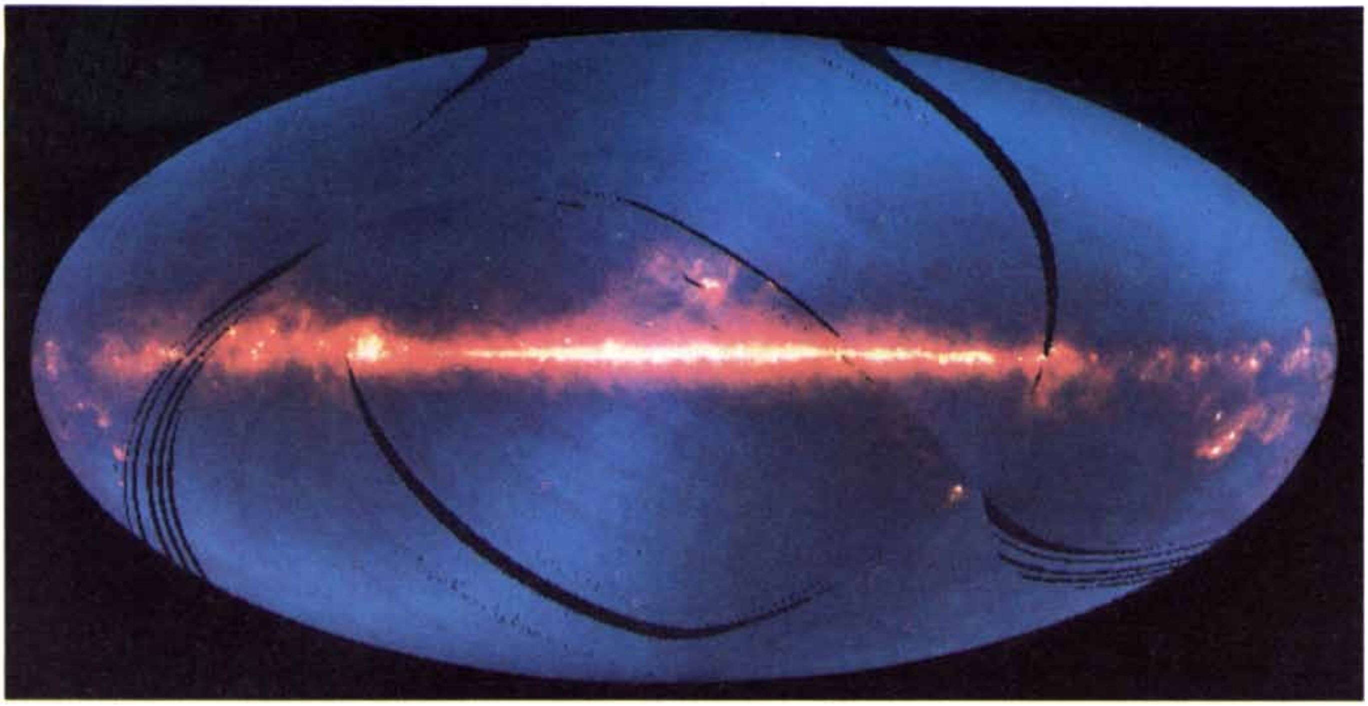
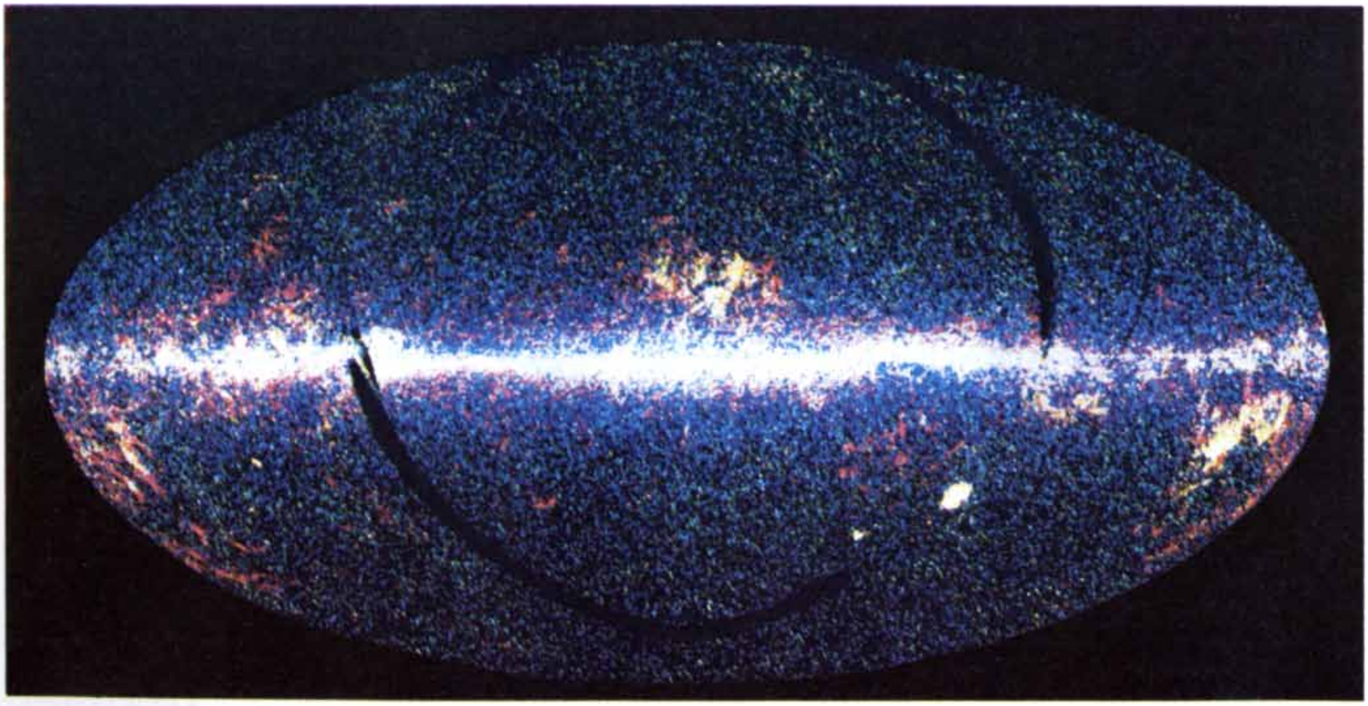
and visible wavelengths, but images of the tail revealed some remarkable differences. The visible tail was faint, narrow and comparatively short, but the infrared images showed a wide, bright tail that extended for at least 200,000 kilometers and probably for 400,000.

Comets are thought to consist of ice mixed with some dust, but the particles in the more distant regions of the tail cannot be ice because they would have evaporated in traveling from the head to the tail. Hence the material of the extended tail must be dust and probably has a silicate composition. It is being shed from the comet at a rate of some 200 kilograms per second, far faster than earlier estimates suggested.

By the end of the mission *IRAS* had discovered four more comets and had also made observations of Tempel 2, a



TOTAL INFRARED EMISSION in the *IRAS* bands in two-arc-minute bins is dominated by radiation from the galactic plane of the Milky Way and the ecliptic plane of the solar system. In this image (and in the others on these two pages) the entire sky is seen in a projection that orients the plane of the galaxy horizontally. The ecliptic plane is the faint, sinuous blue band. Emissions in the 12-, 60- and 100-micrometer bands are shown as blue, green and red respectively. Blank areas represent parts of the sky not covered by the survey.



STARS AND GALAXIES dominate a map of the sky prepared from the *IRAS* catalogue of discrete sources. The majority of stars, being quite hot, were detected at the shortest wavelengths to which *IRAS* was sensitive, namely the 12-micrometer band. They are shown here as blue dots. Most external galaxies gave their strongest signal at longer wavelengths; here they are detected by their emissions at 60 micrometers and are shown as green dots. Away from the galactic plane the distribution of galaxies over the sky is approximately uniform.

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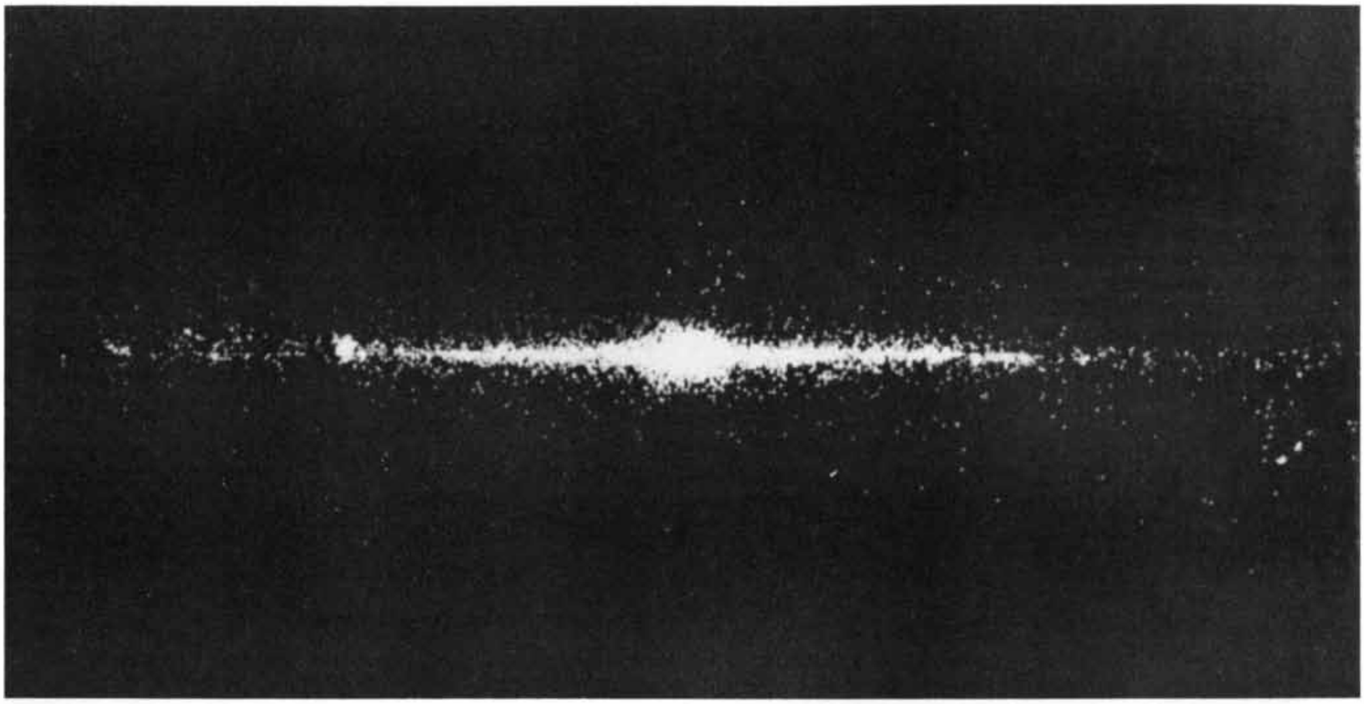
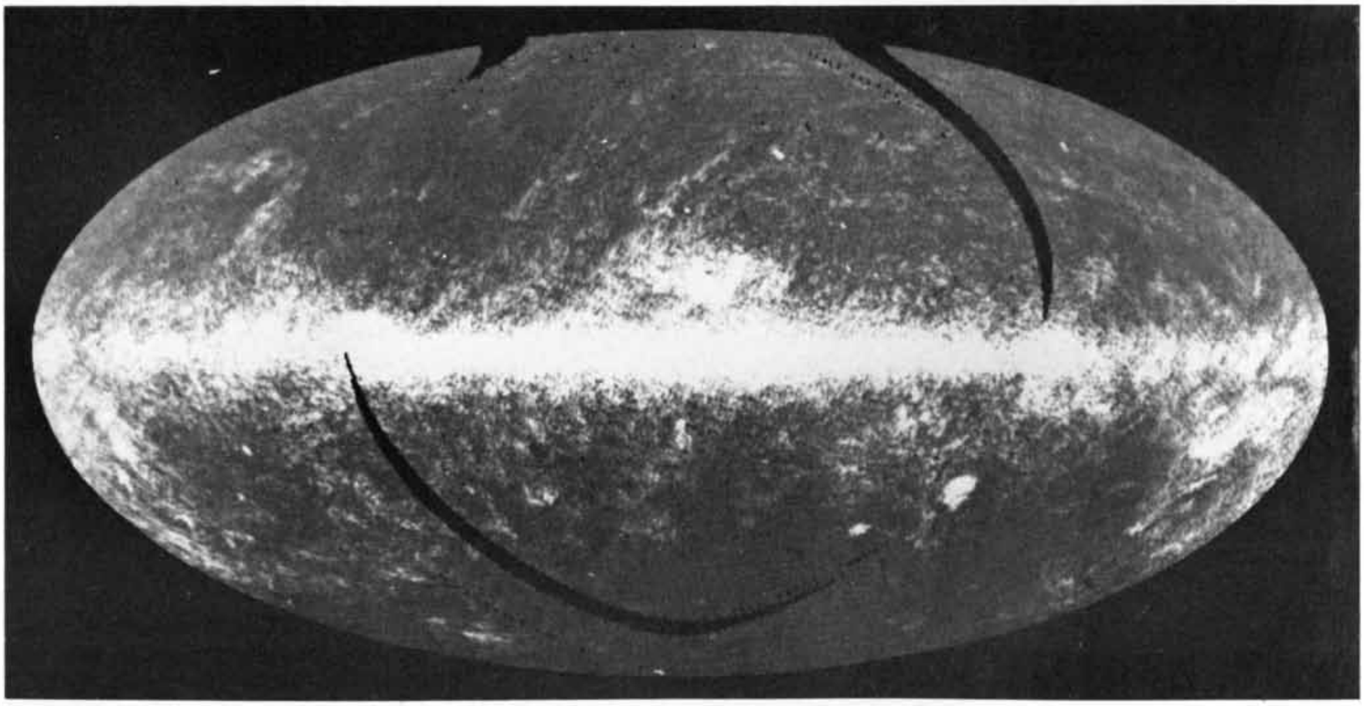
comet known from 16 previous appearances in the inner solar system. At visible wavelengths Tempel 2 appears to have no tail; it was assumed that all the volatile material had been driven off during earlier passages near the sun. The *IRAS* images revealed a long and narrow tail extending 30 million kilometers from the cometary nucleus.

A cometlike body discovered on October 11 turned out to solve a small mystery. Given the designation 1983 TB, the body was taken at first for an asteroid of the kind called an Apollo object; the Apollo objects follow trajectories that pass inside the earth's orbit. Indeed, the path of 1983 TB takes it well inside the orbit of Mercury, to within 20 million kilometers of the sun's surface. Soon it emerged that the orbit of 1983 TB corresponds closely with the orbits of the



OVERALL FORM OF THE MILKY WAY can be perceived in a sky map that shows the distribution of a small subpopulation of stars. The map was generated by selecting only discrete sources whose emissions at 12 and 25 micrometers indicate a temperature of about 400 degrees K. Most of them are dust-shrouded stars that radiate the bulk of their energy in the infrared. The galactic plane is clearly outlined by the distribution of the stars; there is also a bulge near the center of the Milky Way, which cannot be seen at visible wavelengths.



INFRARED CIRRUS CLOUDS are fluffy or wispy trails of cold dust that were found through *IRAS* observations to be distributed over the entire sky. The image is made from data received in the 100-micrometer band, filtered to enhance features with an angular size of between half a degree and 10 degrees. Some infrared cirrus clouds could be part of the outer solar system, but most of them are probably in nearby interstellar space. They may be the exhaust of stars—galactic smog—and are thought to be made up of fine graphite particles.

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Geminid meteoroids, which create an annual shower in December. Other meteor showers are generated by debris from comets, but no source for the Geminid shower had ever been identified. Since 1983 TB is evidently the parent body of the Geminid shower, it is now thought to be not an asteroid but the remnant of a dead comet.

Another solar-system body being sought in the *IRAS* data is a possible 10th planet, beyond the orbit of Pluto. The existence of such a planet has been proposed many times to explain anomalies in the motion of Neptune, and infrared emission is the sign most likely to betray its presence. Indeed, if a 10th planet exists, evidence of it is almost surely there to be found among the *IRAS* point sources that do not meet the elaborate confirmation criteria. As yet it has not been discovered.

Perhaps the biggest surprise of the *IRAS* mission came quite early, when the instruments were being calibrated by observations of bright, nearby stars. One of these "standard candles" was the young, hot star Vega, or Alpha Lyrae, 26 light-years from the sun, which at visible wavelengths is the fifth-brightest star in the sky. Vega is about two and a half times as massive as the sun and 50 times as luminous. It has been observed extensively at wavelengths ranging from the ultraviolet to about 20 micrometers, and its properties were thought to be well understood. In particular, theoretical models were quite successful in describing the star's visible spectrum. The *IRAS* measurements at 12 micrometers were in good agreement with the models, but at longer wavelengths there was a major discrepancy. Emission should have fallen off sharply beyond 25 micrometers; instead it remained almost constant.

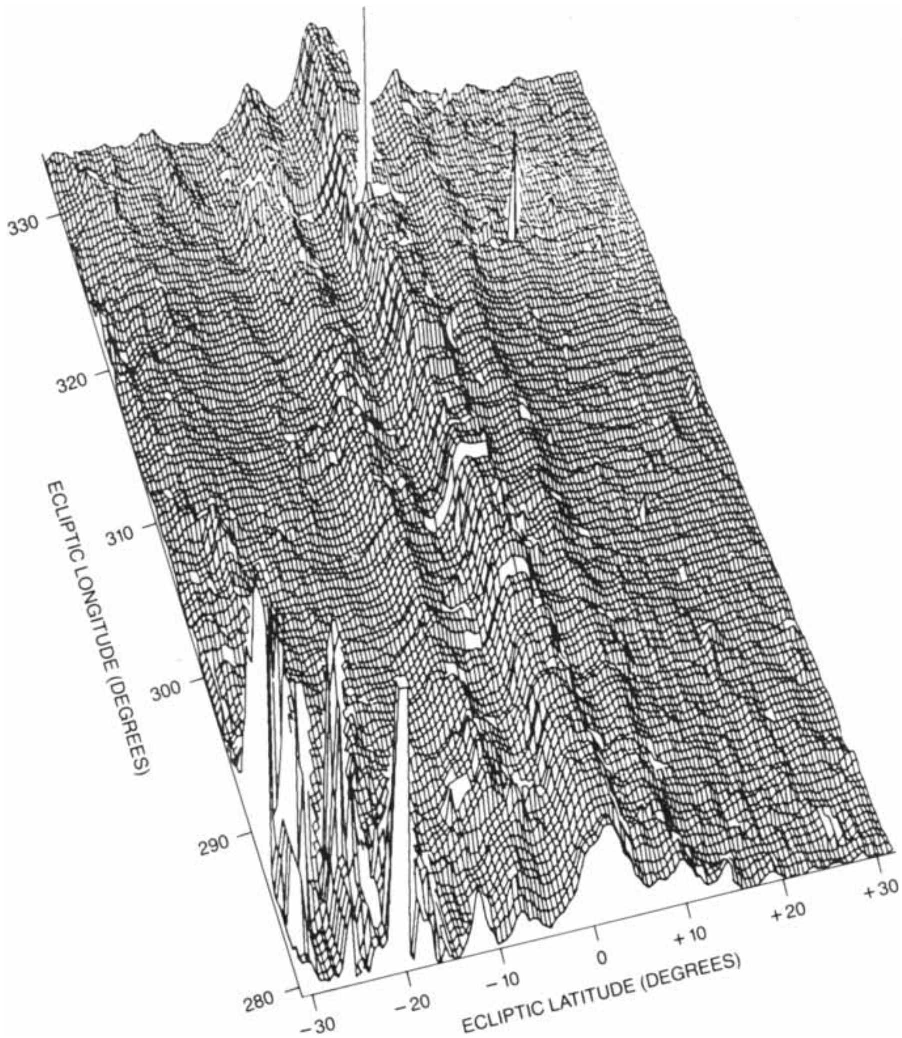
An explanation of the infrared excess in the Vega spectrum can now be offered with some confidence. The long-wavelength emission comes from an abundance of small particles forming a ring around Vega at a distance of some 85 astronomical units. The reasoning that led to this conclusion illustrates how the data from *IRAS* are interpreted.

There are many examples of hot stars surrounded by cooler matter; it is gas and dust expelled by the star itself and is therefore continually replenished. Vega, however, is not losing matter, and so the particles surrounding it must be in stable orbits. The chain of deductions by which the material was characterized began with an estimate of its temperature; given certain simplifying assumptions, the shape of the infrared spectrum implies a temperature of 85 degrees K. The radius of the cloud was determined by means of special observations made with the smallest of the 60-micrometer detectors, in order to achieve the highest possible spatial resolution.

Estimating the size of the particles calls for subtler arguments. If the particles were the size of interstellar dust grains, which are typically less than a micrometer in diameter, they would be blown away by the pressure of Vega's radiation. Particles larger than this but smaller than about one millimeter in diameter would have succumbed to an opposite effect: through a loss of angular momentum to the stellar radiation they would have spiraled into the star's atmosphere. Furthermore, because the particles radiate efficiently at 25 micrometers, they do not appear to be smaller than this. These considerations set a lower limit on the particle size. An upper limit is given by the observed flux of infrared radiation: many small particles, having a larger surface area, radiate more efficiently than a few large ones. If the matter in the band had been gathered up into a single planet, it would not have been detected.

The gravel-size grains in the Vega ring have a total apparent mass of about 1 percent of the earth's mass. Actually larger bodies could well be present but unobserved; if the distribution of particle sizes is like that of the asteroid belt in the solar system, the total mass of the orbiting material could be equal to 300 times the mass of the earth. The Vega ring is the first compelling example of solid matter in orbit around a star other than the sun, and it may well represent an early stage in the condensation of a planetary system. Vega is probably only a few hundred million years old—compared with 4.5 billion years for the sun—and the solar system may have been in a similar stage of development when the sun was the same age.

Following the discovery of the Vega ring a search was made for other nearby stars that might have orbiting material. Some 50 stars were found to have an



BANDS OF DUST IN THE SOLAR SYSTEM consist of finely divided material orbiting at about the same distance from the sun as the asteroid belt (between Mars and Jupiter). The graph shows the intensity of radiation received in the 60-micrometer band as a function of ecliptic latitude and longitude. The central ridge reveals a ring of dust within the ecliptic plane, which could be formed by the grinding up of asteroids. The two outlying ridges are harder to explain. They indicate there is a quantity of dust in orbits inclined by about nine degrees to the ecliptic; one possibility is that the material was formed by the collision of a comet with an asteroid.

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infrared excess that could not readily be explained by some other mechanism, but only in one case is there evidence of millimeter-size particles orbiting the star. The second candidate is Fomalhaut, a southern star that is also less than a billion years old.

A task for which *IRAS* was particularly well suited was the gathering of vital statistics on the birth and death of stars. Current ideas hold that a star is created by the collapse of a dense region within a cloud of cold gas and dust. The surrounding cloud hides the early stages of stellar evolution from visual observation. Similarly, many aging stars exude large quantities of gas and dust and become enveloped in a cloud of their own creation. Infrared observations are sensitive to thermal emission from the dust itself and so offer an effective means of detecting and studying such processes.

In recent years star-forming regions have been examined in detail by ground-based and airborne instruments. Most of the attention has necessarily been given to the birth of large, hot stars; the smaller ones more typical of stellar populations (and also closer in mass to the sun) were too dim to be detected. One of the major benefits of the *IRAS* survey may be the provision of a more representative sample of very young stars.

One area *IRAS* searched for new stars was a small, dark cloud called Barnard 5, in the constellation Perseus. Four discrete sources of infrared emission were detected. The brightest source seems to be powered by a new star that has roughly the same size and mass as the sun but is 10 times as luminous. These characteristics are consistent with models of stellar evolution, which indicate that the first 100,000 years or so in the life of such a star is an episode of exceptional brightness. The star itself is not seen by the detectors; what is registered is radiation from dust that the star has heated to temperatures ranging from 30 to 800 degrees K.

In the cloud called Chamaeleon 1, in the southern sky, a great nest of young stars was discovered. Some 70 point sources were identified, although a number of them are evidently "field stars" that are unrelated to the cloud and simply happen to lie along the same line of sight. Some of the other sources in the cloud are too tightly clustered to be analyzed individually. Among the remaining objects are 17 that resemble the newborn stars in Barnard 5. Some of them are embedded in the cloud; others have drifted out of the cloud but still carry a veil of dust. Another 25 sources have been identified as cool clumps of matter, some of them perhaps on the point of collapsing into stars.

At the opposite end of the stellar age scale are cool red-giant stars approaching the end point of stellar evolution, when they will either disintegrate into a planetary nebula or (more rarely) explode in a supernova. Such stars expel vast quantities of gas and dust, forming a thick blanket that absorbs the stellar radiation and reemits it in the infrared.

As a red-giant star evolves it seems the rate of mass loss accelerates. At first the star spews out a quantity of matter equal to the mass of the sun every 100,000 years; later the same amount of material is lost every 10,000 years. The stars in this latter group cannot be seen in visible light, but they can be detected at mid-infrared wavelengths. Some of them were known before *IRAS* both from ground-based infrared studies and from radio observations of the emissions of hydroxyl (OH) molecules; they are known as OH/IR stars. *IRAS* has discovered many more of them, including more extreme examples.

Most stars in this phase of their existence are variable, which is probably a sign that their supply of nuclear fuel is running out. The *IRAS* results, however, show that the most extreme infrared sources do not vary. It is possible their fuel is so nearly exhausted that they cannot even support pulsations. A convincing interpretation is not yet available, but some of the mysteries that surround the dying stage of stellar evolution will most likely be solved by further analysis of the data. Of great importance will be the spectra obtained with the *IRAS* spectrometer, which are particularly useful for classifying objects of this kind.

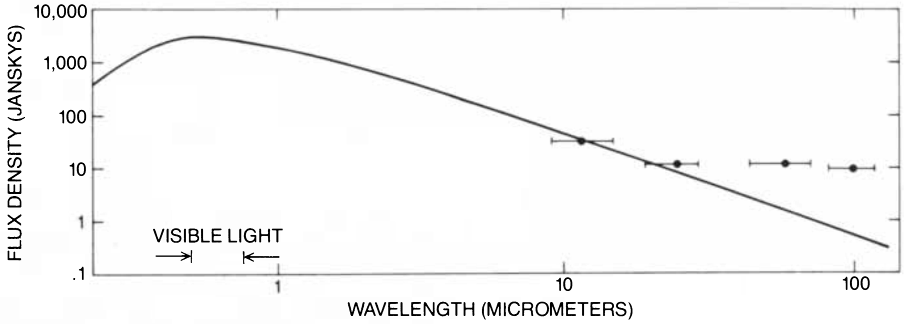
An obvious target for astronomical investigation is the central region of the Milky Way, some 30,000 light-years from the solar system's position in one of the galaxy's spiral arms. Dense aggregations of dust hide the core of the galaxy at visible wavelengths, and so radio and infrared observations offer the only means of access. The *IRAS* images of the core are by no means the most detailed ever made—other instruments have offered higher spatial resolution—but they are capable of showing much fainter sources than earlier infrared images show and their wide field of view gives an unprecedented panorama.

A number of structures near the galactic nucleus that show up prominently in radio-wavelength maps are also conspicuous in the *IRAS* images. Diffuse features too large to fit within the field of view of other instruments can be perceived. Perhaps the most notable of these are wisps of cold matter that extend from the nucleus above and below the galactic plane. In the photographs they appear as delicate, smoky tendrils, but their scale is enormous.

Outside the Milky Way, *IRAS* detected at least 10,000 galaxies. In most cases their infrared luminosity rises steadily with increasing wavelength, so that they are brightest in the 100-micrometer band. Because of interference from the infrared cirrus, however, they are most readily detected at 60 micrometers.

The level of infrared activity in the galaxies varies over a wide range. In some cases the fraction of the total emission that lies in the infrared is negligibly small; in others almost all the radiation emerging from the galaxies is infrared. In general the variation is correlated with the amount of dust in the galaxy. Elliptical galaxies are largely free of dust and have low infrared luminosity; few of them were detected by *IRAS*. The spiral galaxies are much dustier; almost all of those that are visually bright were detected in the infrared, and so were a substantial number that had not been seen in visible-light surveys.

One spiral galaxy is comparatively nearby: it is M31, the great "nebula" in Andromeda. *IRAS* was able to resolve the infrared features of M31 and showed that most of the long-wavelength radiation comes from two regions: the core of the galaxy and a ring coincident with dust lanes in the spiral arms. Details in the structure of the ring agree closely with the distribution of hydrogen clouds detected by radio tele-



RING OF SOLID MATTER in orbit around the nearby star Vega was a surprising discovery made early in the *IRAS* mission. The spectrum of Vega was expected to follow the curve indicated by the solid line, falling off sharply at longer infrared wavelengths. Instead the spectrum is flat between 25 and 100 micrometers, revealing the presence of cool, solid matter. Apparently pebble-size particles orbit Vega at a distance of 85 astronomical units (twice the distance from the sun to Pluto). They may represent an early stage in the formation of a planetary system.

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scopes. Thus the ring is an area rich in interstellar material and is probably a site of active star formation. The bulk of the infrared emission from the ring probably comes from dust grains heated by newly formed hot stars.

M31 would not be seen by *IRAS* if it were not at close range; intrinsically it is a very faint infrared galaxy. Evidently there is not much star-making going on there. The ratio of its infrared emission to its emission of blue light is only about .03. The Milky Way, in comparison, emits roughly equal quantities of infrared radiation and blue light. Many other galaxies are brighter still in the infrared. In a "minisurvey" of 1 percent of the sky *IRAS* detected 86 galaxies, which had infrared-to-blue ratios ranging from .5 to 50; the typical ratio was about 5.

When the results of the minisurvey were first announced a year ago, nine infrared sources had not been identified with any object seen in visible-light photographs. All nine of the "blank field" sources have now been explained. One source turned out to be a clump of material in the infrared cirrus; the other eight sources are distant galaxies emitting enormous quantities of infrared radiation. Their infrared-to-blue ratios range from 30 to 500, and their emission at infrared wavelengths is between 10 and 100 times the total luminosity (at all wavelengths) of a normal spiral galaxy.

The mechanism responsible for the emissions of the infrared-bright galaxies seems to be the same as it is in commoner galaxies, namely the warming of dust by newly formed hot stars. We cannot, however, exclude the possibility that some of the galaxies have strong nonthermal sources like the ones that power "active" galactic nuclei in quasars and similar objects. The nonthermal sources could be obscured by dust.

If star formation is the cause of the emissions, the brightest of the galaxies must be going through a great burst of star-making. Interstellar matter is being gathered up into stars at a rate that ranges from 40 to 400 solar masses per year; at this rate an entire galactic mass of matter would pass through the star-forming cycle in a billion years or less. Since the universe is much older (an estimated 15 billion years), such extreme star-forming activity must be a short-lived phenomenon.

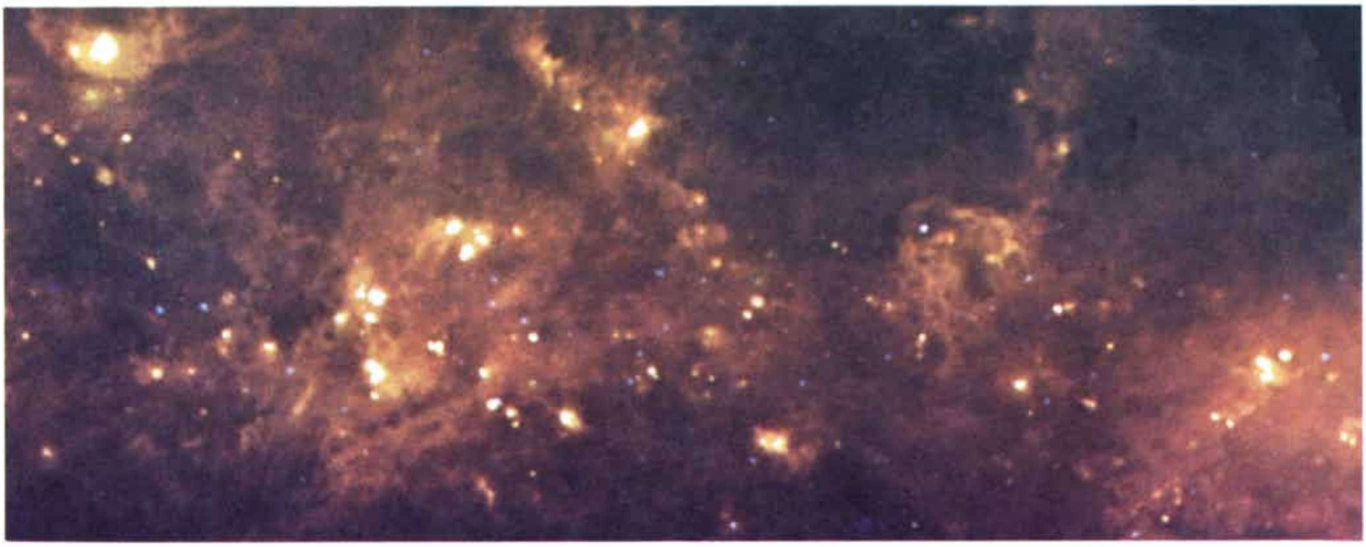
It is probably significant that a disproportionate number of the infrared-bright galaxies have close neighbors or appear to be misshapen in some way. About a fourth of the 86 galaxies identified in the minisurvey fit this description, and so do seven of the eight sources that were initially classified as unidentified. Gravitational interactions or even collisions between galaxies could trigger a burst of star-making.

The galaxy designated Arp 220 may provide a comparatively nearby example of the processes powering the more distant infrared beacons. Arp 220 was classified visually as a "galaxy with adjacent loops" and may be the product of a recent merger of two galaxies. It has an infrared-to-blue ratio of 80 and emits 99 percent of all its radiation at infrared wavelengths. This high proportion of infrared emission is not a result of faintness at other wavelengths; on the contrary, the galaxy has normal visual luminosity and is a bright radio source. There is not a deficiency of visible or radio emission but rather a great excess of infrared emission.

The most luminous of all the objects in the universe are the quasars and objects similar to them, such as Seyfert galaxies and radio galaxies. All such extremely bright, distant objects are now considered to be galaxies with active nuclei. It is thought that in many cases the nucleus harbors a supermassive black hole surrounded by an "accretion disk" of matter gathered from the galaxy. As material from the accretion disk spirals into the black hole, a fraction of its mass is converted into energy. Ultimately the energy appears as electromagnetic radiation over a broad range of wavelengths, from radio to X rays.

It has been supposed that quasars and other active galactic nuclei would emit significant energy in the infrared, but because their great distance makes them dim, few observations were possible. *IRAS* was able to detect a number of these sources, and the data have been analyzed for a few of them.

The strong radio source 3C 390.3 is associated with a giant elliptical galaxy more than a billion light-years away. Its emissions had been studied at radio, visible and X-ray wavelengths, but *IRAS* gave the first far-infrared view. The results were unexpected. The galaxy was detected in all four bands and indeed was found to emit most of its energy in the infrared. The peak emission is in the 25-micrometer band, which is also unusual. Most other active galaxies are strongest at 60 micrometers. The mechanism producing the 25-micrometer emission is uncertain. The most likely possibility is reradiation from interstellar dust heated by ultraviolet radiation in the nucleus. The infrared emission might itself be nonthermal radiation, although the absence of any variability



SITES OF STAR FORMATION have been identified in a dusty region of one of the Milky Way's spiral arms, seen here in a false-color image that covers a 28-by-11-degree area of the sky. Most of the dust is quite cold and radiates mainly in the 100-micrometer band, so that it appears red. Where stars are embedded in the cloud they warm the surrounding material, which then radiates at shorter wavelengths as well. Three bright areas near the center of the image were known from earlier ground-based studies at radio and infrared wavelengths to be sites of star-forming activity. *IRAS* provided the first global view of the area, revealing many more sites of potential interest.

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NUCLEUS OF THE MILKY WAY shines through the dense veil of dust that obscures it from view in visible-light photographs. Details in the structure of the galactic core had been examined in earlier radio and infrared studies, but *IRAS* gave the first wide-field map of the area at far-infrared wavelengths. The image shows an area 16 by 11 degrees. Most of the bright features are well-known regions of ionized gas and dust called H II regions, but many extended structures, such as the wisps of dust that appear above and below the galactic plane near the nucleus, were seen clearly for the first time. The image is a false-color composite assembled from three bands of *IRAS* data.

during the months in which the galaxy was observed by *IRAS* argues against this interpretation.

Quasars are divided into two groups called radio-loud and radio-quiet. The physical processes underlying the distinction have seemed baffling. At radio wavelengths their luminosities differ by a factor of 100,000 or more, but their spectra in the visible and ultraviolet bands are remarkably similar. Clearly the spectra must diverge sharply in the region between the visible and the radio—that is, the infrared—and the differences may well offer some clue to the mechanism of energy production.

IRAS observations have been analyzed for three radio-loud quasars and two radio-quiet ones. No dramatic differences were found in the distribution of energy over the four bands, indicating that the divergence in the spectra must come at a wavelength beyond 100 micrometers. Nevertheless, a subtler discrepancy emerged. For the radio-loud sources the infrared measurements fit smoothly into a continuum bridging the gap between the visible and the radio bands. For the radio-quiet quasars a similar line drawn to connect the two parts of the spectrum should have a steeper slope, signifying that the infrared emission falls off faster with increasing wavelength. The *IRAS* measurements of the radio-quiet sources cannot readily be fitted to such a line; there is an excess of radiation at 100 micrometers.

For now any explanation of these results must be highly tentative, but there is a possibility the 100-micrometer excess has a direct bearing on the nature of the quasar power source. Most of the energy emitted by quasars is thought to be synchrotron radiation, generated by high-energy electrons as they execute spiral motions in a magnetic field. A major source of such electrons could be jets of matter issuing from the core. The absence of any discontinuities in the spectrum of the radio-loud quasars suggests that all the radiation detected comes from this source. The excess infrared emission from the radio-quiet quasars could have an independent origin, namely thermal emission from dust in the surrounding galaxy. One can therefore speculate that radio-quiet quasars may be dustier than radio-loud ones. By disrupting the jets of electrons the dust could even be responsible for the differences in radio-wavelength luminosity.

Although the observational phase of the *IRAS* mission ended a year ago, the project is by no means finished. The publication this month of the catalogue of point sources and the atlases of extended emission will make the data widely available to the community of astronomers. Analysis and interpretation will continue for years. Indeed, most of what the *IRAS* telescope "saw" lies buried in the reels of digital recording tape that store the data, unknown even to those who were most closely involved in the mission. The tapes will remain as an archive to be consulted by astronomers, much as the photographic plates from an optical sky survey are.

The main function of an unbiased astronomical survey is to discover new physical phenomena or objects that warrant closer examination, either at the wavelength of the survey or throughout the electromagnetic spectrum. Much of the follow-up work at wavelengths outside the infrared region and a few of the infrared observations can be done from the ground or with airborne instruments, and some studies are already under way. For the most interesting sources, however, far-infrared measurements will have to be made from space.

To make such observations at least two more orbiting instruments are projected for the 1990's. The Infrared Space Observatory will be launched by the European Space Agency, and the Space Infrared Telescope Facility will be launched by NASA from the space shuttle. Both instruments will have finer spatial and spectral resolution and higher sensitivity than *IRAS* has. If they succeed as well as the scout satellite that pointed the way, infrared astronomy will be well served indeed.

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How LDL Receptors Influence Cholesterol and Atherosclerosis

The receptors bind particles carrying cholesterol and remove them from the circulation. Many Americans have too few LDL receptors, and so they are at high risk for atherosclerosis and heart attacks

by Michael S. Brown and Joseph L. Goldstein

Half of all deaths in the U.S. are caused by atherosclerosis, the disease in which cholesterol, accumulating in the wall of arteries, forms bulky plaques that inhibit the flow of blood until a clot eventually forms, obstructing an artery and causing a heart attack or a stroke. The cholesterol of atherosclerotic plaques is derived from particles called low-density lipoprotein (LDL) that circulate in the bloodstream. The more LDL there is in the blood, the more rapidly atherosclerosis develops.

Epidemiologic data reveal the surprising fact that more than half of the people in Western industrialized societies, including the U.S., have a level of circulating LDL that puts them at high risk for developing atherosclerosis. Because such concentrations are so prevalent, they are considered "normal," but clearly they are not truly normal. They predispose to accelerated atherosclerosis and heart attacks or strokes.

What determines the blood level of LDL, and why is the level dangerously high in so many Americans? Some answers are emerging from studies of specialized proteins, called LDL receptors, that project from the surface of animal cells. The receptors bind LDL particles and extract them from the fluid that bathes the cells. The LDL is taken into the cells and broken down, yielding its cholesterol to serve each cell's needs. In supplying cells with cholesterol the receptors perform a second physiological function, which is critical to the development of atherosclerosis: they remove LDL from the bloodstream.

The number of receptors displayed on the surface of cells varies with the cells' demand for cholesterol. When the need is low, excess cholesterol accumulates; cells make fewer receptors and take up LDL at a reduced rate. This protects cells against excess cholesterol, but at a high price: the reduction in the number of receptors decreases the rate at which LDL is removed from the circulation, the blood level of LDL rises and atherosclerosis is accelerated.

We have proposed that the high level of LDL in many Americans is attributable to a combination of factors that diminish the production of LDL receptors. Recognition of the central role of the receptors has led to a treatment for a severe genetic form of atherosclerosis, and it has also shed some light on the continuing controversy over the role of diet in atherosclerosis in the general population.

The story begins with the discovery of LDL receptors in 1973 in our laboratory at the University of Texas Health Science Center at Dallas. We were studying tissue cultures of the human skin cells called fibroblasts. Like all animal cells, cultured fibroblasts need cholesterol as a major building block of their surface membrane (the plasma membrane); they had been shown to get the cholesterol by extracting it from lipoproteins in the serum of the culture medium. There is a mixture of various lipoproteins in human serum, but we found that the fibroblasts derive most of their cholesterol from a particular lipoprotein: LDL. We were able to attribute this to the presence on the cells of highly specific receptor molecules that bind LDL and related lipoproteins.

LDL is a large spherical particle whose oily core is composed of some 1,500 molecules of the fatty alcohol cholesterol, each attached by an ester linkage to a long-chain fatty acid. This core of cholesteryl esters is enclosed in a layer of phospholipid and unesterified cholesterol molecules. The phospholipids are arrayed so that their hydrophilic heads are on the outside, allowing the LDL to be dissolved in the blood or intercellular fluid. Embedded in this hydrophilic coat is one large protein molecule designated apoprotein *B*-100.

It is apoprotein *B*-100 that is recognized and bound by the LDL receptor, a glycoprotein (a protein to which sugar chains are attached). The receptor spans the thickness of the cell's plasma membrane and carries a binding site that protrudes from the cell surface. Binding takes place when LDL is present at a concentration of less than 10^{-9} molar, which is to say that the receptor can pick out a single LDL particle from more than a billion molecules of water. The receptor binds only lipoproteins carrying apoprotein *B*-100 or a related protein designated apoprotein *E*.

How is LDL taken into the cell? Our collaborator Richard G. W. Anderson discovered in 1976 that the receptors are clustered in specialized regions where the cell membrane is indented to form craters known as coated pits (because the inner surface of the membrane under them is coated with the protein clathrin). Within minutes of their formation the pits pouch inward into the cell and pinch off from the surface to form membrane-bounded sacs called coated vesicles; any LDL bound to a receptor is carried into the cell. (Receptor-mediated endocytosis, the term we and Anderson applied to this process of uptake through coated pits and vesicles, is now recognized as being a general mechanism whereby cells take up many large molecules, each having its own highly specific receptor.)

Eventually the LDL is separated from the receptor (which is recycled to the cell surface) and is delivered to a lysosome, a sac filled with digestive enzymes. Some of the enzymes break down the LDL's coat, exposing the cholesteryl ester core. Another enzyme clips off the fatty acid tails of the cholesteryl esters, liberating unesterified cholesterol, which leaves the lysosome. As we have indicated, all cells incorporate the cholesterol into newly synthesized surface membranes. In certain specialized cells the cholesterol extracted from LDL has other roles. In the adrenal gland and in the ovary it is converted

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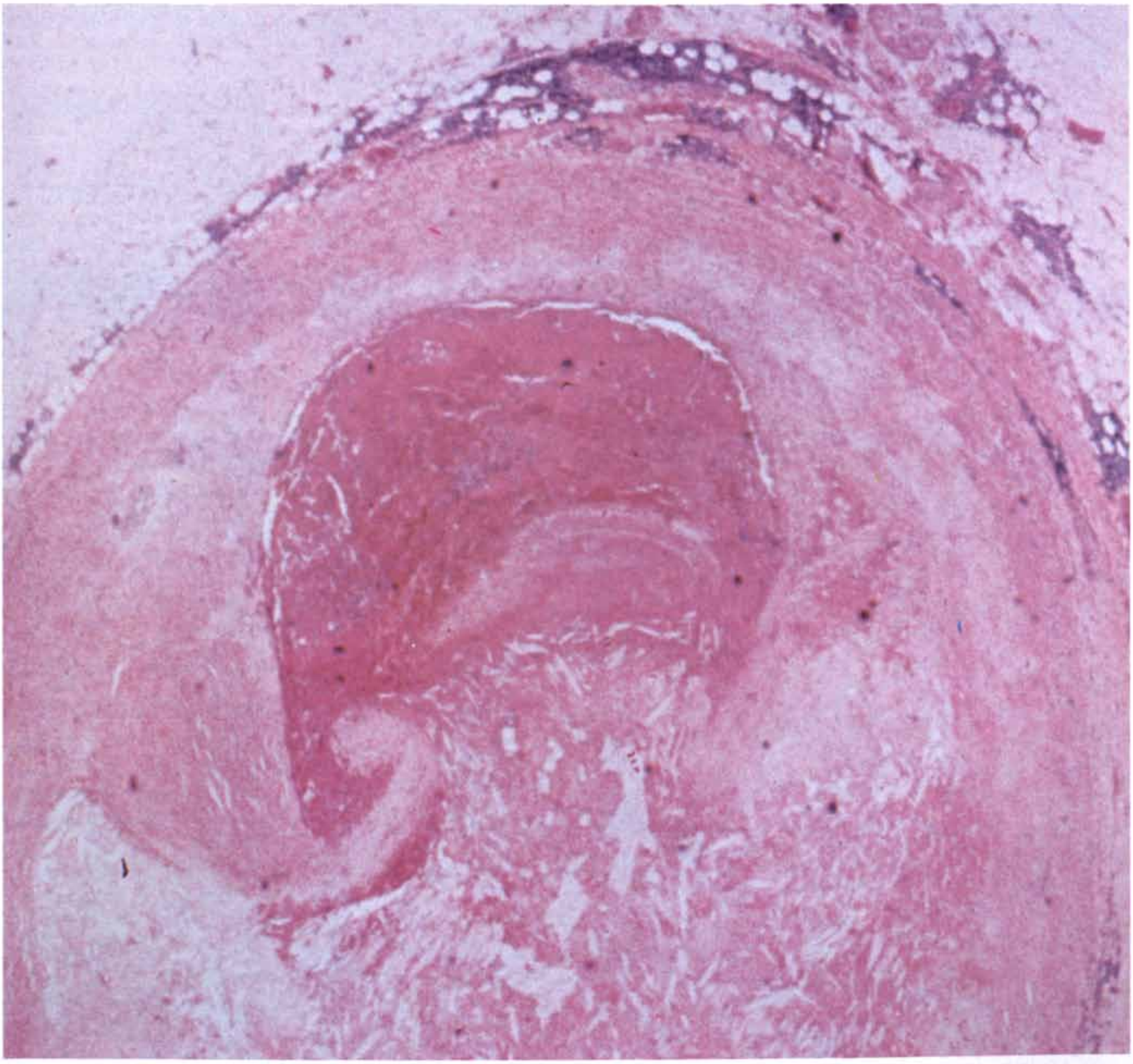
into respectively the steroid hormones cortisol and estradiol; in the liver it is transformed to make bile acids, which have a digestive function in the intestine.

The amount of cholesterol liberated from LDL controls the cell's cholesterol metabolism. An accumulation of cholesterol modulates three processes. First, it reduces the cell's ability to make its own cholesterol by turning off the synthesis of an enzyme, HMG CoA reductase, that catalyzes a step in cholesterol's biosynthetic pathway. Suppression of the enzyme leaves the cell dependent on external cholesterol derived from the receptor-mediated uptake of LDL. Second, the incoming LDL-derived cholesterol promotes the storage of cholesterol in the cell by activating an enzyme called *ACAT.* The enzyme reattaches a fatty acid to excess cholesterol molecules, making cholesteryl esters that are deposited in storage droplets.

Third, and most significant, the accumulation of cholesterol within the cell drives a feedback mechanism that makes the cell stop synthesizing new LDL receptors. Cells thereby adjust their complement of receptors so that enough cholesterol is brought in to meet their varying demands but not enough to overload them. For example, fibroblasts that are actively dividing, so that new membrane material is needed, maintain a maximum complement of LDL receptors (some 40,000 per cell). In cells that are not growing the incoming cholesterol begins to accumulate, the feedback system reduces receptor manufacture and the complement of receptors is reduced as much as tenfold.

Our observations in tissue cultures were confirmed when the receptor system was shown to have an important role in the body. Soon after we found the LDL receptor on cultured fibroblasts it was shown to be present on circulating



BLOOD CLOT in a coronary artery took the life of a 76-year-old man with advanced atherosclerosis. Over the decades cholesterol carried by low-density lipoprotein (LDL) particles had infiltrated the wall of the artery, forming a bulky deposit (*pale pink*) that narrowed the channel. The clot formed suddenly, obstructing blood flow and causing the death of the heart muscle that had been supplied with oxygen and nutrients by this artery. The formation of the clot (*dark red*) appears to have been triggered by a rupture of the lining of the channel that exposed the flowing blood to crystals of cholesterol (*white needle-shaped objects*). The photomicrograph, in which the sectioned artery is enlarged 37 diameters, was made by L. Maximilian Buja of the University of Texas Health Science Center at Dallas.

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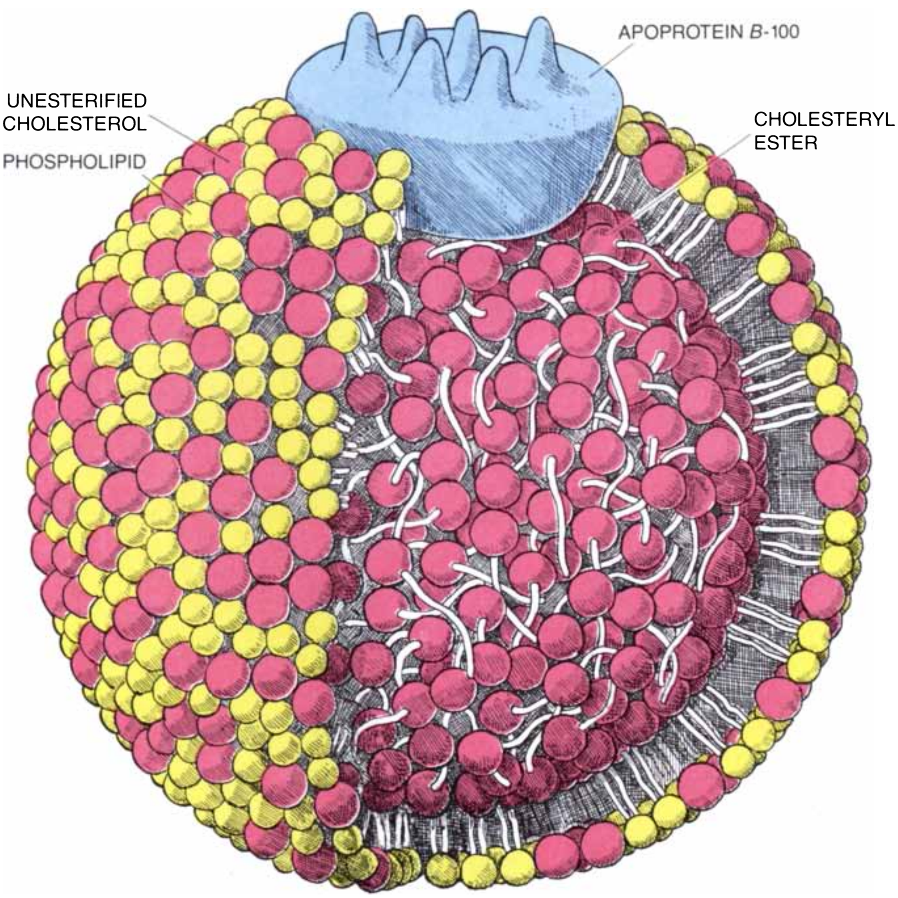
human blood cells and on cell membranes from many different tissues of mice, rats, dogs, pigs, cows and human beings. The relative number of receptors and their functioning can be assessed in living animals and in human volunteers by injecting into the bloodstream LDL labeled with a radioactive isotope and measuring its rate of removal from the circulation. The rate has been shown to depend on the total number of LDL receptors displayed on all cells in the body. This can be demonstrated by modifying the apoprotein *B*-100 before the LDL is injected, so that it can no longer bind to receptors. James Shepherd and Christopher J. Packard of the University of Glasgow showed that the modified LDL circulates much longer than normal LDL.

Where is the LDL taken up? Daniel Steinberg of the University of California School of Medicine at San Diego and John M. Dietschy of the Health Science Center at Dallas have shown that in rats, rabbits, guinea pigs and squirrel monkeys about 75 percent of the receptor-mediated removal of LDL takes place in the liver. We have measured the number of receptors directly, in cell membranes isolated from different tissues. Most tissues are found to have some receptors, but those of the liver, adrenal gland and ovary—the organs with particularly large requirements for cholesterol—have the highest concentration of receptors.

What is the origin of circulating LDL? The mechanism of its production is more complex, and as yet less well understood, than the mechanism of its uptake and degradation. LDL is one component of the system that transports two fatty substances, cholesterol and various triglycerides, through the bloodstream. The fat-transport system can be divided into two pathways: an exogenous one for cholesterol and triglyceride absorbed from the intestine and an endogenous one for cholesterol and triglyceride entering the bloodstream from the liver and other nonintestinal tissues.

The exogenous pathway has been mapped by Richard J. Havel of the University of California School of Medicine at San Francisco and by others. It begins in the intestine, where dietary fats are packaged into lipoprotein particles called chylomicrons, which enter the bloodstream and deliver their triglyceride to adipose tissue (for storage) and to muscle (for oxidation to supply energy). The remnant of the chylomicron, containing cholesteryl esters, is removed from the circulation by a specific receptor found only on liver cells. This chylomicron-remnant receptor does not bind LDL or take part in its removal from the circulation.



LDL, MAJOR CHOLESTEROL CARRIER in the bloodstream, is a spherical particle with a mass of three million daltons and a diameter of 22 nanometers (millionths of a millimeter). Its core consists of some 1,500 cholesteryl esters, each a cholesterol molecule attached by an ester linkage to a long fatty acid chain. The oily core is shielded from the aqueous plasma by a detergent coat composed of 800 molecules of phospholipid, 500 molecules of unesterified cholesterol and one large protein molecule, apoprotein *B*-100. When blood cholesterol is elevated, increasing the risk of atherosclerosis, the reason is almost always an increase in circulating LDL.

LDL is a component of the endogenous pathway, which begins when the liver secretes into the bloodstream a large very-low-density lipoprotein particle (VLDL). Its core consists mostly of triglyceride synthesized in the liver, with a smaller amount of cholesteryl esters; it displays on its surface two predominant proteins, apoproteins *B*-100 and *E*, both of which can be bound by LDL receptors. When a VLDL particle reaches the capillaries of adipose tissue or of muscle, its triglyceride is extracted. The result is a new kind of particle, decreased in size and enriched in cholesteryl esters but retaining its two apoproteins; it is called intermediate-density lipoprotein, or IDL.

In human beings about half of the IDL particles are removed from the circulation quickly—within from two to six hours of their formation—because they bind very tightly to liver cells, which extract their cholesterol to make new VLDL and bile acids. Robert W. Mahley and Thomas L. Innerarity of the University of California School of Medicine at San Francisco have shown that the tight binding is attributable to apoprotein *E*, whose affinity for LDL receptors on liver cells is greater than that of apoprotein *B*-100. IDL particles not taken up by the liver remain in the circulation much longer. In time the apoprotein *E* is dissociated from them, leaving the particles, now converted into low-density lipoprotein (LDL), with apoprotein *B*-100 as their sole protein. Because of *B*-100's lower affinity for LDL receptors, the LDL particles have a much longer life span than IDL particles: they circulate for an average of two and a half days before binding to LDL receptors in the liver and in other tissues.

The central role of the LDL receptor in atherosclerosis was first appreciated when we showed that its absence is responsible for the severe disease called familial hypercholesterolemia (FH). In 1939 Carl Müller of the Oslo Community Hospital in Norway identified the disease as an inborn error of metabolism causing high blood cholesterol levels and heart attacks in young people; he recognized that it is transmitted as a dominant trait determined by a single gene. In the 1960's Avedis K. Khachadurian at the American University in Beirut and Donald S. Fredrickson at the U.S. National Heart and Lung Insti-

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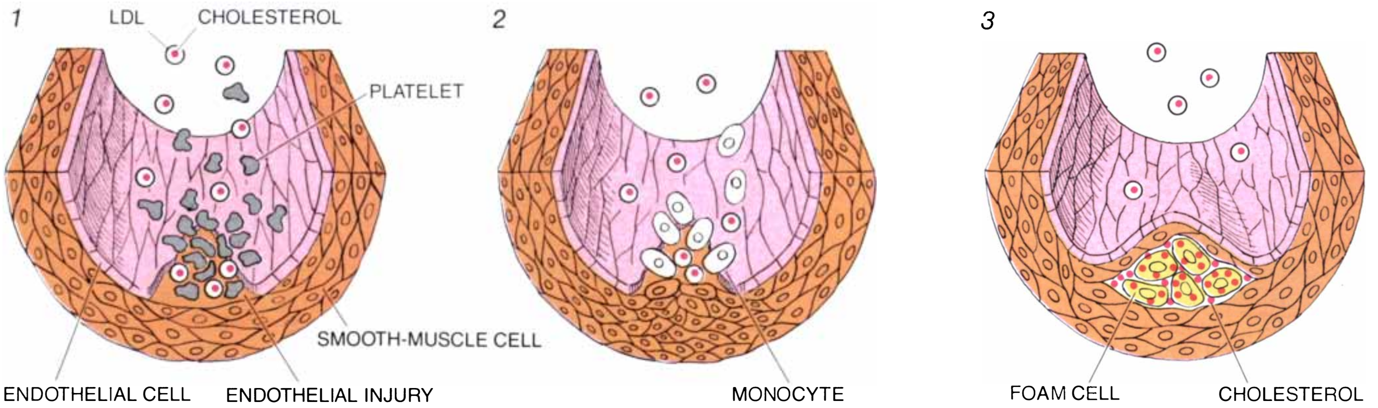
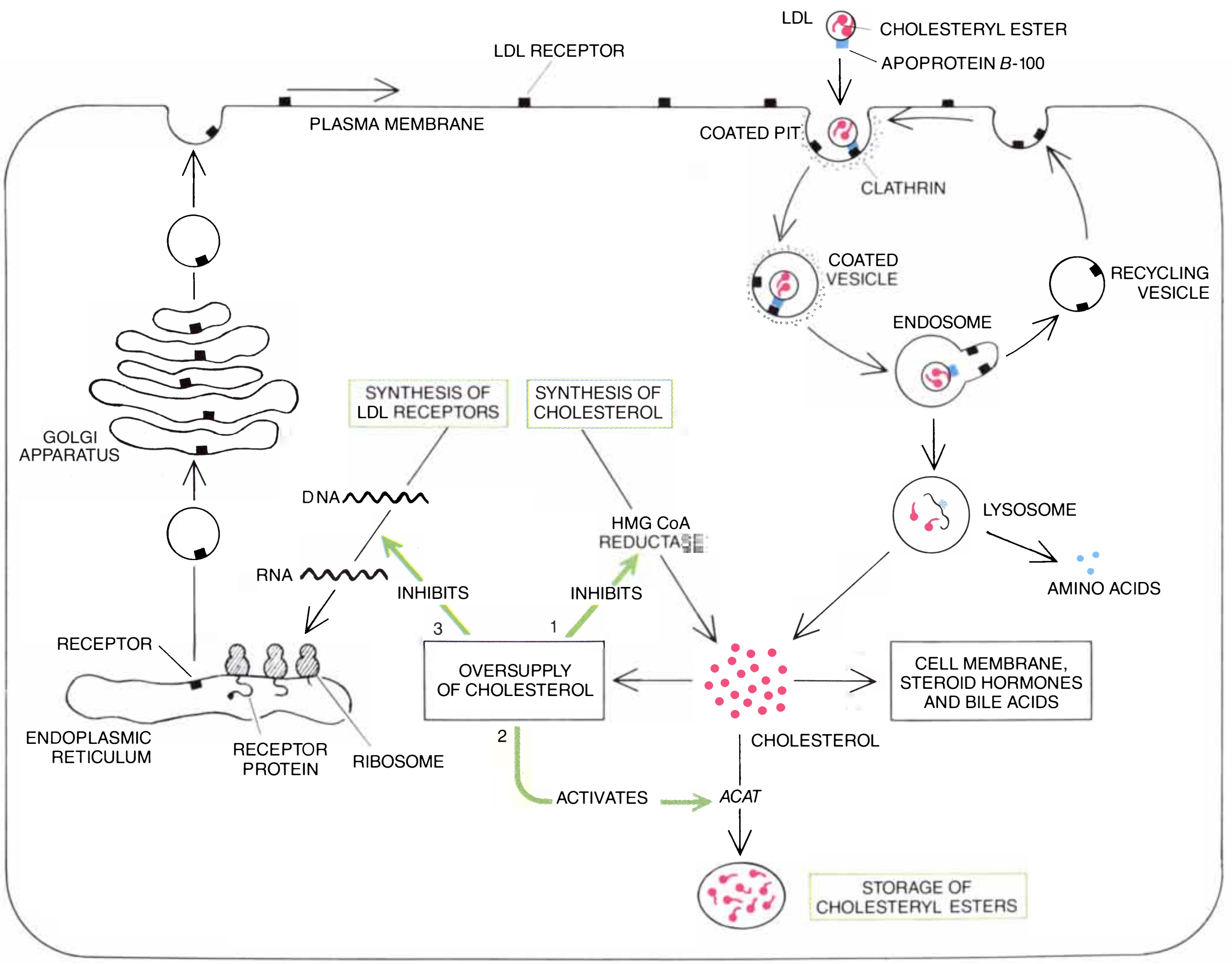


ATHEROSCLEROTIC PLAQUE develops slowly. Damage to the thin layer of endothelial cells that lines an artery initiates plaque formation. According to a model originally proposed by Russell Ross and John A. Glomset of the University of Washington School of Medicine, the damaged endothelium becomes leaky and is penetrated by low-density lipoprotein (LDL) particles and blood platelets (*1*). In response to the release of such hormones as platelet-derived growth factor, smooth-muscle cells in the layer below the endothelium multiply and migrate into the damaged area (*2*); at the same time white blood cells called monocytes invade the area and are activated to become scavenger cells called macrophages. The smooth-muscle cells and macrophages ingest and degrade LDL and become foam cells. If the blood LDL level is too elevated, cholesterol derived from the LDL accumulates in and among the foam cells. The accumulated cholesterol, cells and debris constitute an atheroma (*3*), which in time can narrow the channel of the artery and so lead to thrombosis.



CIRCULATING LDL (*top right*) is taken into a cell by receptor-mediated endocytosis. LDL is bound by a receptor in a coated pit, which invaginates and pinches off to form a coated vesicle. Fusion of several vesicles gives rise to an endosome, in whose acidic environment the LDL dissociates from the receptor, which is recycled to the cell surface. The LDL is delivered to a lysosome, where enzymes break down the apoprotein *B*-100 into amino acids and cleave the ester bond to yield unesterified cholesterol for membrane synthesis and other cellular needs. The cellular level of cholesterol is self-regulating. An oversupply of cholesterol has three metabolic effects. It inhibits the enzyme HMG CoA reductase, which controls the rate of cholesterol synthesis (*1*); it activates the enzyme *ACAT*, which esterifies cholesterol for storage (*2*), and it inhibits the manufacture of new LDL receptors by suppressing transcription of the receptor gene into messenger RNA (*3*), which would ordinarily be translated on ribosomes of the endoplasmic reticulum to make the receptor protein.

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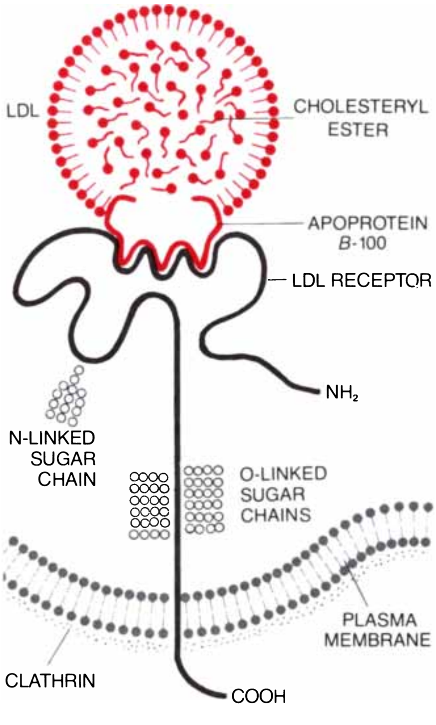
tute showed there are two forms of the disease, a heterozygous form and a more severe homozygous form. Heterozygotes, who inherit one mutant gene, are quite common: about one in 500 people in most ethnic groups. Their plasma LDL level is twice the normal level (even before birth) and they begin to have heart attacks by the time they are 35; among people under 60 who have heart attacks, one in 20 has heterozygous FH.

If two FH heterozygotes marry (one in 250,000 marriages), each child has one chance in four of inheriting two copies of the mutant gene, one from each parent. Such FH homozygotes (about one in a million people) have a circulating LDL level more than six times higher than normal; heart attacks can occur at the age of two and are almost inevitable by the age of 20. It is notable that these children have none of the risk factors for atherosclerosis other than an elevated LDL level. They have normal blood pressure, do not smoke and do not have a high blood glucose level. Homozygous FH is a vivid experiment of nature. It demonstrates unequivocally the causal relation between an elevated circulating LDL level and atherosclerosis.



LDL RECEPTOR, a glycoprotein embedded in the plasma membrane of most body cells, was purified from the adrenal gland by Wolfgang J. Schneider in the authors' laboratory. David W. Russell and Tokuo Yamamoto cloned complementary DNA derived from its messenger RNA. The DNA's nucleotide sequence was determined and from it the 839-amino-acid sequence of the receptor's protein backbone was deduced. Sites of attachment of sugar chains to nitrogen (*N*) and oxygen (*O*) atoms were identified, as was a stretch likely to traverse the membrane. The actual shape of the receptor is not yet known; the drawing is a highly schematic representation.

By what mechanism is the LDL level elevated? What is the particular function of the mutant gene? When we looked at cultured skin fibroblasts and circulating blood cells from FH homozygotes, we saw that the cells have either no functional LDL receptors at all or very few and therefore cannot bind, internalize and degrade LDL efficiently. The defective gene, in other words, encodes the protein of the LDL receptor. Homozygotes, having inherited two defective receptor genes, cannot synthesize any normal receptors. The cells of FH heterozygotes have one normal receptor gene and one mutant gene; they synthesize half the normal number of receptors and can therefore bind, internalize and degrade LDL at half the normal rate.

Although all FH patients studied to date have a mutation in the gene encoding the LDL receptor, the mutations are not always the same. Depending on the particular site that has undergone mutation, the receptor may not be synthesized at all or it may be synthesized but then fail to be transported to the cell surface, fail to bind LDL or fail to cluster in coated pits.

Studies with radioactively labeled LDL show that the particles survive in the bloodstream of FH homozygotes about two and a half times as long as they do in people with a normal LDL-receptor gene. (Eventually the LDL is removed from the circulation by alternate but much less efficient pathways.) The predictable slowdown in the removal and breakdown of LDL is one major reason for the extremely high LDL level characteristic of FH, but it does not account for the entire rise. In addition to degrading LDL more slowly, a person homozygous for FH actually produces about twice as much LDL per day as a normal person. How can a defect in the LDL receptor lead to the overproduction of LDL? The answer to this question came from studies of a remarkable strain of rabbits with a genetic defect resembling the one in human FH.

The rabbits were discovered in 1978 by Yoshio Watanabe of the Kobe University School of Medicine and are called WHHL rabbits (for "Watanabe heritable hyperlipidemic"). They are homozygous for a mutant LDL-receptor gene and produce less than 5 percent of the normal number of receptors; they have high circulating LDL from the time of birth and develop atherosclerosis leading to heart attacks by the age of two. Studies done by us in collaboration with Toru Kita and David W. Bilheimer and by Steinberg and his colleagues showed that the rabbits, like their human counterparts with homozygous FH, make too much LDL as well as taking too long to break it down.

To learn the reason for LDL overproduction, Kita injected radioactively labeled VLDL, a precursor of LDL, into WHHL rabbits and normal animals and tracked the radioactivity through the fat-transport pathway. He found that triglyceride was removed from the VLDL, generating IDL, at the same rate in both groups. In normal rabbits the vast majority of the IDL particles disappeared rapidly from the circulation as they bound to LDL receptors on liver cells. In the WHHL rabbits, however, the liver cells lack LDL receptors, and so more IDL particles remained in the circulation and were eventually converted into more than the normal amount of LDL. In other words, a reduction in receptors has two effects in the rabbits—increased production and decreased removal of LDL—that act synergistically to raise the LDL level, which therefore rises disproportionately. Nicholas B. Myant and his colleagues at Hammersmith Hospital in London have shown the same thing is true in FH homozygotes.

Knowledge of the receptor deficiency in FH suggested a way to help the large number of patients with the heterozygous form of the disease. Perhaps we could stimulate the heterozygote's one normal gene to direct the synthesis of twice as many receptors as usual and so provide the patient with a normal complement of functional receptors. The possibility of such treatment was raised by something we had learned from cultured skin fibroblasts, namely that the feedback regulation of receptor synthesis takes place at the level of transcription. An excess of cholesterol reduces transcription of the LDL-receptor gene into messenger RNA, the nucleic acid that is subsequently translated by the cell's protein-synthesizing machinery to make the receptor protein; a cholesterol deficiency stimulates transcription and thus steps up the manufacture of receptors. We found we could get cultured cells from FH heterozygotes to make a normal number of LDL receptors (by making more messenger-RNA molecules from their single receptor gene) when we reduced the amount of cholesterol in the culture medium. How might we create an analogous cholesterol deficiency in the FH patient?

The liver takes up and degrades more cholesterol than any other organ because of its large size and its high concentration of LDL receptors. The bile acids into which most of the cholesterol is converted are secreted into the upper intestine, where they emulsify dietary fats. Having done their work, the bile acids are not simply excreted, however; they are largely reabsorbed from the intestine, returned to the bloodstream,

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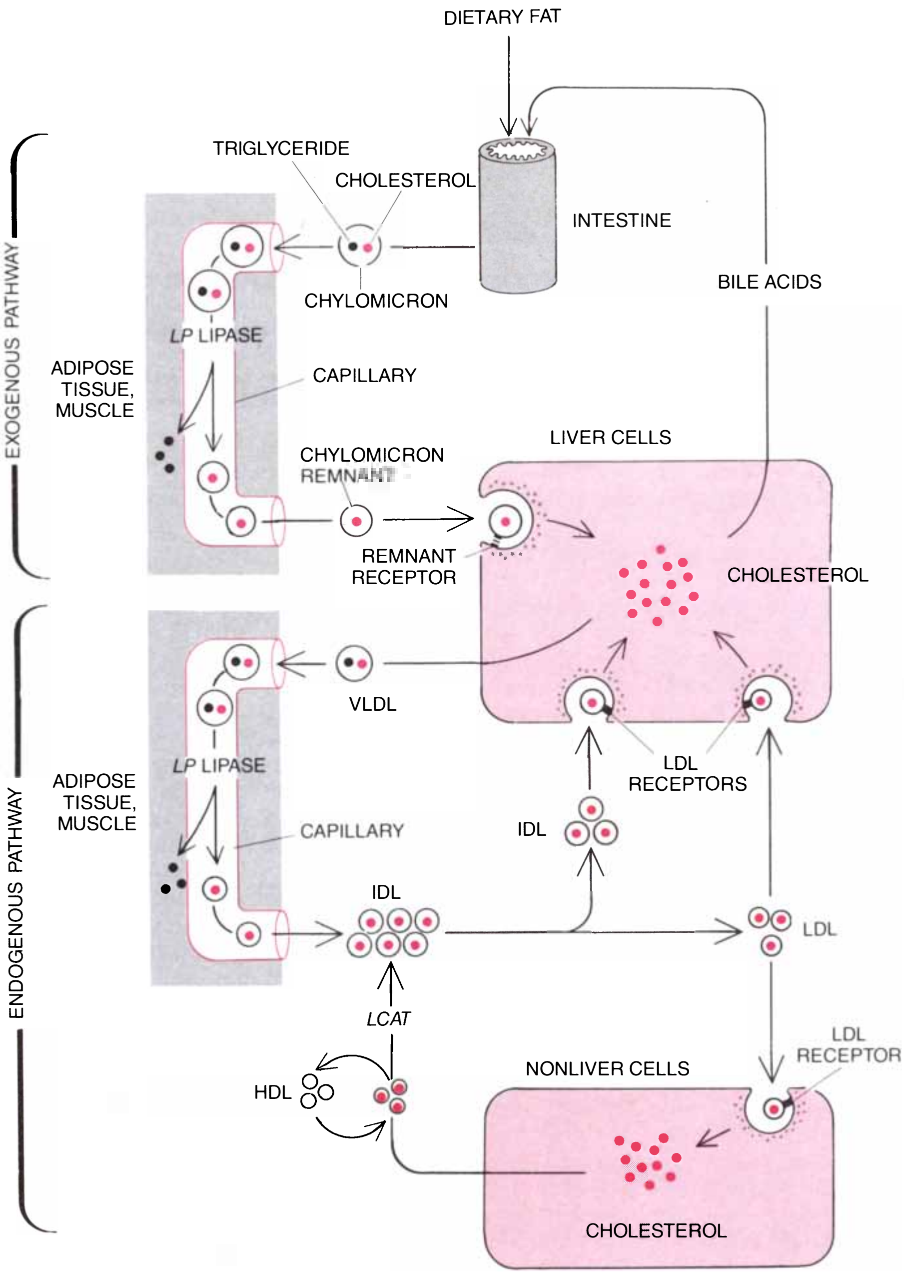
taken up by the liver and again secreted into the upper intestine. This recycling of bile acids ordinarily limits the liver's need for cholesterol. We reasoned that if the recycling could be interrupted, the liver would be called on to convert more cholesterol into bile acids and this should lead the liver cells to make more LDL receptors.

A class of drugs that interrupt the recycling of bile acids was already known. They are the bile-acid-binding resins, gritty polymers carrying many positively charged chemical groups. Taken orally, these resins bind to the negatively charged bile acids in the intestine; because the resins cannot be absorbed from the intestine, they are excreted, carrying the bound bile acids with them. The first bile-acid-binding resin, cholestyramine, was synthesized more than 20 years ago and was found to lower the blood LDL level by an average of 10 percent. (A recent 10-year prospective study done by the National Heart, Lung, and Blood Institute indicated that such a reduction was enough to cut the incidence of heart attacks in a test group of middle-aged men by 20 percent.) What we had learned about LDL metabolism provided the missing rationale for such results: the interruption of bile-acid recycling increases the number of LDL receptors on liver cells.

The 10 percent drop in LDL level attainable with cholestyramine and other such resins was encouraging, but clearly a more profound reduction is necessary for treating FH heterozygotes. The limited efficacy of the resins stems from the dual response of the liver to a cholesterol deficiency. In addition to making more LDL receptors the liver increases its manufacture of HMG CoA reductase and makes more of its own cholesterol. We reasoned that this increased de novo synthesis of cholesterol partially satisfies the resin-induced demand for more cholesterol and so prevents the liver from maximally increasing the number of LDL receptors.

We thought inhibition of cholesterol synthesis might force the liver to rely more on LDL uptake and thus stimulate greater production of receptors. To block cholesterol synthesis we took advantage of the discovery by Akira Endo, now of the Tokyo University of Agriculture and Technology, of a remarkable natural inhibitor of HMG CoA reductase. In 1976 he isolated from a penicillin mold a substance called compactin. A side chain of the compactin molecule closely mimics the structure of the natural substrate of HMG CoA reductase, and so it binds to the enzyme's active site and inhibits the enzyme's activity. Alfred W. Alberts of the Merck Sharp & Dohme Research Laboratories and his colleagues isolated from a different mold a structural relative of compactin, called mevinolin, that is an even more potent enzyme blocker. Compactin and mevinolin were shown, by Endo and Alberts respectively, to lower the blood LDL level in animals. If our idea was correct, the drugs should be even more effective in conjunction with a bile-acid-binding resin.

In collaboration with Petri T. Kovanen we administered a bile-acid-binding resin to dogs either alone or along with one of the enzyme inhibitors. After two weeks we assessed the number of LDL receptors by measuring the ability of biopsied liver membranes to bind radioactive LDL. We found, as expected, that the resin alone generated a modest rise in the number of receptors. When the



EXOGENOUS AND ENDOGENOUS fat-transport pathways are diagrammed. Dietary cholesterol is absorbed through the wall of the intestine and is packaged, along with triglyceride (glycerol ester-linked to three fatty acid chains), in chylomicrons. In the capillaries of fat and muscle tissue the triglyceride's ester bond is cleaved by the enzyme lipoprotein (*LP*) lipase and the fatty acids are removed. When the cholesterol-rich remnants reach the liver, they bind to specialized receptors and are taken into liver cells. Their cholesterol either is secreted into the intestine (mostly as bile acids) or is packaged with triglyceride in very-low-density lipoprotein (VLDL) particles and secreted into the circulation, inaugurating the endogenous pathway. Again the triglyceride is removed in fat or muscle, leaving cholesterol-rich intermediate-density lipoprotein (IDL). Some IDL binds to liver LDL receptors and is rapidly taken up by liver cells; the remainder stays in the circulation and is converted into LDL. Most of the LDL binds to LDL receptors on liver or other cells and is removed from the circulation. Cholesterol leaching from cells binds to high-density lipoprotein (HDL) and is esterified by the enzyme *LCAT*. The esters are transferred to IDL and then LDL and are eventually taken up again by cells.

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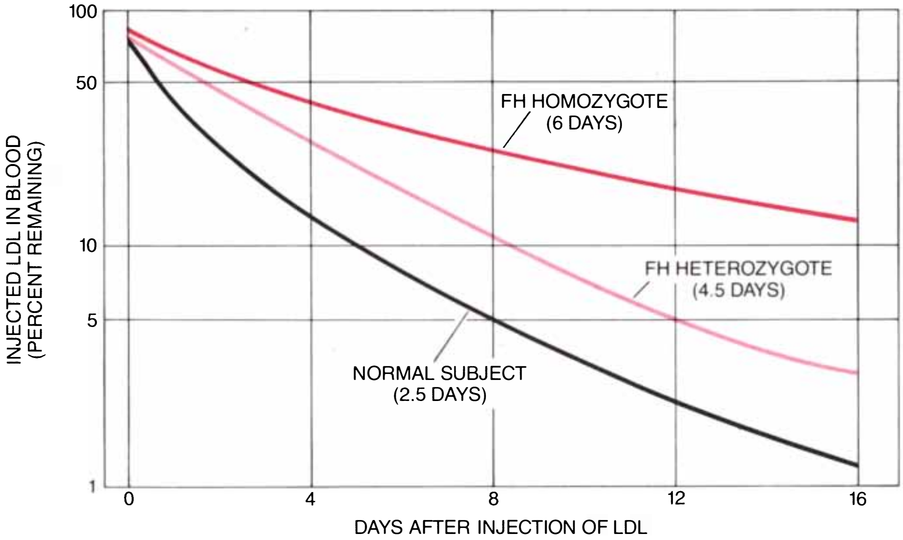

NUMBER OF LDL RECEPTORS in the body is assessed by injecting LDL labeled with a radioactive isotope and measuring the amount of radioactivity in blood samples for several weeks; the loss of radioactivity reflects the cellular uptake of LDL and hence the number of LDL receptors. The curves trace the removal of LDL from the circulation in patients with the homozygous and heterozygous forms of familial hypercholesterolemia (FH) and in normal subjects. In each case the mean life span of an LDL particle is shown in parentheses.

enzyme inhibitor was given too, the number of receptors rose much more. At the whole-body level this led to a marked increase in the rate of removal of LDL from the circulation. Together the two drugs caused a remarkable 75 percent decline in the dogs' LDL level.

With Bilheimer and Scott M. Grundy we went on to administer a resin and mevinolin to patients with heterozygous FH. Their LDL level fell by approximately 50 percent, into the normal range. Tests with radioactive LDL showed the drop was caused by an increase in LDL receptors. The single normal gene had been made to work twice as hard as usual, producing enough receptors to allow LDL to be removed from the circulation at a normal rate.

As might be expected, FH homozygotes, lacking even one normal receptor gene, do not respond to this two-drug treatment. Another approach must be found if they are to be helped. Thomas E. Starzl of the University of Pittsburgh School of Medicine has tested a surgical approach, following up on a suggestion that the homozygote's lack of receptors might be partially corrected if the patient could be given a liver from a normal donor. He transplanted the liver of a child killed in an accident into a six-year-old girl suffering from severe homozygous FH. (The patient had already had several heart attacks and her heart was so weakened that a heart transplant was necessary at the same time.) More than six months after the operation the patient was maintaining a total blood cholesterol level in the range of 300 milligrams per deciliter, compared with a preoperation level of about 1,200. Obviously liver transplantation is not an ideal treatment, but the results to date make it clear that receptors on the cells of the transplanted liver are functioning to remove LDL from the circulation.

What about the vast number of people in Western industrial societies who suffer heart attacks or strokes without having any genetic defect in the LDL receptor? Is what we have learned about FH relevant to the high incidence of atherosclerosis in the general population? We believe it is. The LDL-receptor hypothesis states that much of the atherosclerosis in the general population is caused by a dangerously high blood level of LDL resulting from failure to produce enough LDL receptors. The inadequate number of receptors can be attributed to subtle genetic and environmental factors that limit receptor manufacture even in people without FH. One environmental factor is a high dietary intake of cholesterol and of saturated fats derived from animal tissues.

Epidemiologic surveys done in many countries over the past 30 years have uniformly shown that atherosclerosis becomes severer as the mean LDL level rises in a population. As long ago as 1958 Ancel Keys of the University of Minnesota Medical School studied populations, in seven countries, in which the mean total cholesterol level varied from a high of 265 milligrams per deciliter to a low of 160. (He did not measure LDL cholesterol specifically, but because the level of lipoproteins other than LDL does not vary much, one can assume that the variations in total cholesterol reflected differences in LDL level.) Keys recorded the cholesterol level of 12,763 age-matched men in the seven countries, and 10 years later he determined which of the men had had a heart attack.

Two variables were found to correlate strongly with cholesterol level: the incidence of coronary atherosclerosis (as measured by fatal heart attacks) and the dietary intake of animal fats. In two villages (in Japan and Yugoslavia) where the mean total cholesterol level was 160 the incidence of fatal heart attacks was less than five per 1,000 men per 10 years. In eastern Finland, where the mean total cholesterol level was 265, the incidence of fatal heart attacks was 14 times as high. In populations with intermediate cholesterol levels (as in the U.S.) the incidence fell between the two extremes.

The correlation between cholesterol level and dietary intake of animal fats was even stronger than the correlation between cholesterol and atherosclerosis. Populations consuming small amounts of animal fats (as in Japan and Yugoslavia) had low cholesterol levels. Populations with a high intake of such fats (as in eastern Finland) had high levels. Subsequent studies of many different populations have confirmed Keys's findings: high LDL levels are the rule in populations that consume a large part of their calories as fats from meat and dairy products.

The LDL-receptor hypothesis provides a likely explanation of the epidemiologic data. A high average intake of cholesterol makes cholesterol accumulate in liver cells. The accumulation seems to be accentuated by ingestion of animal fats rich in saturated fatty acids. Even a modest accumulation of cholesterol in the liver would partially suppress the manufacture of LDL receptors. This could lead to an increase in the average LDL level that would be detectable in an entire population.

Animal experiments by our group and by Mahley and Innerarity support the hypothesis that a high-fat diet reduces LDL receptors in the liver. In baboons, rabbits and dogs maintained on low-fat diets the number of LDL receptors is high and the animals degrade injected LDL rapidly; their LDL level is much lower than it is in human beings. When rabbits and dogs are fed diets high in cholesterol, their manufacture of receptors in the liver is suppressed by as much as 90 percent, and the result is a buildup of both IDL and LDL in the bloodstream. At birth human infants have LDL concentrations similar to those of other animal species; apparently newborn human beings make a large number of LDL receptors. During the childhood and early-adult years in industrialized societies, however, the LDL level rises three- or fourfold. Studies in adults injected with LDL suggest that the increase is attributable to a decrease in the number of receptors with age.

The causes of the acquired receptor deficiency in human beings are not all known. The high dietary intake of ani-

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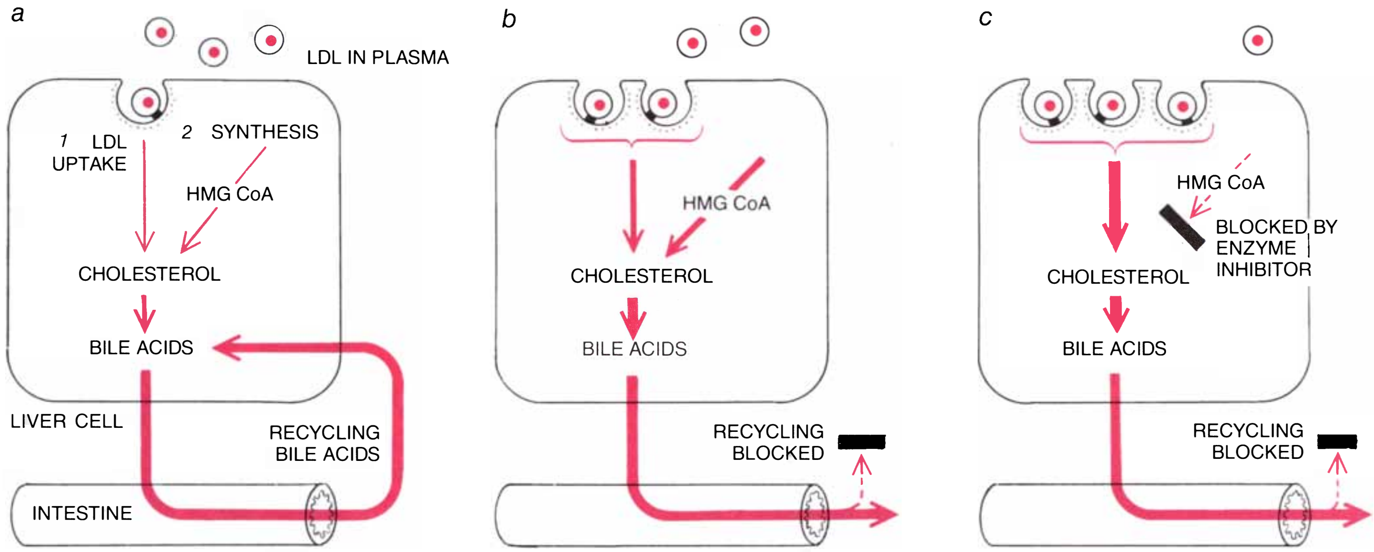
mal fats seems to be an important factor, but it is not the only one: even in people raised on diets extremely low in fats the LDL level tends to be higher than it is in other species. Such hormones as estradiol and thyroid hormone are known to stimulate the manufacture of LDL receptors in the liver, and it is possible that subtle abnormalities in these and other hormones contribute to the age-related decrease in receptors.

The concentration of LDL eventually attained in most middle-aged adults in the U.S. and in similar societies is associated by epidemiological data with accelerated atherosclerosis. Experiments with cultured cells show why. The receptors bind LDL optimally when it is present in the blood at a concentration below 50 milligrams per deciliter. The receptors in animals and in humans (judging by the LDL level in human infants) have apparently been selected by evolution to function at just such levels. Yet in Western industrial countries the average "normal" LDL level in adults is about 125 milligrams per deciliter, considerably above the concentration at which receptors bind LDL most efficiently.

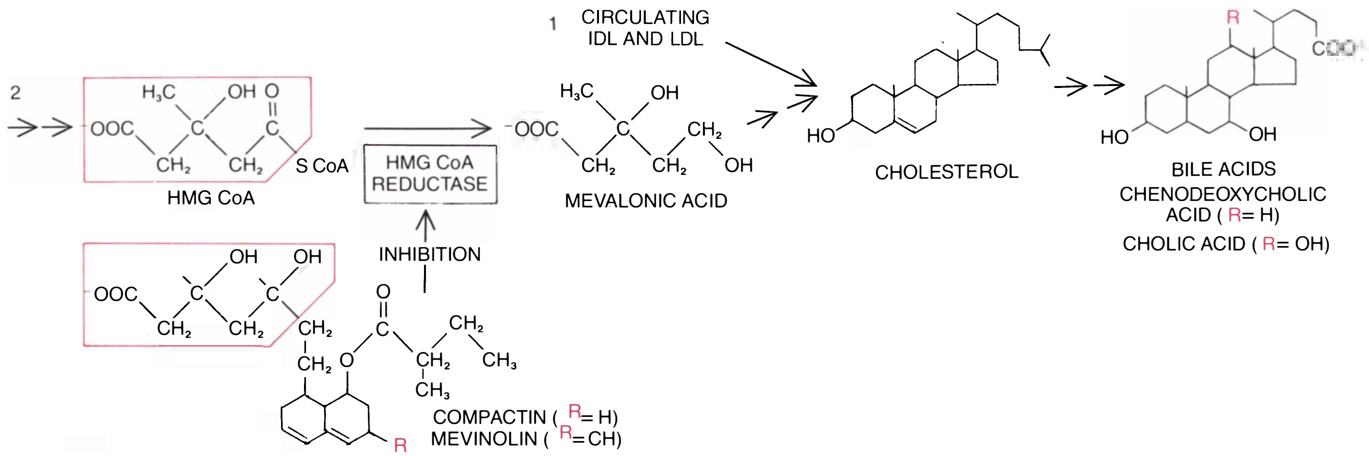
One finding that is consistent with the LDL-receptor hypothesis has been reported by William R. Hazzard of the Johns Hopkins Hospital and his colleagues. They showed that ingestion by adults of a high-cholesterol diet (including three egg yolks per day) does lead to a decrease in the number of LDL receptors, which they measured directly in circulating lymphocytes. A definitive test of the hypothesis will, however, require a comprehensive and well-controlled study of the rate of metabolism of injected VLDL and LDL in members of populations with low-fat and high-fat diets and with varying LDL levels. That has not yet been done systematically.

If the LDL-receptor hypothesis is correct, the human receptor system is designed to function in the presence of an exceedingly low LDL level. The kind of diet necessary to maintain such a level would be markedly different from the customary diet in Western industrial countries (and much more stringent than moderate low-cholesterol diets of the kind recommended by the American Heart Association). It would call for total elimination of dairy products as well as eggs, and for a severely limited intake of meat and other sources of saturated fats.

We believe such an extreme dietary



LIVER GETS CHOLESTEROL for conversion into bile acids from IDL and LDL taken up from the circulation (*1*) or by synthesizing it de novo (*2*). A key step in the long synthetic pathway is reduction of HMG CoA to mevalonic acid, a reaction catalyzed by the enzyme HMG CoA reductase. The enzyme is inhibited by the drugs compactin or mevinolin, whose side chain is so similar to that of HMG CoA (*colored frames*) that it blocks the enzyme's active site. Enzyme inhibition leaves liver dependent on uptake of IDL and LDL.



HETEROZYGOUS FH can be treated with a combination of drugs that stimulates manufacture of LDL receptors. Ordinarily the liver's demand for cholesterol is modified by the recirculation of bile acids (*a*). If the recirculation is prevented by a bile-acid-binding resin (*b*), more cholesterol is needed. Liver cells respond by increasing the number of LDL receptors, but also by increasing the rate of cholesterol synthesis. If a second drug is given to block enhanced synthesis (*c*), still more receptors are made and the blood LDL level is lowered.

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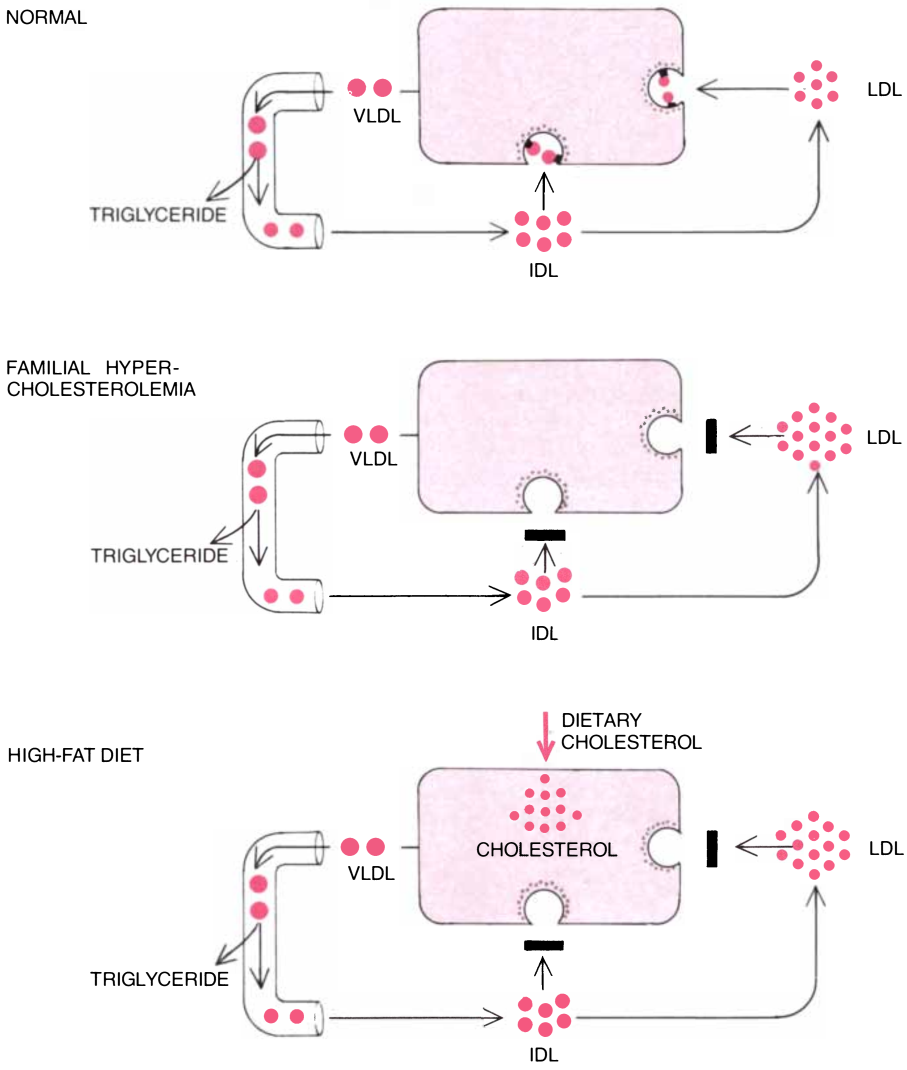
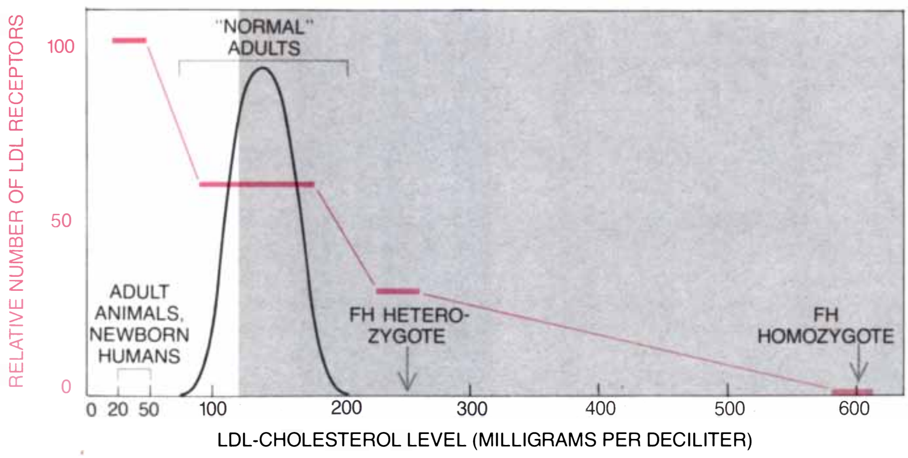


LDL-RECEPTOR DEFICIENCY, whether genetic or acquired, has two synergistic effects that combine to raise the blood LDL level. VLDL secreted by the liver is converted into IDL in fat and muscle. In normal people about half of the IDL particles are taken up by LDL receptors on liver cells; the rest are converted into LDL (*top*). In FH (*middle*) a genetic defect diminishes the number of receptors on liver cells; an analogous deficiency is caused by diets that fill liver cells with cholesterol and so reduce receptor synthesis (*bottom*). In either case there are the same two consequences. IDL not taken up by liver cells remains in the circulation and is converted to yield increased amounts of LDL; the LDL in turn is removed more slowly.



RANGE OF LDL LEVELS in "normal" adults in Western industrial societies, indicated by the curve, is compared with the range in adult animals and human infants and with the levels seen in FH patients. Levels in the shaded region of the chart are above the threshold associated with accelerated atherosclerosis; more than half of the adults have LDL levels above the threshold. The LDL level is inversely associated with the number of LDL receptors (*color*).

change is not warranted for the entire population. There are several reasons. First, such a radical change in diet would have severe economic and social consequences. Second, it might well expose the population to other diseases now prevented by a moderate intake of fats. Third, experience shows most Americans will not adhere voluntarily to an extreme low-fat diet. Fourth, and most compelling, people vary genetically. Among those who consume the current high-fat diet of Western industrial societies, only 50 percent will die of atherosclerosis; the other 50 percent are resistant to the disease.

Some individuals resist atherosclerosis because their LDL level does not rise dangerously even though they consume a high-fat diet; they may inherit genes that somehow circumvent the usual feedback system and maintain receptor manufacture at an adequate level. Barbara V. Howard of the National Institutes of Health Clinical Research Center in Phoenix has shown, for example, that Indians of the Pima tribe have relatively large numbers of LDL receptors, and maintain low LDL levels, in spite of a high-fat diet. In other individuals the arteries apparently resist the damaging effects of elevated LDL. For example, 20 percent of men with heterozygous FH do not have a heart attack before the age of 60 even though their blood LDL is very high.

Given these reasons for constraint, what can be done to prevent accelerated atherosclerosis? One approach is to individualize dietary recommendations. A diet moderately low in animal fats would seem to be prudent for most people. The diet proposed by the American Heart Association, for example, would reduce blood cholesterol levels by as much as 15 percent and should somewhat lessen the incidence of heart attacks. On the other hand, people who have a strong family history of heart attacks or strokes, and who may therefore be particularly susceptible to the damaging effects of LDL, might well be encouraged to follow a diet extremely low in cholesterol and saturated fats—even if their LDL level is near the mean "normal" level. One can hope additional research will identify factors that either sensitize people to the ill effects of LDL or protect them from those effects.

Finally, therapy with drugs that increase the number of LDL receptors may turn out to be appropriate for at least some people who do not have FH but in whom the number of receptors is reduced by diet or other factors. If it is shown that these drugs do prevent diet-induced suppression of receptors and if the drugs can be shown to be safe for long-term use, it may one day be possible for many people to have their steak and live to enjoy it too.

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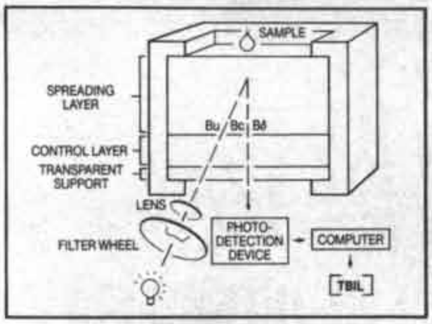
Making headway against jaundice a fraction at a time.

Kodak scientists have isolated what may be the first true human "biliprotein." The existence of this bilirubin fraction may lead to an advance in the diagnosis and treatment of jaundice-related disorders.

This important verification came to light during product-improvement testing procedures for Kodak Ektachem clinical chemistry slides. In the process of separating and identifying different bile pigments in serum, a fourth bilirubin fraction, delta (B_δ), was rediscovered. It is distinct from unconjugated bilirubin and is strongly linked (possibly covalently) to albumin.

Not only have we isolated and characterized this virtually unknown fourth fraction, we have developed a new assay procedure which enables labs to measure the delta fraction simply, rapidly, and accurately.

Last year we introduced an Ektachem chemistry slide to measure neonatal bilirubin. By means of dry film layers, this slide measures both unconjugated bilirubin (Bu) and mono- and diconjugated bilirubin (Bc) together. But the delta bilirubin fraction, which is tightly bound to a serum protein believed to be albumin, is not detected by the BuBc slide.



This year we are introducing a Kodak Ektachem fractionated bilirubin panel composed of BuBc and TBIL (Total Bilirubin), from which estimates of B_δ can be calculated. The new TBIL slide quantitates all three bilirubin fractions ($Bu + Bc + B_\delta$) while the BuBc slide now measures Bu and Bc as individual fractions. The difference in bilirubin quantitated by the two slides is B_δ.

We think the fractionated bilirubin panel may lead to a better understanding of the molecular basis of jaundice. This, in turn, can make it easier for health care professionals to diagnose biliary atresia and cytomegalovirus in newborn infants. And to screen for hepatobiliary disease, make differential diagnoses, indicate therapeutic strategies, and support prognoses.

For more information, write for "Bilirubin—Its Components in Serum and the Kodak Assay" to: Eastman Kodak Company, Dept LCSA-1, 343 State Street, Rochester, NY 14650.

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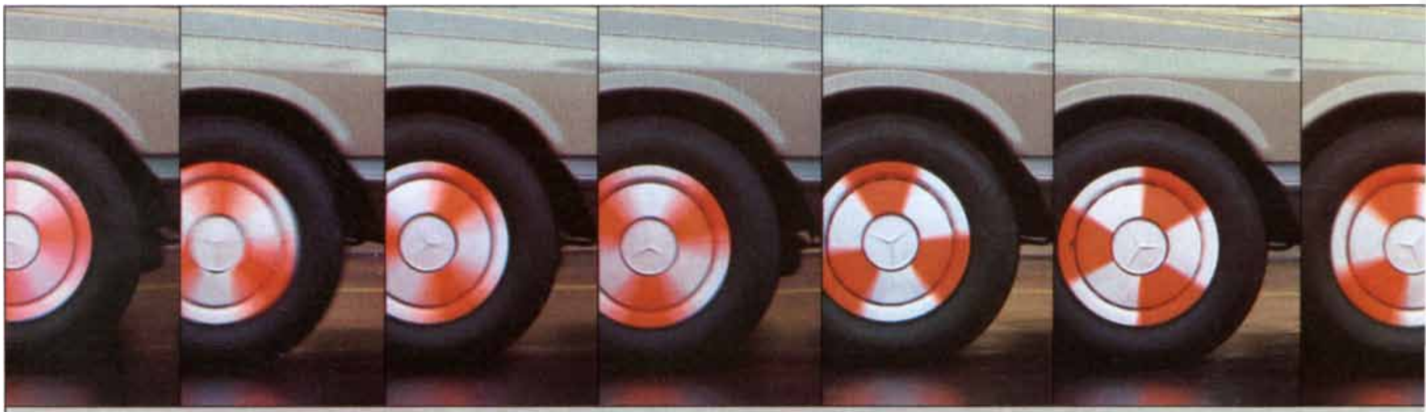

Wet road, hard braking–and within the one-second sequence dramatized above, the Mercedes-Benz Anti-lock Braking System acts to electronicall

For 1985, Mercedes-Benz introduces something more important than a new model.

THE MERCEDES-BENZ sedan speeds straight toward a patch of test track slicked down with a diabolical mixture of soapsuds and water.

A splash as the tires meet wet pavement–and then the driver slams on the brakes.

But what seems bound to happen in the next heart-stopping instant, doesn't happen. Violent braking action on that treacherous surface sets off no violent counterreaction.

That Mercedes-Benz sedan simply snubs down to a quick, straight-line stop. Soapsuds and water and all.

THE MERCEDES-BENZ ANTI-LOCK BRAKING SYSTEM COMES TO AMERICA

That Mercedes-Benz sedan has just demonstrated the most emotionally reassuring advance in passenger car braking control since the disc brake.

It is the Mercedes-Benz Anti-lock Braking System, or ABS. And having pioneered both its early development and its subsequent use in production automobiles, Mercedes-Benz now proudly introduces this significant engineering feature to America. It is being fitted as standard equipment to every 1985 Mercedes-Benz 500 SEC Coupe, 500 SEL Sedan, 380 SL Coupe/Roadster, 380 SE Sedan and 300 SD Turbodiesel Sedan, and as an extra-cost option to the 190 E 2.3 and 190 D 2.2 Sedans.

Functioning in concert with the car's four-wheel disc brakes, the Mercedes-Benz Anti-lock Braking System is meant to first sense the impending lockup of one or more of the car's wheels in a sudden braking emergency –then to act, with lightning speed, to avert it.

The benefits are clear. By minimizing the risk of the car's wheels locking up in hard braking, the system can also minimize the potential consequences: the sudden loss of tire adhesion that could turn a steerable vehicle into a sliding object no longer under the driver's full control.

More reassuring still, the system is designed for braking emergencies on slippery-wet roads as on dry roads–indeed, to maintain optimum braking performance almost regardless of road surface conditions.

SENSING TROUBLE BEFORE IT BECOMES TROUBLE

The decision-making "brain" of the Mercedes-Benz Anti-lock Braking System is an on-board computer. Electronic sensors, placed at both front wheels and at the drive pinion of the rear axle, are the system's vital nerve ends.

In a moving car under normal driving conditions, those sensors are constantly signaling the rotational speed of the wheels to the computer. Registering a millisecond-by-millisecond electronic bulletin on the precise state of adhesion between the car's tires and the road surface.

Then comes that sudden emergency. The driver reacts to danger ahead by reflexively hitting the brake pedal hard; hard enough, in a conventional braking system, to risk locking up one or more of the car's wheels.

But those electronic sensors

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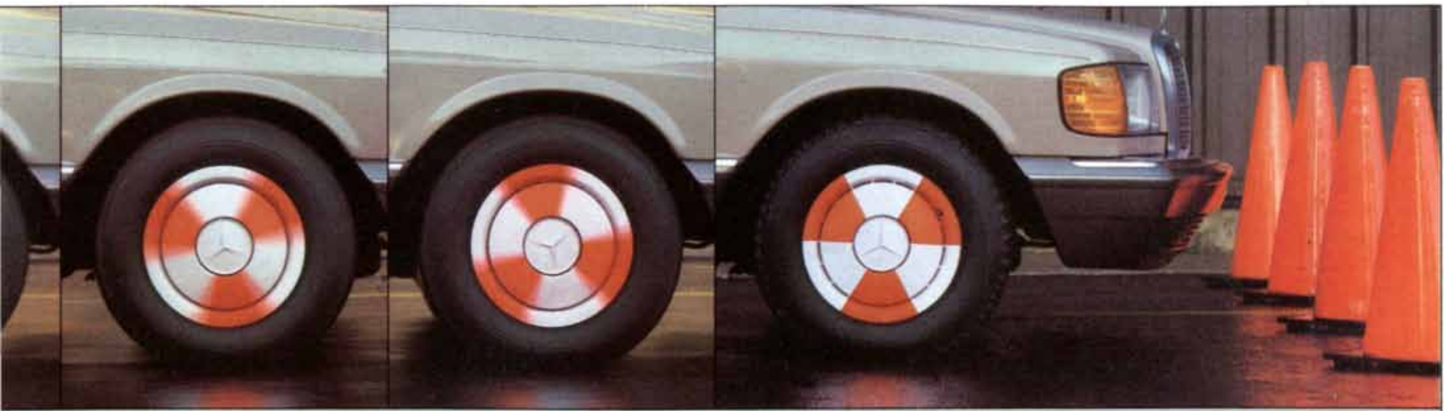


modulate braking action as often as 10 separate times. Preventing wheel lockup—and **keeping the car** precisely steerable **throughout**. .

have already detected the onset of wheel slip and alerted the computer. And the computer starts regulating fluid pressure in the brake lines. Modulating and cadencing brake pressure, via solenoid valves in the brake lines, as often as *ten times* per second. Countering lockup of all four wheels or any individual wheel.

And thereby allowing the car to be swiftly and smoothly decelerated. Allowing the car to be precisely steered and maneuvered *as* it decelerates. Helping the driver to avoid a collision, or simply to stay on the road.

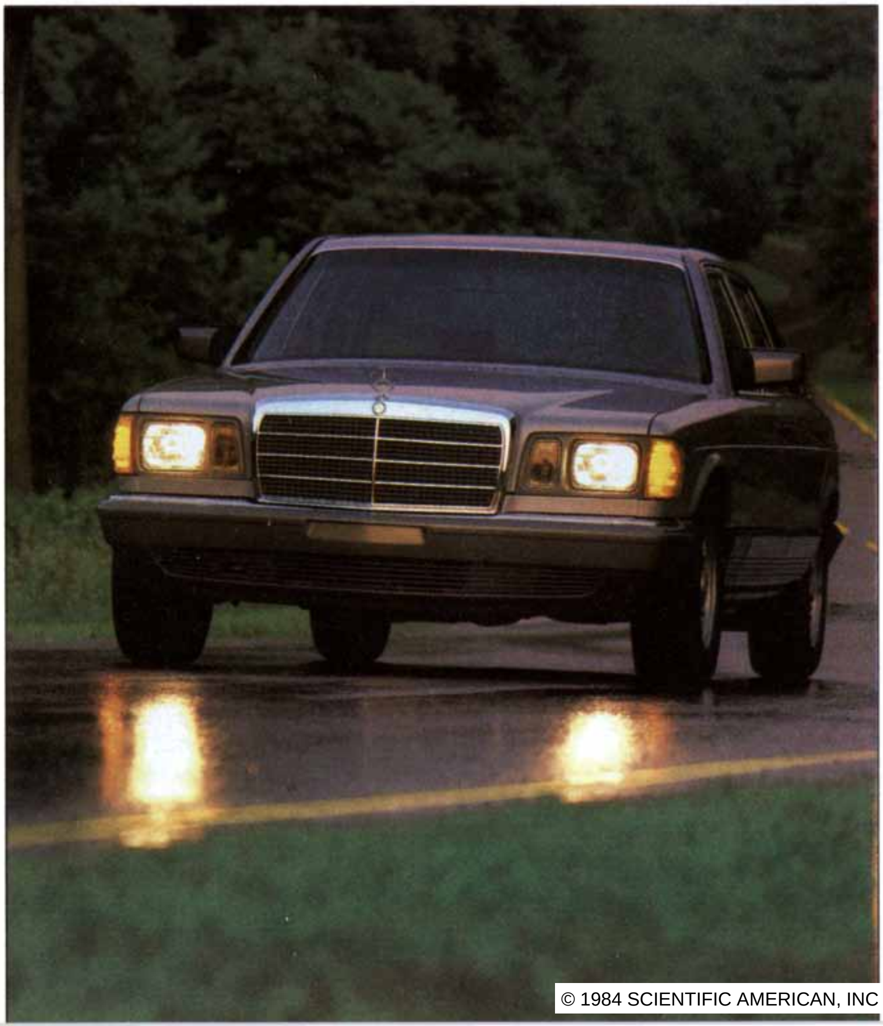
6,000,000,000 MILES

Mercedes-Benz began development work on the principle of the anti-lock braking system as far back as 1959, first fitted a working system to a production automobile in 1978, and has since seen 250,000 of its cars roll up over *six billion miles* of experience with the system worldwide.

Once again following where Mercedes-Benz has shown the way, some domestic and foreign makers will shortly introduce similar anti-lock braking systems to America. They can emulate the idea. They cannot emulate this depth of experience.

More than 50 percent of the logic circuitry programmed into that on-board computer is safety circuitry: the entire system is designed to be electronically self-checking, constantly monitoring itself and primed to shut down instantly should a malfunction ever be indicated. The car's separate four-wheel disc brake system would, of course, remain fully operational.

In terms of enhancing control of the car in a braking emergency, the Mercedes-Benz Anti-lock Braking System may be the best ally a driver has ever had. In terms of automotive leadership, this major advance underscores the truth of the motto below: for 1985, as for the past 99 years, the automobiles of Mercedes-Benz are indeed engineered like no other cars in the world.



Engineered like no other car in the world

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SCIENCE AND THE CITIZEN

To Boldly Go...

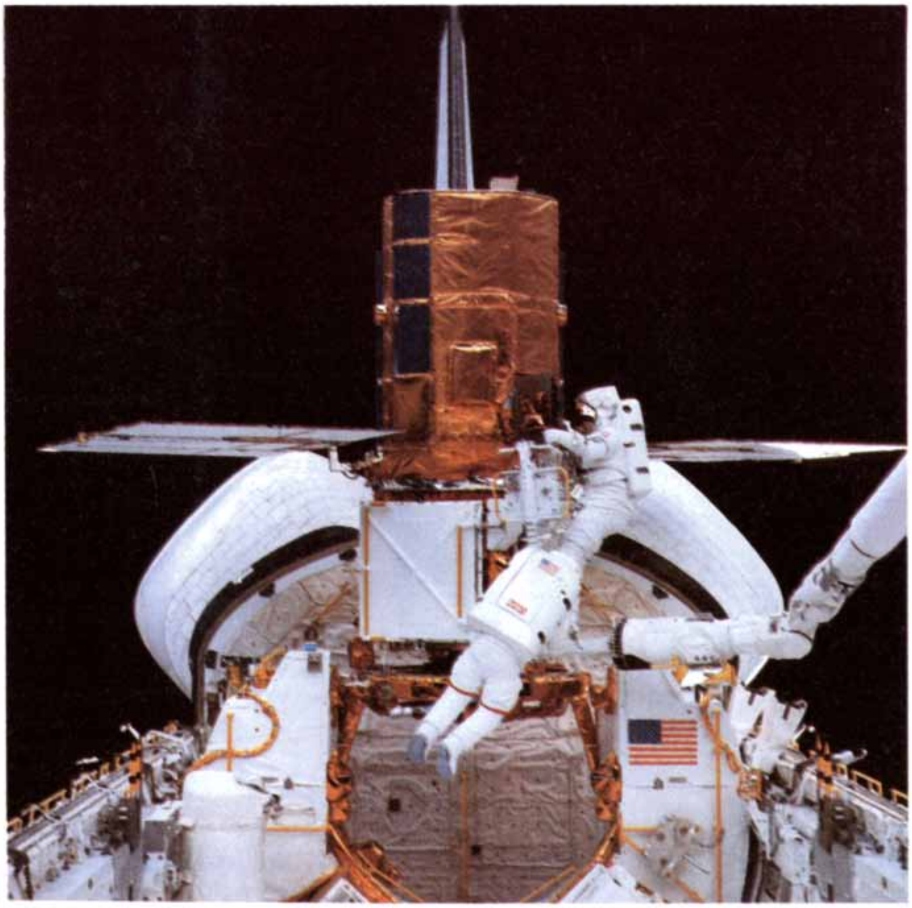
NASA has "a commitment from the Administration to spend $8 billion on something by 1992," according to John Hodge, who is in charge of planning for the National Aeronautics and Space Administration's proposed manned space station.

That "something" in all likelihood will be the space station. Just what form the station will take and what its missions will be, however, have yet to be defined. Many scientists criticize the space-station project on just these grounds: they say NASA and the Administration have decided that they want a space station and have determined what they want to spend on it before they know what purposes it should serve. The space station, these critics say, is a project that was designed from the concept down rather than from the necessity up.

For all its current lack of definition the space station has experienced no lack of publicity. President Reagan favored the project with a glowing description in his 1984 State of the Union Address. The space station and its companion in the manned program, the space shuttle, were highly touted at an all-day presidential briefing for the press on America's future in space. The president spoke, as did Phillip Culbertson, the director of the space-station project. The invitees included senior editorial management from the major print and electronic media, including the *Los Angeles Times,* the *New York Times,* the *Washington Post, Nature, Newsweek, Science,* SCIENTIFIC AMERICAN, *Time* and all three major television networks.

The Administration has also sought to broaden the industrial constituency for the program. Corporations have been urged to develop manufacturing procedures for semiconductors, pharmaceuticals and other products that could utilize the unique environment offered by the space station. The military is said to be interested; the Soviet Union is developing a space station of its own, and the Air Force does not want to be left without a matching capability.

NASA has been seeking to engage the scientific community in the project as well. In response to widespread skepticism, the space agency appointed a committee of scientists, headed by Peter M. Banks, professor of electrical engineering at Stanford University, to determine the possible uses and requirements of a space station; the committee met for a week at Stanford this summer.



A manned mission: shuttle astronauts repair the **Solar Maximum** *satellite*

Its preliminary conclusion is that there are indeed useful experiments that could be performed on a manned space station. In addition the possibility that the station may serve as a facility in which to build future planetary probes is a promising one. On the other hand, several committee members say that most experiments, particularly in the physical and astronomical sciences, could be performed equally well or better on unmanned orbiting craft. In fact, because of vibration and heat, the most delicate observations and experiments would be made not on the space station itself but on the unattached orbiting platforms that are to accompany it.

A deeper strain of concern pervades the opposition. In an echo of the controversy that attended the establishment of the shuttle program, many planetary scientists say that construction of the space station will divert money and attention away from the extremely successful, although less glamorous, unmanned program. They point out that the manned program has powerful congressional, bureaucratic and industrial constituencies, which would coalesce into a daunting force in any struggle for funding. Such critics also suggest that the construction of a space station has been proposed in order to give the space shuttle (which they say has proved uneconomical as a satellite launch vehicle) something to do: in NASA's plans the shuttle will ferry people and matériel to and from the station.

NASA administrators maintain that the space station represents no danger to the unmanned program. They point out that space-science funding has constituted the same proportion of the NASA total budget since the mid-1960's. The lesson, they argue, is that any increase in the NASA budget will carry space science along with it.

James A. Van Allen of the University of Iowa rejects the importance of the coattail effect. Van Allen, an eminent figure in high-altitude research with rockets, satellites and space probes and the discoverer of the Van Allen belts, observes that other, less visible scientific agencies, for example the U.S. Geological Survey, have been able to do excellent scientific work in space. Van Allen also disputes the NASA claim that spending on unmanned programs has paralleled spending on the manned program. He and other scientists point to the drastic cutback in programs that occurred as a result of space-shuttle cost overruns in the late 1970's. He also recalls the Federal Government's 1981

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proposal to effectively terminate the program of solar-system exploration.

Other critics, such as Thomas Gold of Cornell University, say that the shuttle's adverse effect on space science can be seen in the cancellation of the proposed 1986 mission to Halley's comet. Gold asserts that since the mid-1970's, when the shuttle began receiving major funding, programs that would have been the natural continuation of earlier work have simply not been started. Such programs include a new lunar orbiter and the second Mars lander. If the space station is built, this period of low start-ups could continue well into the future. Projects such as the orbiting telescope seem relatively safe, but development of the space station may endanger others, such as the *Galileo* mission to Jupiter and the Venus exploration program.

Joseph F. Veverka, also of Cornell, believes the major threat is not so much to programs that acquire new data as it is to the funding necessary for data analysis. He points out that funding cuts due to shuttle cost overruns delayed the analysis of *Pioneer 10* and *Pioneer 11* measurements of charged particles in the atmosphere of Jupiter. This delay forced engineers to base their designs for the *Galileo* probe on an incorrect model. Once the data were broken down, the probe had to be partially rebuilt. He adds that as much as one-fourth of the images from the Viking orbiters have not seen detailed analysis.

There may well be grounds for the concern that the cost of the space station will cause cutbacks in other programs. The $8 billion mentioned by Hodge will not buy a completed space station. That preliminary figure is only intended to cover the cost of the basic module and living quarters, around which the rest of the station will grow. In fact, the $8 billion does not even include the cost of launching the space-station components into orbit; that expense will come out of the shuttle budget. Some members of the Banks Committee estimate privately that the total cost may be as high as $20 billion or more in 1984 dollars.

Critics such as Van Allen fear that this heavy commitment to the inherently less flexible manned program may do permanent damage to the relatively inexpensive unmanned program, which has a 26-year history of success.

Strategic Boomerang

As the Trident II, the Navy's new submarine-launched ballistic missile (SLBM), moves into production critics in Congress are again raising the argument that the weapon may act as a strategic boomerang, reducing rather than enhancing national security.

The warheads carried by the Trident II will be three times more accurate and four times more destructive than those carried by its predecessor, the Trident I. In theory this combination of capabilities will give the Navy the ability to attack the most powerful component of the U.S.S.R.'s strategic weaponry, the land-based missile force, by 1989, when the planned fleet of 20 Trident submarines, bearing 24 Trident II missiles each, is to be fully deployed.

How might the U.S.S.R. respond to such a perceived threat? In the short term it could decide to deploy more land-based missiles on mobile launchers, thereby enhancing their survivability. It could also adopt a "launch on warning" policy, guaranteeing that any incoming U.S. warheads would hit only empty silos. In the long term the U.S.S.R. would almost certainly do what it has always done when confronted by a new U.S. advance in military technology. In the absence of any treaty constraints it would proceed to build its own force of advanced SLBM's comparable in accuracy and megatonnage to the Trident II and deploy them on submarines off the U.S. coast.

Given the present composition of U.S. forces the adverse effect on national security would be particularly severe. U.S. security, military planners say, rests on a "triad" of land-based missiles, submarine-based missiles and long-range bombers. Land-based missiles and bombers are said to synergistically enhance each other's survival. This view holds that only the land-based missiles of the U.S.S.R. are currently capable of threatening the U.S. land-based missile force. The flight time for such missiles is approximately 30 minutes, giving the U.S. ample time to get its bomber force safely airborne after the attack is detected. Bombers on the ground could be destroyed in 15 minutes or less by the present generation of SLBM's, but the detection of such a close-range attack could trigger the release of the land-based missiles from their silos, thereby thwarting a preemptive attack on them.

In theory a Russian SLBM force comparable to that of the planned Trident fleet could simultaneously destroy both land-based components of the U.S. triad. Such an attack would halve decision-making time and enhance the attractiveness to the U.S. of a launch-on-warning strategy. Some members of Congress and strategic experts conclude that the best hope of preserving the deterrent value of the triad may lie in a prompt bilateral nuclear-weapons freeze.

Hot Ice

Can diamond exist as a liquid? Workers at Cornell University have serendipitously found that it can.

The Cornell workers, Jon S. Gold (a graduate student) and William A. Bassett, Maura S. Weathers and John M. Bird of the Department of Geological Sciences, were attempting to convert one of the two crystalline forms of carbon, graphite, into the other, diamond. Their experiment was part of an inquiry into the nature of carbon in the interior of the earth. To convert the graphite into diamond Gold placed a specimen between the anvils of a diamond-anvil pressure cell. The diamond anvils are capable of generating pressures as high as 450 kilobars (450,000 times atmospheric pressure at sea level).

Gold subjected the graphite to a pressure of about 120 kilobars. He then directed a laser beam through one of the anvils to simulate the temperature in the lower mantle. "The ... intent of the experiment was to observe the melting behavior of graphite at high pressure," the workers report in *Science*. "However, the focused laser was inadvertently run at a very high power density." The result was damage to the face of the anvil that was later shown to have been caused by melting. "This is the first time that experimental evidence has been produced to show melting of carbon at high pressure when diamond is used as the starting material," the workers write. It is conceivable, they imply, that carbon can be liquid in the lower mantle.

Polymer Power

Polyaniline, an organic nitrogen polymer known for nearly a century, can be converted through a novel yet simple doping technique into a substance that conducts electricity as a metal does. The technique was devised by Alan G. MacDiarmid and his colleagues at the University of Pennsylvania.

In 1977 MacDiarmid and Alan J. Heeger discovered the first conducting polymer, polyacetylene, which they doped with iodine. Since that time about 10 more conducting polymers have been identified, but most are hard to handle in the laboratory and all are costly to make, which limits their practical use. In contrast the aniline monomer is inexpensive, and the synthesis and doping of polyaniline can be done under common laboratory conditions because it does not lose its conductive properties when it is exposed to air and water.

In their ordinary state polymers are insulators because they lack free electrons that would carry an electric current. One way of overcoming this deficiency is p-doping, which creates "positive holes" in the polymer structure (in effect movable positive charges) by adding a substance that tends to draw electrons out of the molecule.

In conventional p-doping the dopant is an oxidizer such as iodine that actually removes electrons from double bonds in the polymer molecules. The Pennsylvania group's new technique for doping polyaniline involves the converse process: the addition of protons to the poly-

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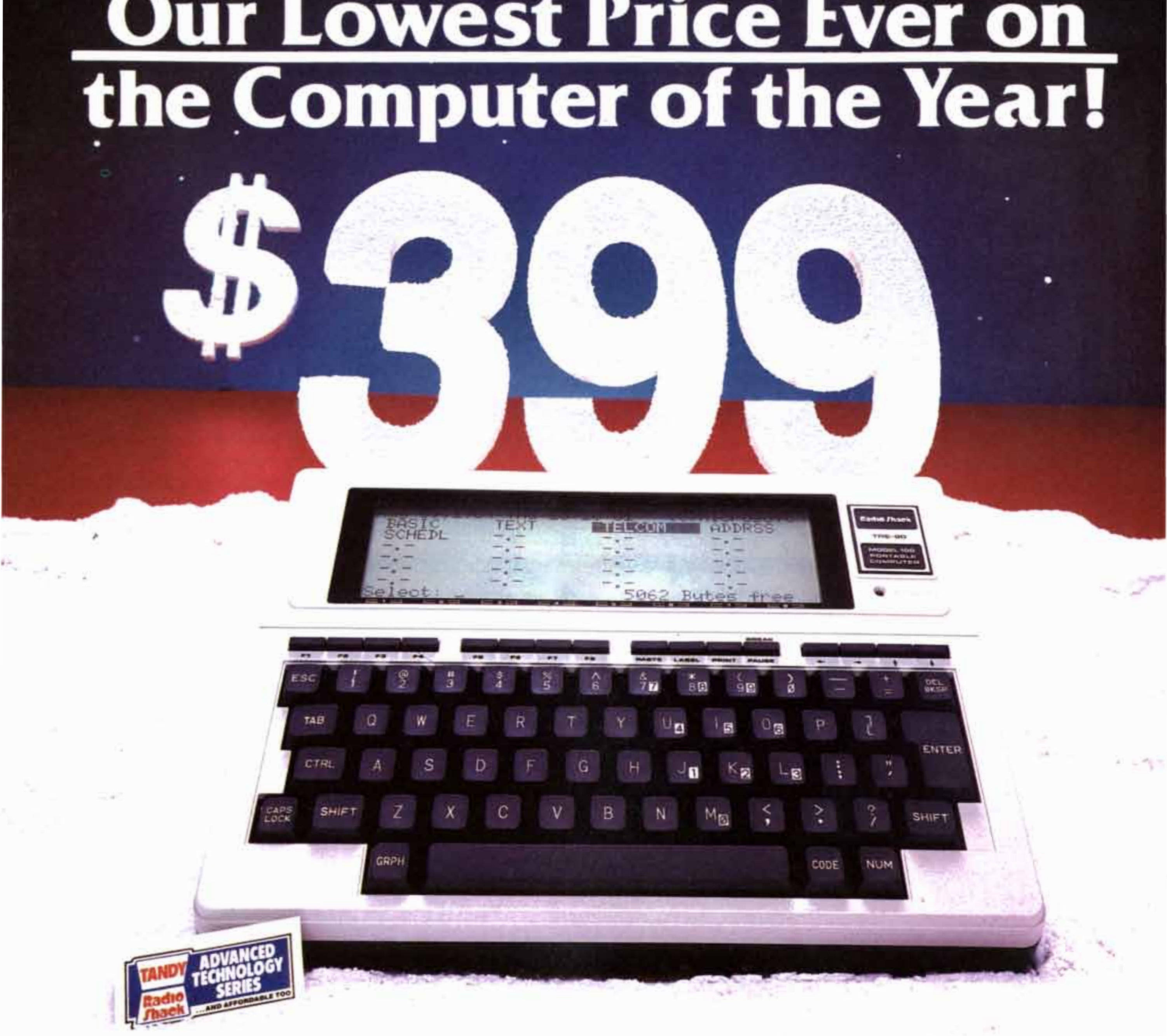

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mer. This is accomplished by allowing polyaniline, a base, to react with a solution of hydrochloric acid; hydrogen ions in the acid provide the protons. The resulting hydrochloride salt has a conductivity 10^{11} times greater than that of the ordinary polymer.

MacDiarmid and his co-workers do not yet know why the addition of protons should be so effective. When the doped molecule is treated with an aqueous base, however, it reverts readily to its insulating form. MacDiarmid said investigators should be able to exploit this easy convertibility to study the differences between the conducting and the insulating forms of polyaniline, in order to learn more about the general phenomenon of conductivity in polymers.

There may be practical applications for polyaniline. The Pennsylvania workers have discovered that both the doped and the insulator forms of the polymer are readily reduced (that is, they accept electrons) and then oxidized back to their original state. Consequently they might serve as electrodes in rechargeable batteries; in fact in the laboratory the workers have made a polyaniline flashlight battery that can be recharged repeatedly. According to MacDiarmid, it may someday be possible to manufacture such batteries at about the cost of the current throwaway models.

A Garden of Echinoderms

Echinoderms, a group that includes starfish, sea cucumbers, sea urchins and other simple marine animals, are quite sedentary and often retreat from intruders in shallow waters, where they are best known. New observations show that at greater depths some varieties undergo a change in behavior.

For the past year a team of biologists from the Smithsonian Institution's National Museum of Natural History and the Harbor Branch Foundation, Inc., in Fort Pierce, Fla., has been studying the remarkable concentrations of echinoderms that populate precipitous underwater terrain off the Bahamas, at depths of 100 to 800 meters. The discovery of the sites, says John E. Miller of Harbor Branch, head of the expeditions, was "pure serendipity." Specimens recovered from the area by other workers prompted Miller to explore the region in a research submersible. On the first dive, says Miller, he and his colleagues were "overwhelmed with the number and diversity of echinoderms." They returned from their first expedition with specimens of 60 species, many of them previously thought to be rare.

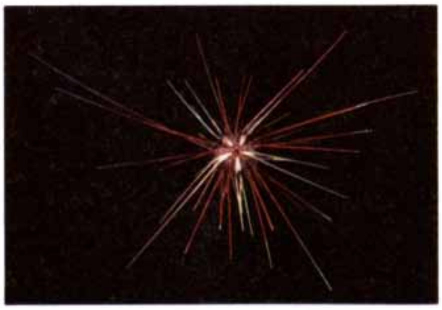
During later dives the workers studied the behavior of the deep-living echinoderms. In shallow waters, brittle stars scuttle along the bottom but do not swim. In contrast, when brittle stars at the Bahamas site were disturbed, they propelled themselves off the sea floor and up into the water with whiplike motions of their arms. It may be, says Miller, that the behavior allows them to rise out of harm's way when sediment slides cascade down the steep slopes.

Some sea lilies, or stalked crinoids, also displayed mobility. Such species had been thought to remain fixed to the same spot throughout their adult lives, but when Miller's group uprooted sea lilies, the animals crept across the sea floor by extending their feathery arms and dragging themselves forward. The finding suggests that the sea lilies of the Bahamas may be able to detach themselves at will and seek more favorable sites for feeding.

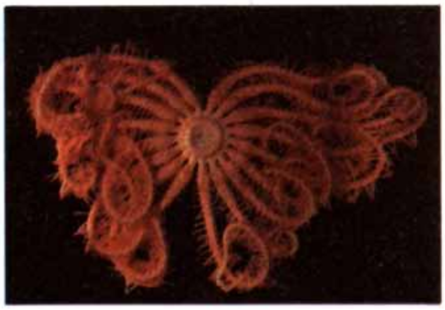
Unlike their shallow-water kin, which often retreat when they are disturbed, these echinoderms seem to lack defensive behavior. The reason may be that they face fewer menaces at the deepwater Bahamas site than in shallow water.

Colony of sea lilies at 450 meters

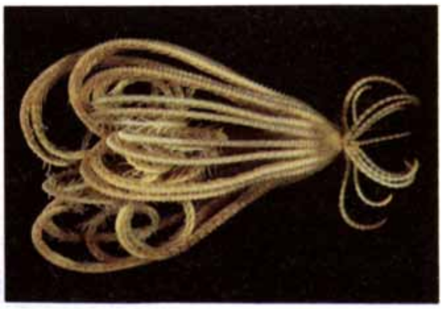
Brittle star at 400 meters



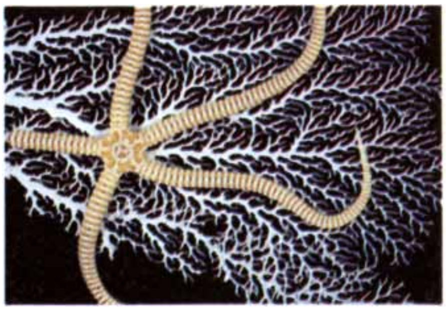
Deep-living sea urchin



Sea star



Feather star



Brittle star on coral

Beware the Beef

Two common practices have been blamed for the alarming spread of transferable antibiotic resistance among strains of pathogenic bacteria. One is the prodigal and sometimes inappropriate administration of antibiotics to human patients. The other is the inclusion of subtherapeutic doses of antibiotics in animal feeds to promote weight gain.

A report in *The New England Journal of Medicine* by investigators at the Centers for Disease Control has shown how both practices contributed to an outbreak of food poisoning by resistant bacteria that affected 18 people in four Middle Western states in 1983 and led to the death of one of them.

Drug manufacturers, who sell millions of pounds of antibiotics annually for inclusion in feeds, have maintained that the relatively low doses ingested by beef cattle, pigs and poultry do not promote the development of resistance in bacteria that colonize the animals and that in any case those bacteria are not likely to be passed along to the human end of the food chain. The report by

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Scott T. Holmberg, Michael T. Osterholm, Kenneth A. Senger and Mitchell L. Cohen finds otherwise.

They began by investigating an outbreak in Minnesota of diarrheal disease caused by the bacterium *Salmonella newport.* Bacteria isolated from all the patients were resistant to the antibiotics ampicillin, carbenicillin and tetracycline and carried the same plasmid. (A plasmid is a small circle of the genetic material DNA, distinct from the bacterial chromosome, that often carries genes conferring resistance to several different antibiotics.) A survey of *S. newport* strains recently isolated from livestock turned up the same resistance pattern and plasmid in bacteria that had caused diarrheal disease in cows on a dairy farm in South Dakota several months before.

A beef feedlot adjoins the dairy farm. The cattle there had been fed tetracycline. A shipment of beef from the herd could be traced to supermarkets where it had been ground to make hamburger. Most of the affected patients had eaten hamburger bought at one or another of those supermarkets during the week before they became sick. Three others had got beef directly from the feedlot. All the remaining cases could be connected in some way to a hamburger-linked case. Both the epidemiological and the laboratory data thus point to specific beef cattle as the source of the resistant salmonella.

Interviews with patients revealed that 12 of them had taken an antibiotic (one to which the *S. newport* strain was resistant) for a minor nondiarrheal illness just before developing salmonellosis. The implication is that what would have been an asymptomatic salmonella infection was rendered virulent by "selective pressure": the antibiotic killed off harmless intestinal bacteria that would normally have competed with the salmonella, and in doing so it allowed the pathogens to proliferate.

The authors conclude that resistant bacteria of animal origin can indeed cause serious human disease, particularly in people taking antibiotics, and that subtherapeutic dosage of animals tends to select for such bacteria. They advocate more prudent use of antibiotics "in both people and animals."

Breaking Bieberbach

One of the most celebrated conjectures in mathematics, first made by the German mathematician Ludwig Bieberbach in 1916, has been proved by a mathematician whose previous work is often discounted by the American mathematics community. The proof is due to Louis de Branges of Purdue University, who, some of his colleagues say, lost much of his credibility 30 years ago when he published an erroneous proof. De Branges is now happy to point out that the implications of his proof are so wide-reaching that he may have put some of his colleagues out of work.

Bieberbach, a notorious figure in the history of mathematics for his association with the Nazis, was motivated by a much earlier conjecture made in 1851 by Georg Friedrich Bernhard Riemann. Riemann's conjecture was one of the first to link functional, or algebraic, analysis with topology, which is a generalized study of geometry. The conjecture can be understood by considering any region of a plane that is simply connected; in other words, the region can be arbitrarily complicated except that it must not have any holes. According to Riemann, there must be some function, or mapping, such that every point in the arbitrary region is associated with one and only one point inside a circle with unit radius.

Functions that map regions in the plane into other regions in the plane are best represented by complex numbers. (A complex number is a number with a real part and an imaginary part.) It is often easier to manipulate such a function mathematically if it can be represented as a power series, which is an infinite sum of terms. For example, given the complex number z, the function e^z can be expressed by the infinite series $1 + z + z^2/2! + z^3/3! + \ldots$.

What Bieberbach conjectured is that there is a connection between the conditions imposed on a function by Riemann's conjecture and the numerical coefficients of the terms in a power series that represents the function. Bieberbach initially considered a function of a complex variable studied by the mathematician Paul Koebe. It is the function $z/(1 - z)^2$, where z is, once again, any complex number. Under the mapping specified by Koebe's function, the image of all the values of z that lie inside the unit circle in the plane is the entire plane, with the exception of a single line segment that begins on the horizontal coordinate axis of the plane at the value $-1/4$ and extends to infinity. There are no two values of z within the unit circle, however, for which the function gives rise to the same point.

If Koebe's function is expanded by formal algebraic long division, it is equal to the infinite power series $z + 2z^2 + 3z^3 + \ldots$. Bieberbach then made something of a leap of faith. He conjectured that if a function gives a one-to-one association between points in the unit circle and points in a simply connected region of the plane, the coefficients of the power series that represents the function need never be larger than the coefficients of the series that represents Koebe's function. In short, the first term need never be larger than 1, the second term need never be larger than 2 and so on.

De Branges actually has proved a much stronger conjecture, made in 1971 by I. M. Milin of the V. A. Steklov Institute of Mathematics in Leningrad. The Bieberbach result is a consequence of the Milin conjecture, as are several other theorems in the branch of mathematics called geometric function theory. De Branges received his first serious hearing at a seminar held at the Leningrad institution, and his work, still unpublished in the U.S., may receive its first formal publication in the U.S.S.R.

Mind Expanding

Do neurons continue to multiply in the brain during adulthood? The consensus is that in vertebrates they generally do not. Research by investigators from Rockefeller University, however, reveals a notable exception.

The workers, John A. Paton and Fernando N. Nottebohm, report in *Science* that functioning neurons are regularly generated in the brains of adult canaries, in a nucleus that controls vocalizations. The canary's song plays an important role in mating, and the corresponding nucleus is known to expand and shrink seasonally, in step with changing levels of hormones.

The new finding grew out of research conducted by Nottebohm to determine the cellular basis of the change in size. Nottebohm and others found evidence of changes in cell size and packing arrangement as well as evidence of multiplication by non-neuronal cells. In a test done simply as a control Nottebohm and Steven A. Goldman were startled to find indications that proliferation of the neurons also was swelling the nucleus. The authors then undertook to confirm the surprising finding; in Paton's words, "the control became the experiment."

To identify any newly generated neurons the investigators injected adult canaries with regular doses of tritium-labeled thymidine, a precursor of DNA. In any cells formed during the test period the radioactive marker would be incorporated into the nuclear material, making the new cells easy to detect.

Thirty days after the last injection of thymidine the workers pinpointed functioning neurons in the birds' vocal-control nucleus. By inserting microelectrodes into the birds' skulls they detected the electrical activity of individual neurons. They tagged each of the cells from which electric potentials were recorded with tiny doses of horseradish peroxidase (HRP), an enzyme commonly used to stain neurons.

When the brains of the birds were examined, seven of the total of 74 neurons that the Rockefeller University workers had stained with HRP also bore the radioactive marker in their nuclei. These double-labeled cells, the authors concluded, were functioning

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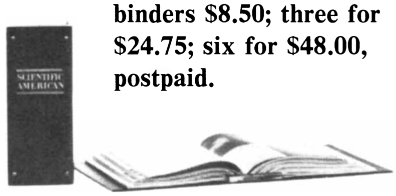

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neurons that had been generated during the two-week regimen of thymidine injections.

Paton and Nottebohm are not the first to present evidence of neuron growth in adult brains, but earlier studies all identified newly formed cells as neurons by morphological criteria, leaving the results open to dispute. The Rockefeller workers singled out neurons on the basis of function; they present their finding as the first proof of neurogenesis in an adult vertebrate brain.

Tuning a Deaf Ear

The development of microprocessors and of miniature electronic components has made possible yet another artificial organ: the cochlear implant. A one-channel device, manufactured by 3M, is expected to be approved by the Food and Drug Administration for general use this fall. More sophisticated, four- and eight-channel versions made by other manufacturers are being tested at the Stanford University Medical Center and the University of California at San Francisco. All told, a total of six such devices are in clinical trial at various medical centers.

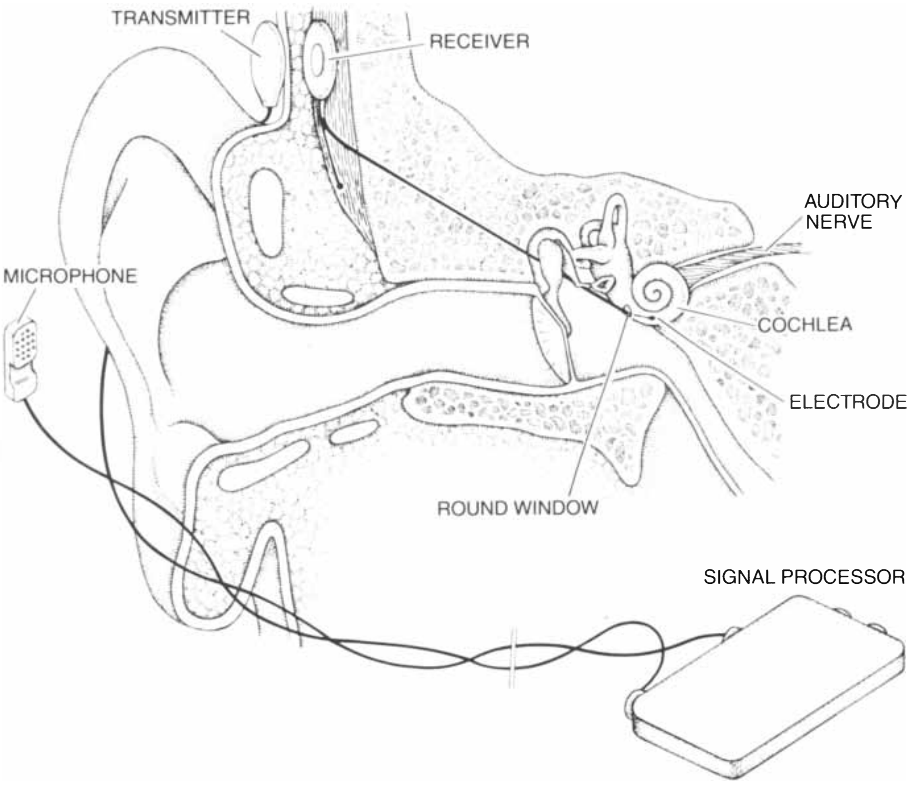
The cochlear implant could be of great benefit to the roughly 300,000 people in the U.S. who suffer from sensorineural deafness. In sensorineural deafness, which is one of several types of deafness, the functioning of the hair cells that line the cochlea is impaired. In a healthy ear these hairs convert sound pressure waves into electrical impulses that are conveyed to the brain by the auditory nerve.

The one-channel 3M device relies on a tiny microphone placed near the ear. The electrical signal from the microphone is modified by a processor and then carried to a transmitter placed behind the fleshy external part of the ear.

The transmitter generates a signal that travels to a receiver implanted under the skin. Extending from the receiver are two electrodes. One electrode is a ground. The other reaches the cochlea through an opening called the round window.

When a sound arrives at the microphone, current flows between the ground and the electrode in the cochlea, stimulating the auditory nerve. Equipped with the device, people who suffer from sensorineural deafness can hear sounds such as car horns and doors slamming. They can also hear speech rhythms and changes of volume. The implant does not enable them to understand conversation. A refined, multichannel implant, however, may offer that possibility.

In multichannel devices the processor divides the electrical signal into bands corresponding to different frequency ranges. Several electrodes are implanted in the cochlea and each band is transmitted to a separate electrode. The division of the signal into frequency bands could allow intelligible reproduction of human speech. Such a device is still far from general availability.



Cochlear implant

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JAPANESE TECHNOLOGY TODAY

THE AUTHORS

The 1984 edition of "Japanese Technology Today" was written by Dr. James C. Abegglen and Mr. Akio Etori.

Dr. Abegglen is vice president of Asia Advisory Service, Inc., and concurrently professor of international management at Sophia University in Tokyo. He has written numerous articles and books, including *The Japanese Factory*, a pioneering study of Japanese corporate organization.

Mr. Etori is an award-winning and respected writer on science and technology who has covered these areas for over 20 years. He is managing editor of *Saiensu*, the Japanese-language edition of SCIENTIFIC AMERICAN and Japan's leading science publication.

THE COVER

The Radio High-density Circuit, one of the latest developments from Matsushita Electric, is dramatically highlighted by photographer Michael Radencich. The new RHC component technology, consisting of a carrier integrated circuit, a ceramic capacitor network and a film circuit, has created a whole new breed of audio products, such as a sensitive FM stereo built into a pair of featherlight headphones and an AM/FM stereo that is just slightly larger than a credit card. Both are available from Panasonic.

Art direction and supervision of the text and illustrations were provided by Ted Bates Advertising/New York.

The establishment of a world-scale, independent research and technology capability has become the driving force in Japanese planning for the balance of the 20th century. There is a general view that the long economic crisis of the past decade has been successfully weathered. "The Japanese economy is now moving toward recovery after emerging from a long period of economic adjustment," says the Economic Planning Agency of Japan in its annual survey of the economy. "The Japanese economy has still not lost its development potential, judging by the high savings ratio, the strength of technological development and the strong propensity of enterprises to invest."[1]

A strong, fresh view of what direction progress should take accompanies the sense of renewed growth. Once again, this highly literate and relatively homogeneous people are creating a consensus regarding the future. The process of consensus forming may have been signaled by the publication by the Ministry of International Trade and Industry of *Sangyo Kozo No Choki Bijiyon* ("The Long-Term View of Industrial Structure"). According to this view Japan will continue to grow faster than the other developed economies, especially in high-technology manufacturing, and be particularly strong in services, as the resources of the economy shift to the higher-value-added activities in this tertiary sector. Technological innovation will drive the growth and restructuring. Japan's Long-Term Credit Bank notes, "It has been argued for 20 years, beginning in 1965 when Japan faced a recession, that the Japanese industrial structure should make a changeover to knowledge-intensive industries and industries characterized by a high degree of information processing."[2]

As early as 1971, the *Industrial Vision for the 1970's* issued by the Ministry of International Trade and Industry pointed out that the industrial structure would be upgraded by continuing high growth in knowledge-intensive industries in which there was a high degree of information processing and technology.

"In the materials industries," according to the Bank, "a changeover is beginning from steel to new materials, from chemicals to new materials and biological products, and from conventional fibers to new fibers such as carbon and aramide ones as well as to new materials and biological products. In the processing industries, more electronics is being incorporated into electrical machinery. Automobiles are being built with more advanced technology using semiconductors, computers, optics and new materials. What was predicted a decade ago is finally becoming a reality."[3]

[1]*Economic Survey of Japan (1982-1983).* Economic Planning Agency, Japanese government, Tokyo, 1984, p. 200.
[2]*Japan's High-Technology Industries (2).* The Long-Term Credit Bank of Japan, Ltd., Tokyo, February, 1984, p. i.
[3]Ibid.

There has indeed been a long discussion in Japan of a new era, characterized by much talk of the information revolution and knowledge-intensive industries. Only during the past two or three years, however, have the issues come into focus and the concepts become more specific. There is now a strong sense of being on the threshold of revolutionary change.

The Economic Planning Agency describes the process as follows: "When the Japanese record of technological innovation after the war is observed, three large waves can be discerned. The first occurred from 1955 to 1965 and centered around synthetic fibers, plastics, synthetic rubber, household electrical appliances and the oxygen-based blast furnace technology. The second, during 1965-75, focused on automobiles and large-scale blast furnaces. The third came after 1975, involving microelectronics such as numerical control processing equipment, robots, semiconductors, video tape recorders and air conditioners.

"There is a view that information technology during the third wave underwent a revolution with the same impact on human society as the technological revolutions in agriculture and industry that preceded it. As the previous technological revolutions presaged the advent of new agricultural and industrial societies, so too may the revolution in information technology bring about an information-oriented society, and this revolution in information is characterized by its rapidity."[4]

The Long-Term Credit Bank analysis presents the specific features of this technological revolution as they are seen by many Japanese: "In Japan, the term 'advanced technology' applies to a high-level, knowledge-intensive field such as (1) semiconductors, (2) computers, (3) information and telecommunications, (4) office automation, (5) robots (or unmanned production systems), (6) optics, (7) aerospace, (8) new materials and (9) biotechnology. Industries that make intensive use of these technologies are referred to as 'advanced-technology industries' or 'high-technology industries.'

"It is noteworthy that almost all of the fundamental principles on which advanced technologies are based were discovered in the 1950's in the United States. Therefore, first of all, the United States, as a trailblazer with a head start, is a major country of advanced technology. Second, there is the principle that it takes 20 years to develop a new discovery into a practical technology. It can be seen from a study of today's high-technology industries that investment in development of a basic or innovative technology takes a long time to pay off.

"How can the high-technology industries be characterized?

"First, the new technologies are a different type from the older technologies that form the basis for the heavy industries

[4]Economic Survey, op. cit., p. 153.

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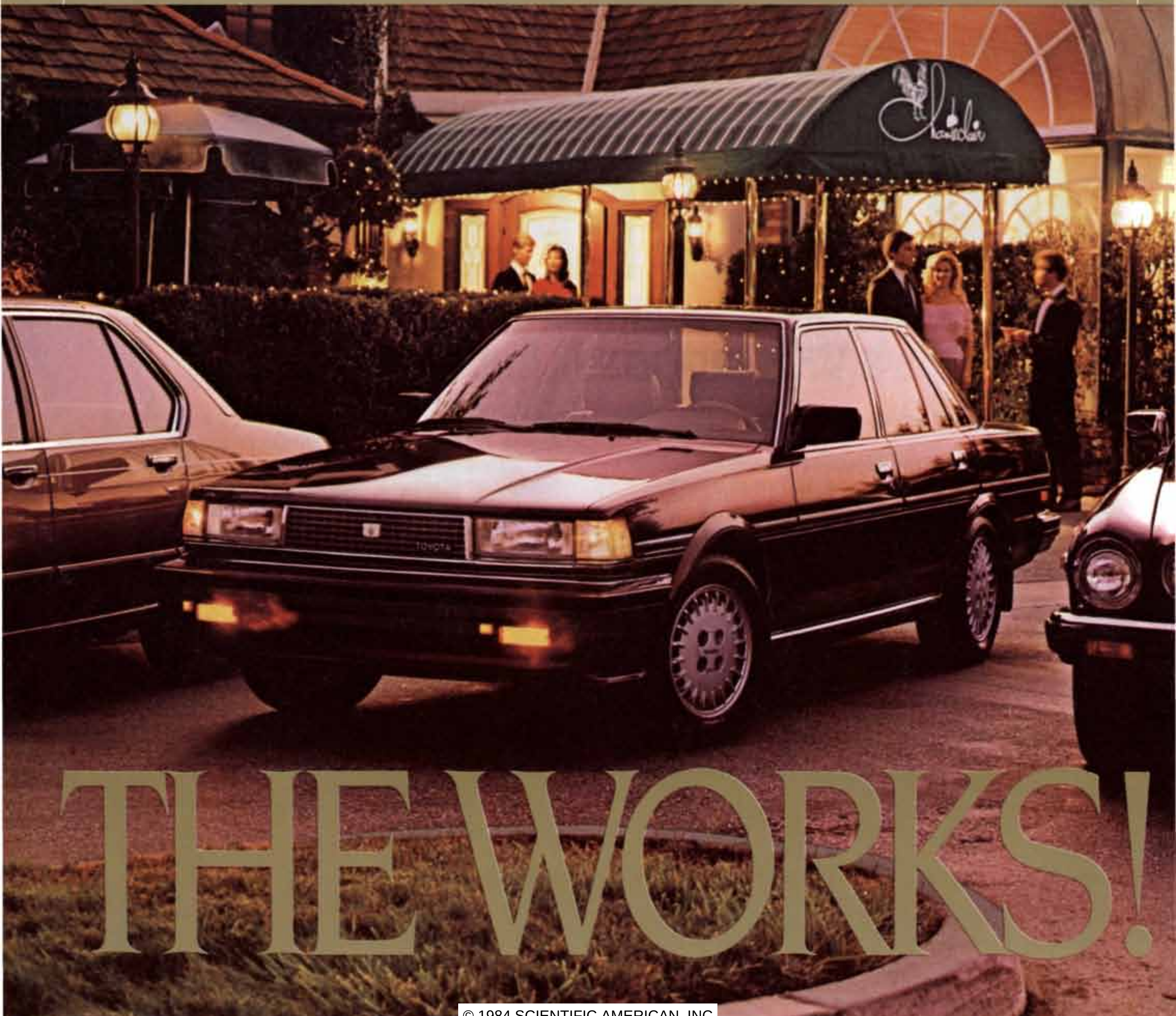

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such as steel, automobiles and electrical machinery and the chemical industry.

"Second, although these technologies are still in an immature stage, their range of possible applications is very broad, and it is considered certain that they will have a major impact on the economy and society. Hence it is accurate to say that it is unpredictable just what new products will appear or what new areas will be opened up as these technologies mature.

"Third, Japan, along with the United States, is in the forefront in developing high technology."[5]

Apparently there is a widespread view in Japan that the economy is ready to move forward rapidly into a period of change that promises to be revolutionary in its overall impact and raises the possibility of catching a long-term upswing in world economic growth. There is also the view that Japan, as a leader in technological innovation, is well positioned to take advantage of that upswing.

This view will come as a surprise to those who regard Japan as a copier and plunderer of commercially applicable Western technology. Does the image of Japan as an originator of technology and a leader in innovation square with the facts? Specifically, does Japan make available sufficient resources to play a major role in technological innovation? A recently published report from the Organization for Economic Cooperation and Development, *OECD Science and Technology Indicators* (Paris, 1984), provides a basis for some overall national comparisons.

First, Japan has been increasing the level of resources devoted to science and technology more rapidly than the other major economies have (see Table 1). Japan's allocation of resources for research expenditure and personnel has been increasing two to three times as rapidly as that of the United States.

Japan ranks just behind the United States and West Germany in amount of resources devoted to research and development. Together these three currently account for about 75 percent of the total OECD member country effort. The OECD notes, "By the end of the 1970's the United States was no longer the country that devoted the highest proportion of its resources to R&D. Germany was slightly ahead for gross expenditure as a percent of GDP—and possibly also for R&D personnel as a percent of the labor force.... Both Japan and Germany devote a higher percentage of GDP to civil R&D than the United States."

The United States alone accounts for half or nearly half of the OECD total of funds and half of the total of personnel in the R&D area (see Table 2). By the end of the 1970's, however, Japan's outlay was about 40 percent of that of the United States. Japan's expenditure for research and development and technological personnel was equal to that of the United States when measured in relation to population and GNP. Clearly Japan's allocation of resources to research and development is second only to that of the United States among OECD member countries in total amount.

West Germany's private sector contributes the largest percentage of funds to research and development of the three economies; Japan is second and the United States third (see Table 2). This underlines the familiar fact that in Japan government funding of research and development is a small part of the total. The government of Japan contributed less than 30 percent of the total during the 1970's, whereas well over half of U.S. research and development is government funded. These statistics are the result of two factors. First, nearly two-thirds of U.S. government R&D funds is devoted to defense and to aerospace programs, whereas only 17 percent of the Japanese government's research funds goes into these sectors.

A second and related factor is noted by the OECD report. "It is against the fundamental principles of the United States science policy to give direct aid to industrial technology development.... This does not mean, however, that the Federal government does not support industrial R&D, only that it prefers to do so via other objectives—especially defense and aerospace" (p. 98).

This indirect funding becomes very large indeed. "The national government directly funds about one-third of all manufacturing R&D in the United States and the United Kingdom, but...the proportions are lower in France and Germany. In Japan manufacturing industry finances almost all of the R&D it performs" (pp. 117–118).

Clearly Japan has now in place a large research establishment and effort, the second largest in the free world. The economy is devoting resources to research and development at a rapidly increasing rate (see Table 3). Japan's research effort is now proportionate to its economic importance. The Japanese government provides a far smaller proportion of those resources than do the governments of other developed countries. In fact, almost all of the funding comes from the private sector. (It might be noted too that given government budget stringencies, this pattern is unlikely to change soon, even if a change in policy were seen as desirable.)

As the OECD report notes, almost all of manufacturing research and development

Table 1

ANNUAL GROWTH IN RESEARCH EFFORT, 1970–79 (Percent)

	R&D Expenditure	Research Scientists and Engineers
Japan	6.4	4.7
West Germany	4.7	4.4
France	3.3	2.5
United Kingdom	2.8	2.1
United States	1.7	2.1

Source: OECD Science and Technology Indicators, Organization for Economic Cooperation and Development, Paris, 1984, p. 75.

Table 2

SHARE OF TOTAL OECD R&D, 1979 (Percent)

	United States	Japan	West Germany	Other 20 OECD Countries	Total
R&D Expenditure	47	15	10	28	100
R&D Personnel	40	18	11	31	100
Business Enterprise R&D Expenditure	50	14	11	25	100
Business Enterprise Scientists and Engineers	50	20	9	21	100
Private Business R&D Expenditure	45	18	12	25	100
Private R&D Expenditure as Percent of Domestic Product	1.30	1.35	1.55	–	–

Source: Adapted from *OECD Science and Technology Indicators,* OECD, Paris, 1984, pp. 21, 51.

[5]*Japan's High-Technology Industries,* op. cit., pp. 1–3.

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in Japan is privately funded; it is therefore necessary to examine the levels of company funding to estimate the general level of effort in manufacturing research and development. Table 4 presents roughly comparable data of outlays for research and development by manufacturing firms in Japan and the United States. The information is drawn from business publications in the two countries. No Japanese companies spend at the level of the four U.S. giants, GM, IBM, AT&T and Ford. However, the top five Japanese companies in R&D expenditure compare well in level of funding with the top 10 U.S. firms just below the level of the giants. By this measure Japanese companies compare well with most of the top U.S. companies.

It is useful to try to gain a sense of how corporate spending on research and development in the two countries has varied. The OECD study includes corporate data for expenditures by the top 15 companies ranked in 1979 by total R&D expenditure. The data are directly comparable to the information displayed in Table 4. In 1979, the top U.S. corporations spent an average of $719 million. For 1983 the average is $1,107 million—representing an increase of 55 percent in four years. That is a substantial, 11.4 percent annual rate of growth.

The 15 Japanese companies that spent the most for research and development in 1979 laid out an average of $195 million. The average amount they spent in 1983–84 is an even $500 million at an exchange rate of ¥220=$1.00. That amounts to an increase over the period of 256 percent, or 26.5 percent annually—well over twice the U.S. rate of increase. Like the level of national research expenditure, Japan's corporate expenditure is some 40 percent of U.S. corporate expenditure. It is, however, commensurate with the relative size of the two economies and the companies in them; the rate of increase in Japanese corporate expenditure is very fast indeed.

Do Japanese companies spend as high a percentage of sales on research and development as comparable U.S. corporations? A comparison of five companies in the United States in such high-technology fields as computers, semiconductors, optics and pharmaceuticals with five such companies in Japan shows that the relative effort in research and development by Japanese companies may well even be greater than that of many U.S. companies (see Table 5).

These comparisons, of course, concern only level of effort; they are not entirely satisfactory, given the rather elastic definitions of research and development that corporate accounting allows. They do, however, suggest that Japanese capabilities in research and development can be ignored only at some competitive peril.

Another measure of research effort is patents issued. This, too, is not entirely satisfactory. Because of the effort, cost and, in some industries, declining value of this kind of protection some U.S. companies have become quite selective about applying for patents. Table 6 presents the number of patents issued in the United States to a half-dozen of the world's giants in the field of electrical equipment and electronics. Whatever the drawbacks of this measure, it is very difficult to escape the impression that the two Japanese companies, Hitachi and Toshiba, have in only 20 years developed strong research and development capabilities where none had existed before.

The balance of technological payments provides another measure of Japanese parity (see Table 7). Japan's balance has been very steadily improving. Income from technology sales is now about one-third of payments for technology purchased. If only new contracts are considered, Japan has in fact for the past several years enjoyed a surplus in technological trade; the continued imbalance largely results from long-term payments for contracts entered into earlier.

What response has the emergence of Japan as a technologically strong nation evoked from the United States and other countries? The reactions are complex, even contradictory—as Western response to this culture has always been. Particularly in the United States there appears to be considerable alarm at Japanese technological progress.

As understandable as it may be, alarm

Table 3

REAL INCREASE IN RESEARCH EXPENDITURE (1975=100)

	Japan	United States	West Germany
1965	43	96	53
1970	87	102	83
1975	100	100	100
1980	130	125	132
1982	152	128	133

Source: *Kagaku Gijutsu Hakusho* ("Science and Technology White Paper"), Kagaku Gijutsu Cho, Tokyo, 1983, p. 104.

Table 4

R&D EXPENDITURE, Top 15 U.S. and Japanese Companies, 1983–84

U.S. Companies*	1983 Total ($ M)	Increase over 1982 (%)	Japanese Companies**	1984 Total (est.) ($ M)	Increase over 1983 (%)
General Motors	2,602	19.6	Hitachi	950	12.9
IBM	2,514	22.5	Toyota Motor	860	8.6
AT&T	2,491	41.2	NEC	860	18.8
Ford Motor	1,751	-0.7	Toshiba	680	20.0
United Technologies	971	16.3	Nissan Motor	680	7.1
Du Pont	966	9.9	Fujitsu	550	21.0
General Electric	919	17.7	Matsushita Electric	550	10.4
Eastman Kodak	746	5.1	Honda Motor	480	6.1
Exxon	692	-2.1	Mitsubishi Electric	410	9.8
Xerox	555	-1.8	Mazda Motor	340	23.0
ITT	518	-3.9	Mitsubishi Heavy Industries	310	0.0
Hewlett-Packard	493	16.3	Nippon Steel	230	0.0
Dow Chemical	492	7.0	Sharp	220	14.1
Digital Equipment	472	35.1	Sony	200	8.4
Boeing	429	-37.9	Canon	180	36.5

Source: **Business Week*, July 9, 1984.

***Nihon Keizai Shimbun*, July 17, 1984. Exchange rate: ¥220=$1.00

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may lead to missed opportunities. At the very least U.S. corporations and corporations in other countries could license or otherwise acquire Japanese technology for application in home markets. This is precisely the approach used by the Japanese in the postwar period. It provided two major advantages. The first was considerable protection from the high risks of research expenditures. The second was a dramatic reduction in the costs of acquiring technology.

Alarm at home has been accompanied by indifference abroad. Foreign companies in Japan seem not yet able or willing to look to Japanese companies as sources of technology. In a recent survey of 12 major foreign companies with substantial operations in Japan, only two of the 12 consistently scanned and evaluated Japanese technologies for possible application. Both of the two companies had in fact acquired Japanese technology and successfully introduced such products into their manufacturing and marketing systems.

Some of this complacency (or is it arrogance?) toward Japanese research efforts is understandable. Most companies abroad have vivid memories of teams of Japanese visitors with notebooks and cameras ready, searching out world sources of technology. A great many of those firms in fact sold technology to Japanese firms, to their subsequent considerable regret; the sale of technology helped to nurture what became in many cases formidable competitors.

Japanese ability to adapt acquired technology and improve on it is quite properly held in high regard. In fact, Japanese firms have done a remarkable job in the postwar period of acquiring foreign technology. During the three decades from 1951 to 1982 a total of nearly 40,000 technological contracts were entered into by Japanese entities for the import of foreign technology (see Table 7). In the early 1970's the annual rate of signing of such contracts peaked at more than 2,000. Contracts for the purchase of foreign technology continue to number about 2,000 per year.

Table 6

U.S. PATENTS ISSUED, 1960–82

	General Electric	IBM	Philips	Siemens	Hitachi	Toshiba
1960	773	296	234	96	2	3
1965	1,063	537	321	161	14	14
1970	1,000	631	290	231	102	80
1975	839	519	411	451	386	90
1980	770	386	332	369	409	257
1982	741	439	386	477	544	301
Compound Annual Growth Rate (%)	−0.2	1.8	2.3	7.6	29.0	23.3

Source: Internal analysis by major U.S. company.

Table 5

R&D EXPENDITURE AS PERCENT OF SALES
Some U.S. and Japanese Companies

United States, 1983		Japan, 1984	
Company	R&D as % of Sales	Company	R&D as % of Sales
IBM	6.3	Hitachi	7.3
Texas Instruments	6.6	NEC	11.0
Motorola	7.8	Fujitsu	10.0
Xerox	6.6	Canon	8.9
Eli Lilly	9.7	Shionogi	9.3

Sources: Business Week, July 9, 1984; *Nihon Keizai Shimbun,* July 17, 1984.

It is of special interest to note that the cumulative cost of the three-decade-long acquisition of foreign technology by Japanese companies equaled only $15 billion. That is, the cost of buying essentially all the technology in the world of interest and value was only a fraction of the current annual R&D expenditure of the United States. There can be no doubt about the cost efficiency of the Japanese approach to obtaining technological parity, or about the skill with which the process was carried out. Given this history, it is understandable that Japan might not be regarded as being capable of producing technological progress.

Unfortunately, this recent history obscures the present and prospective reality. Viewed in perspective it is clear that the Japanese actions represent a series of logical responses; they are not merely reflexive displays of national character. The Japanese economy began the postwar period in a state of desperate technological poverty, isolated by the legacy of World War II from both Western and Asian nations. The first response to the problem was to put aside any thought of independent development. Instead it was decided to focus on acquiring technologies as rapidly as possible from Western (mainly U.S.) sources.

During the early period, which extended well into the 1960's, Japanese companies searched the world for the best technology available. Their negotiating disadvantage was balanced by active intervention of the Japanese government to hold down the cost of purchase—both the amount of the payments and their duration. The Japanese government helped to prevent technological monopolies from developing by working to ensure that more than one Japanese firm had access to a given technology.

By the late 1960's, government intervention in the process of purchase was discontinued. Japanese firms' negotiating positions had improved and the technologies being acquired became less basic and critical.

Through the early period, Western business in general saw the Japanese market as remote, small and difficult to enter. The sale of technology represented windfall income from assets already amortized, from companies in Japan that appeared to represent no long-term threat. With few exceptions, therefore, the Western firms sold willingly. By the late 1960's, the sellers had less to offer and were anyway less willing to sell.

In the next period, from the late 1960's to the late 1970's, Japanese firms moved to adapt and develop the technologies already acquired and to build a research capability of their own. In any event fewer significant technologies were available for purchase. Earlier acquisitions made them scarce and Western corporations became reluctant to sell as they began increasingly to perceive Japanese firms as formidable competitors.

Through the 1970's, Japanese firms moved toward technological parity in industry after industry. Now, in the 1980's, the Japanese economy is moving quite clearly and rapidly into a third phase. Research budgets and facilities are equal to the most lavish in the world. The research effort is increasingly well focused. Government support is directed toward research in what are generally agreed to be the critical sectors.

Several issues of Japanese technological advances, and the U.S. response, were well described by Professor Harvey Brooks of Harvard University in tes-

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timony to the House of Representatives' Committee on Science and Technology in June, 1983. "Although Japanese success in recent years has been based on adaptation of Western, mainly American, technology, and on the capacity to commercialize it more rapidly than its competitors," Brooks said, "it would be wrong to conclude from this that the Japanese are mere imitators who, once they have attained to the world state of the art in a field, will not continue to move forward the frontiers of technology. On the contrary, history suggests that imitation, followed by more and more innovative adaptation, leading eventually to pioneering, creative innovation forms the natural sequence of economic and industrial development.

"Successful imitation, far from being symptomatic of a lack of originality as used to be thought, is the first step of learning to be creative. This is probably true of nations, as it seems to be of individuals, something which Americans may have forgotten with our almost obsessive belief in originality and individual creativity. It may be only those who try continually to reinvent the wheel who will lose out in the innovative race. In my opinion, the U.S., so long accustomed to leading the world, may have lost the art of creative imitation, and is deficient in scanning the world's science and technology for potential commercial opportunities relative to what is done by its competitors, particularly Japan."

Dr. Brooks's important statement has been underlined by other observers. Writing recently in the *International Herald-Tribune,* Daniel Greenberg noted that, "The Reagan administration has cut by two-thirds the modest $750,000 that the government used to spend to collect and translate scientific papers representing billions of dollars worth of foreign research."

Perhaps it is because Japanese firms have been seen as buyers of technology that Western observers have focused on the Japanese government in explaining Japanese technological progress. Such a view founders on the facts. The Japanese government contributes a smaller percentage of total R&D budgets than do most other governments. For some time, governmental research and development in Japan has been about 30 percent of total expenditure, compared with about 60 percent in the United States. Government also contributes a relatively small part of the cash flow to Japan's research effort.

According to the OECD the Japanese government devotes a disproportionate amount of its relatively small research budget to research in the areas of agriculture and energy. Military R&D expenditures are relatively low. On the whole the Japanese pattern of government involvement resembles that of West Germany more than that of the other major countries studied—at least when patterns of spending are the criterion (see Table 8).

There is no indication that the Japanese government's agencies have shown any special prescience in understanding where to focus industrial research. Japan's list of important sectors is much the same as the lists of other governments. It is probably true that in the context of Japanese government-business relations it is possible to achieve more effective cooperation in joint projects than is the case in many other countries. This fact could produce more efficient use of research funds.

Finally, there is by no means general agreement in Japan on the role government should play in research activities. A recent newspaper article provides an interesting example of deep disagreement. The *Japan Economic Journal* of July 17, 1984, reported:

"A high-technology fever has taken over the Ministry of International Trade and Industry (MITI).... The fever may reflect MITI's desire to make high technology an engine to pull the Japanese economy, but there is also a bureaucratic motive to make the most of high technology to restore MITI's declining position.

"MITI enjoyed a reputation as the helmsman of 'Japan, Inc.,' throughout the industrial reconstruction period and the ensuing high-growth era. But the two oil crises in the 1970's debased many industries under its jurisdiction into 'structurally depressed' industries.... To the extent that the past glory was spectacular, MITI's sense of crisis and frustration is deep, and its determination to roll back the receding tide is strong.

"MITI has devised a three-part strategy for the next fiscal year's budget. The first is to exempt high-technology development appropriations from the Finance Ministry–imposed overall ceiling on budget requests.... MITI's second strategy is to legislate a basic law concerning policy to promote high-technology industries.... The third strategy is to set up a high-technology special account,...intended as a 'money box' of the technology development budget.

"The idea has been given a cool reception, however. MITI's high-technology orientation is 'a bit too superfluous,' one Liberal Democratic Party leader pointed out.... Industry's reaction to MITI's high-tech fever is cool, too, probably because high-technology advancement basically calls for free and intense competition. 'We welcome government assistance, whether it be subsidies or tax and financial privileges, but we don't like the government beginning to interfere in high-tech industries using the assistance as a tool,' says an executive of a major electrical machinery maker.

"When the fiscal 1985 budget ceiling is decided, the battle between MITI and the Ministry of Finance, which maintains budget austerity, will be kicked off, and MITI faces an uphill fight."

These kinds of comments certainly do not suggest monolithic policy agreement, nor a central government role in research, nor special powers of a ministry to direct policy. Rather, they reflect the situation of a heterogeneous economy in which corporate competition is the driving force, and in which the marketplace will determine the direction of research investment.

The direction MITI would like development to take is spelled out in *The Vision of MITI Policies in the 1980's,* published in April, 1980. The report proposes, according to an OECD summary, the concept of a "'technology-based nation.' MITI has launched a 10-year program to develop

Table 7

JAPAN'S TECHNOLOGICAL TRADE, 1951–82

	Cases of Technical Import (No.)	Payments for Technology ($ M)	Receipts from Technology Sales ($ M)	Balance of Receipts/ Payments (%)
1951–54	880	47	0.5	1
1955–59	1,370	206	2	1
1960–64	4,124	613	35	6
1965–69	6,779	1,278	141	11
1970–74	10,271	2,926	394	13
1975–79	9,898	5,086	1,183	23
1980–82	6,438	4,946	1,442	29
Total	39,760	15,102	3,197	21

Source: Economic Statistics Annual, 1968 and 1983, Bank of Japan.

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new technologies for next-generation industries, which is focused on three fields: new industrial materials, information processing and biotechnology. The long-term aim is to promote a 'technology-oriented nation' and increase industrial diversification. R&D is selected that has the potential to radically change existing industries or create new ones.

"In the *materials field,* MITI plans to spend ¥53 billion ($217 million) (about seven percent of direct public funds in 1979) in six areas: high-performance ceramics, synthetic membranes for new osmotic techniques, advanced composites (e.g., plastics reinforced by carbon fibers), polymeric materials that are electrically conductive, advanced alloys of crystal and amorphous composition, and high-performance engineering plastics. Private firms will cooperate in the program, contributing six to 10 times the amount provided by MITI.

"In *biotechnology* the focus is on recombinant DNA, bioreactor development and large-culture cell growth. This, too, is a cooperative effort involving several large Japanese firms, particularly in the chemical industry, which are members of the 'Biotechnology Development Technical Association.' An objective of the program is to help the Japanese chemical industry lessen its dependence on oil and aid it in developing pharmaceutical, food and textile products.

"In *information processing,* the areas selected for research are development of atomic grid electronic components, three-dimensional integrated circuits and integrated circuits for use under extreme environmental conditions. Most of this work is to be done in MITI's own laboratories (at the Agency for Industrial Science and Technology).

"Two other MITI information-processing projects are

"1. The 'Supercomputer Project'—development of a large, high-speed computer for use in complex areas such as weather forecasting, aerospace design and nuclear research;

"2. The fifth-generation computer, a machine with dramatically improved software and human-machine interfaces.

"The first is to be completed by 1990 at a cost of some ¥30 billion ($123 million); the second project may run to 10 years, and possibly cost about $500 million.

"An element in making Japan a technology-based nation is the '*Technopolis*' concept advanced by MITI. This idea calls for the development of several centers of high-technology industries near to and integrated with regional cities of more than 200,000 population. Each Technopolis would include one or more high-technology industries and academic and scientific research organizations (which would cooperate collectively in R&D and innovation) as well as dwellings, schools, stores and other facilities. MITI has made a first selection from the 20 regional cities that nominated themselves as sites, and development plans are being devised.

"Another important event is the construction of the Science City at Tsukuba, in the vicinity of Tokyo. There, in 1985, the government will hold an international science and technology exhibition and offer a preview of 21st-century science and technology."

The situation in Japan with respect to research and development policy can be summarized as follows:

1. There is a general and clear understanding in government and business that Japan's future depends on independent and innovative research and development.

2. Japanese corporations are now devoting resources to research and development at a level comparable to that of their world competitors. The level of expenditure is increasing very rapidly.

3. Continued high levels of savings and investment in Japan provide the capital base for rapid application of new developments.

4. The Japanese government will play an important role in supporting and facilitating research efforts, although its direct funding participation will continue to be low relative to that of other countries.

This means that over the next decades Japan will assume a leadership role in technological development fully commensurate with the size and importance of its economy. Japan will be a major source for technologies of the future.

At the same time, Japan appears to have a full appreciation of its limits. In a speech to the Federation of Economic Organizations on July 18, 1984, Mr. Naohiro Amaya, adviser to and former vice minister of the Ministry of International Trade and Industry, stated that "Japan has no course other than to be dependent on the United States." Mr. Amaya described the United States as being at present a "driving-force country" in the technologies of the information society whereas Japan is a "dependent country." "Technology is a living thing. It cannot simply be transferred anywhere. Progress will first be made where social values best fit with engineering and systems. In system flexibility the United States is in first place. I have some doubt as to whether the special values of a group-centered society are best suited to the information era. Individualism and individual creativity are necessary for producing the new technology. In these respects, the United States surpasses Japan. Like it or not, Japan's is a merchant society and the United States will be the driving force, with Japan dependent."

Although Mr. Amaya may well have understated Japan's potential role in order to give a cautionary message to his audience, the view that the United States is in the lead followed by Japan is generally accepted. The Long-Term Credit Bank states: "The United States is the birthplace of the advanced technologies; it is also in the lead. In the past four or five years the high-tech industries in the United States seem to have begun to grow at an accelerating rate."

Japan gives full credit to the United States as technological leader; Japan also presses to increase its own position as a source of technology for the world. The activities of the two nations in research and development need not, and should

Table 8

GOVERNMENT FUNDING OF R&D
BY SOCIOECONOMIC OBJECTIVE, 1980
(Percent)

	United States	United Kingdom	France	Germany	Japan
Defense	47	59	40	15	5
Aerospace	17	5	9	9	12
Agriculture	3	5	4	3	25
Industry	0	4	8	12	12
Energy	12	7	8	21	26
Infrastructure	3	3	8	10	8
Health and Welfare	15	4	8	16	11
Advancement of Knowledge	3	13	15	14	4
Total	100	100	100	100	104

Source: *OECD Science and Technology Indicators,* OECD, Paris, 1984, p. 87. Note that the error in the Japan total is in the original OECD publication.

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not, be seen as competitive. They are complementary, for the two economies continue in a close and mutually supporting trade relation. The revolutionary changes in technology that the Japanese see as impending will no doubt provide ample room to accommodate the efforts and resources of both great economies. In any reasonable view of the well-being of the world, contributions to the fund of knowledge and technology are only to be welcomed as contributions to the greater good of all.

The revolutionary impact that Japanese planners anticipate from new technologies is being seen first in areas influenced by microelectronics. For most of the other areas in which major advances are anticipated, real results will be seen later in this decade and in the 1990's.

The Long-Term Credit Bank of Japan continues: "The high-technology industries vary in content, size and growth. But two statements can be made: (1) the electronics industry is already large, has a considerable impact on other industries and enjoys a rapid growth rate. (2) The other high-technology industries, which entered, although small in size and impact, their growth curve in the early 1980's, should by the latter half of this decade reach a scale comparable to that of the electronics industry today. The latter half of the 1980's will truly be the era of high-technology industries." The Bank's estimates of the size and growth of the high-technology industries of Japan are shown in Table 9.

The first sector in which substantial commercial application has been achieved is electronics. The basic driving technology is microcircuitry. It is often suggested that integrated circuits are as fundamental to current and future economies as steel has been to the major manufacturing sectors of the first industrial revolution. If that is the case, there is growing evidence that Japan may do as well in this basic element as it did in setting world standards for volume, quality and low cost for the other.

An effective measure of progress in integrated circuits is the trade balance (see Table 10). From 1978 through 1983 Japan's exports of integrated circuits increased by about eight times in value. Given rapid declines in price levels of these products, it can be assumed that the volume of exports increased substantially and rapidly. Japan has turned the slightly negative trade balance for 1978 into a very considerable surplus in integrated circuit trade. At the same time Japan has remained a substantial importer of integrated circuits.

Exports to the United States of integrated circuits have increased more than 10 times during this six-year period. For the United States the bilateral trade balance has shifted from a considerable surplus to a large deficit. Japan's exports of integrated circuits to the United States in 1983 are estimated to be half again the value of Japan's imports from the United States.

These trade trends appear to be intensifying. Midyear press reports from Tokyo stated that in the first half of 1984 Japanese semiconductor exports to the United States nearly doubled to ¥157 billion compared to the same period in 1983. Japan's net surplus on semiconductor trade with the United States in the first half of 1984 was already larger than its surplus for all of 1983.

U.S. industry specialists are concerned by comparative trends in this basic sector. The U.S. market research firm Dataquest is reported in press statements as having noted that the U.S. share of world semiconductor production fell from 54.4 percent in 1982 to 52.9 percent in 1983, while Japan's share rose from 34.3 to 36.9 percent. (Western Europe occupies a minor, declining position in this industry; its share of world production has fallen from 11 percent in 1982 to 9.4 percent in 1983.) These shares are of a total world semiconductor market of $18.8 billion in 1983.

Mr. Erich Bloch, a vice president at IBM Corporation, presented an analysis and interpretation of Japan's position in the semiconductor industry in his statement at the hearings before the House Committee on Science and Technology on June 29, 1983. (The published minutes of the hearings carry the formidable title, "Japanese Technological Advances and Possible United States Responses Using Research Joint Ventures.") Mr. Bloch states:

"The semiconductor industry has been in existence for only 30 years, but in this short time it has grown to a $15 billion worldwide industry. More important, it is a basic industry, just as basic as steel, oil or chemicals were in the past. Its products are pervasive and are the foundation of other high-technology sectors such as computers, telecommunications and instrumentation.

"Up to five years ago, the semiconductor industry was primarily a U.S. industry, not only in innovation and new applications, but also in both demand and supply of products. By 1982, however, the U.S. semiconductor industry share of the worldwide market had eroded to 55 percent, while that of Japan had increased to 35 percent.

"But there is a more ominous sign. The most important product segment is that of MOS (metal oxide semiconductor) memory and logic. A specific high-volume logic chip such as a microprocessor is at the heart of most recent innovative applications. Both memory and logic are interdependent from the standpoint of the manufacturing process.

"While the manufacturing process for a memory chip forms the base process for logic chips, memory chip volume is a

Table 9

SIZE AND GROWTH OF JAPAN'S HIGH-TECHNOLOGY INDUSTRIES

Industry	Size ($ M) 1980	1985	1990 (predicted)	Annual Growth Rate (Percent) 1985/1980	1990/1985 (predicted)
Electronics	39,450	98,180	N.A.	20	N.A.
Computers	5,860	11,730	N.A.	15	N.A.
Telecommunications	4,450	8,270	N.A.	13	N.A.
NC Machine Tools	1,550	4,820	N.A.	26	N.A.
Semiconductors	3,910	8,230	N.A.	17	N.A.
Office Automation	3,140	9,550	19,090	25	15
Office and Personal Computers	1,180	5,230	11,180	35	16
Word Processors	30	500	1,180	79	19
Industrial Robots	350	1,270	2,410	29	14
Optoelectronics	360	4,090	9,550	61	19
Biotechnology	N.A.	450	12,950 (1995)	N.A.	44 (1995/1985)
Aerospace	1,860	4,050	8,000	18	14
New Materials	2,500	5,680	14,090	18	20
Fine Ceramics	1,360	2,320	6,360	14	22
Carbon Fiber	70	150	640	22	34
Engineering Plastics	910	1,820	4,090	19	18

Source: Adapted from *Japan's High-Technology Industries,* Long-Term Credit Bank of Japan, Tokyo, February, 1984, p. 2. Exchange rate: ¥220 = $1.00.

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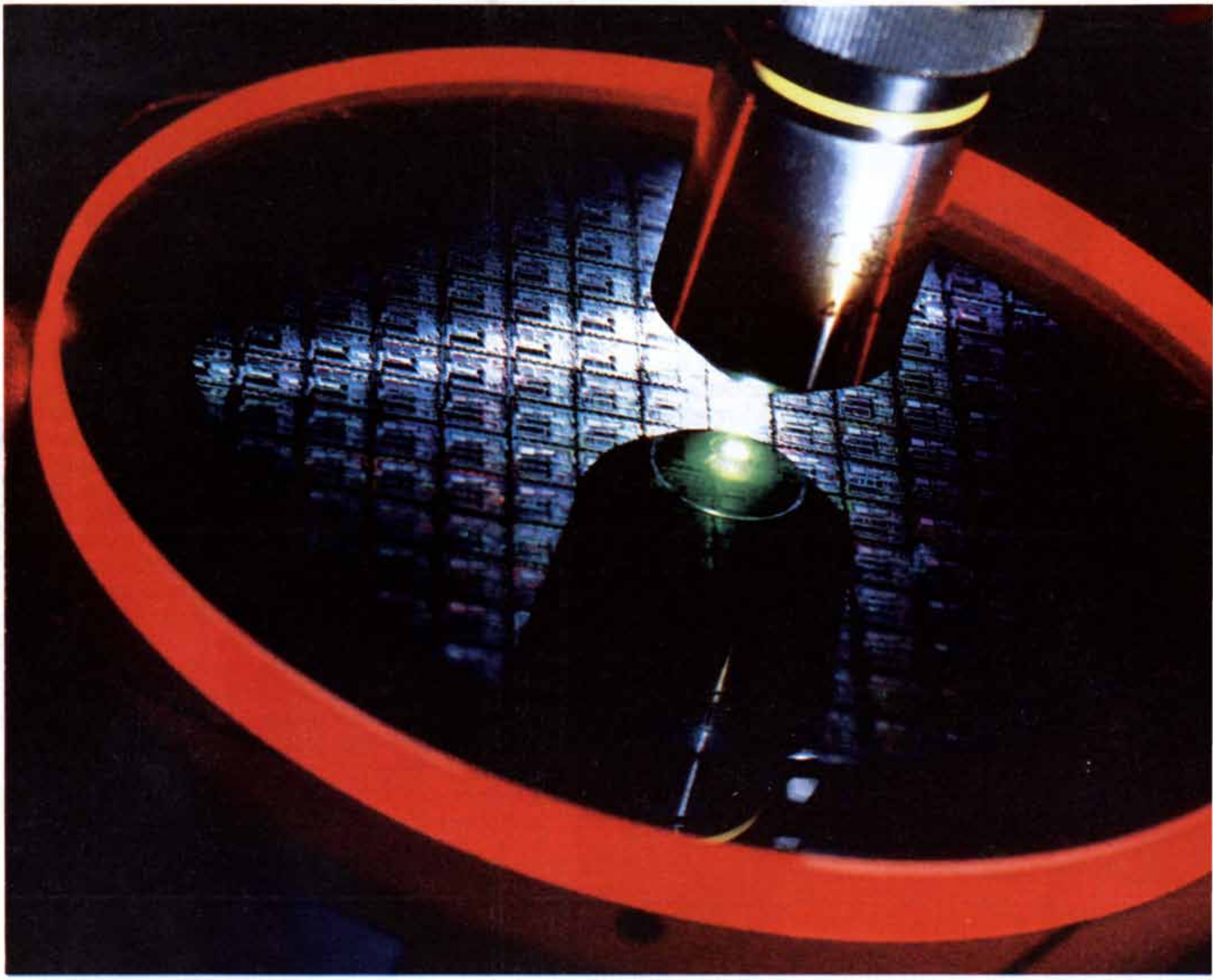

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prerequisite for cost efficiency in microprocessors. Preeminence in memory, therefore, is a prerequisite to, and harbinger of, preeminence in logic and microprocessors. Yet in 1982 the worldwide MOS sales of Japanese companies increased by 14.5 percent, while those of U.S.-based companies increased by only 8.6 percent. Even in the U.S. market, Japan outstripped U.S. companies in a sales increase of 67 percent vs. 17 percent for our domestic producers. U.S. sales of semiconductors in the Japanese market are about a 9.3 percent share of that market and are declining, whereas the Japanese share of the U.S. market is 12.4 percent and growing.

"Why this turn of events?

"First of all, foreign countries—in particular, Japan—have recognized the strategic importance of the semiconductor industry.

"Second, the rapid worldwide diffusion of U.S. technology and innovation has provided a base to build on.

"Third, Japan has especially targeted the MOS memory products as an efficient way to achieve a market share in semiconductor products and appears to be using it as an entry wedge to become a world force in semiconductors.

"Fourth, Japanese industry under MITI guidance received financial support from government agencies through favorable loans and research subsidies. In addition, pooling of engineers and scientists from industry and government has fostered growth in research and development. This has resulted in investment on a greater scale than the U.S. semiconductor industry could afford to do. This, despite the fact that the investment in capital and R&D by the U.S. semiconductor industry in 1982 was 14 percent and 9.8 percent respectively, compared to seven percent and three percent by U.S. industry as a whole. Japan, however, is outspending U.S. semiconductor companies in both of these areas: 20 percent in capital investment and 15 percent in R&D spending.

"Fifth, Japan has consistently provided quality products that are comparable to the best available in the U.S. This was a key strategy and essential to their market share growth. Despite important efforts by the U.S. merchant semiconductor industry, there is still a perception that Japan has equal or better quality."

Mr. Bloch's analysis is a powerful one, despite his unfortunate tendency to speak of Japan as a single entity rather than as an economy with a number of individual and competing companies. His views are reinforced by the report of Dataquest that three of the five largest producers of memory chips in the world now are Japanese. Hitachi is the world's largest producer, followed by Texas Instruments and Nippon Electric Company.

This change in shares of world chip production is not simply a temporary phenomenon. Trends in trade rule out that conclusion; so do developments that loom in the future. Dataquest predicts that in 1984, for the first time in history, Japanese chip makers will overtake their U.S. competitors in total capital spending in the industry. U.S. investment will increase by an extraordinary 70 percent to a total of $2.6 billion in 1984 compared to 1983. Capital spending by Japanese chip makers during that period will increase by 80 percent to a total of $2.7 billion.

No other trend can match the significance of capital spending for this industry. The semiconductor industry has become very capital intensive as the technology has advanced. Growth in sales must of course be preceded by growth in assets, and the cost of asset growth is high. Thus the capital spending trends signal future production trends, and suggest that if current patterns continue, Japan may well duplicate in semiconductors what it earlier accomplished in steel.

Capital investment in semiconductors illustrates a critical point that must be weighed in considering the rate of technological advance. The pace at which technology is developed and applied is not simply a function of R&D effort and output. It is also driven to a critical degree by the level of capital investment. Technological information tends to flow fairly freely, and developments in one country or by one firm are likely to be quickly picked up in another country or by another firm. The outcome of the technology race is therefore likely in the long run to be determined by the speed with which new developments can be put into industrial practice. Capital investment largely determines this speed. The investment rate determines how quickly new equipment can be installed; new equipment is on balance likely to incorporate the latest in technological advances.

The rate of capital investment in Japan is high. According to the Bank of Japan, Japan's capital investment averaged 25 percent of GNP from 1980 to 1982. That is, for every dollar of output in Japan, one quarter was reinvested. This high level of capital investment is possible on a sustained basis only if the total savings rate is sufficiently high to sustain that rate of investment. Japan's overall savings rate is high, the highest of the major market economies.

In contrast, in the same 1980–82 period, public and private capital investment in the United States totaled only 14 percent of GNP. That is, on a per capita basis, Japan is both saving and investing at about twice the rate of the United States. Comparable figures for the same period for the United Kingdom and West Germany are 13 and 15 percent respectively. Japan's investment rate is very high, and its rate of technological progress is rapid.

A key factor that determines the rate of investment is the cost of capital. Calculations of cost of capital can be complex, and so interest rates can be used instead. It is basic to Japan's fiscal and monetary policies that interest rates be kept low. Thus currently both in nominal and in real terms, Japanese interest rates are about half the level of interest rates in the United States. Further, the willingness and ability of Japanese firms to use higher levels of debt as a source of investment funds and to provide relatively low levels of dividend payout further favorably affect their relative cost of capital. High levels of corporate investment can be expected under these conditions, and the impact of technological advance is very great.

High investment rates help to ensure rapid growth of markets for high-tech-

Table 10

JAPAN'S TRADE BALANCE IN INTEGRATED CIRCUITS
(¥ bil.)

	Total Exports	Total Imports	Balance	Exports to U.S.	Imports from U.S.	Balance
1978	52.2	61.3	−9.1	17.4	40.7	−23.3
1979	108.3	98.5	+9.8	41.8	74.1	−32.2
1980	183.3	108.9	+74.4	72.4	69.6	+2.8
1981	199.6	114.3	+85.3	71.2	70.5	+0.7
1982	285.1	127.4	+157.7	116.8	83.5	+33.3
1983 (est.)	418.0	144.0	+274.0	178.0	100.5	+77.5

Source: Nomura Electronics Handbook 1984, Nomura Securities Co., Ltd., Tokyo, February, 1984, p. 70.

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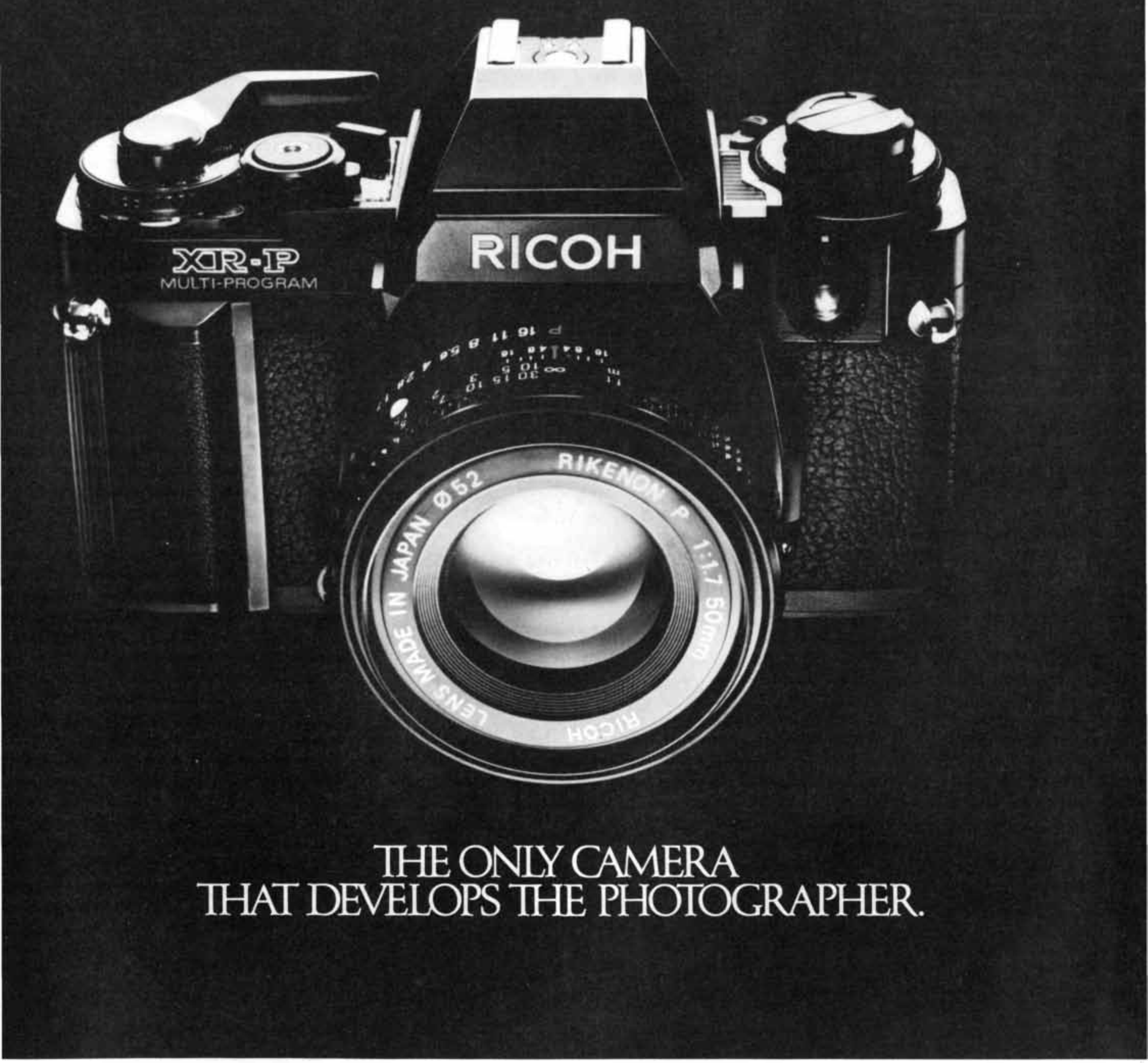

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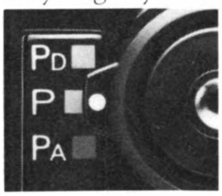

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nology products. The rate at which large Japanese companies are acquiring equipment for office automation is increasing rapidly (see Table 11). As the market size and growth numbers provided by the Long-Term Credit Bank suggest, the sectors of this industry are growing very rapidly indeed. It should be noted too that this is domestic growth. Exports follow domestic market growth, expanding rapidly as it slows. Thus Japan's exports of facsimile equipment, a category in which Japan has world leadership, are growing by more than 50 percent per year. Japan's share of the world market for copy machines is estimated to be about 85 percent.

In other sectors, such as personal computers, the domestic market continues to grow very rapidly; yet given the disadvantage of Japanese producers in software, exports of personal computers from Japan are not yet a factor in world markets. The products experiencing significant export success are those for which sales growth is slow, such as calculators and copiers (see Table 12). The high domestic growth product efforts are still focused on meeting domestic demand (see Table 13).

In Japan, as in the United States, automated office equipment still tends to be purchased in the form of "stand-alone" units, rather than as an integrated system. Systems development in Japan has been slowed by the policies of the Nippon Telegraph and Telephone Public Corporation. NTT, which has dominated public communications, will itself be reorganized under new laws that are now being prepared. The corporation will be divided into several units and gradually returned to the private sector. More important, it will shortly lose its monopoly position. A "second NTT" is being organized by a powerful group of private interests who plan an optical fiber system between Tokyo and Osaka.

This situation clearly has parallels to the breakup of American Telephone and Telegraph in the United States. The change will no doubt greatly accelerate applications of the whole range of electronics developments. Further, NTT itself has under construction its new Information Network System (INS), announced in 1981. This project will establish digitalized communications networks throughout Japan. These integrated, digital networks utilizing optical fiber and satellite links will transmit not only telephone conversations but also data, characters and images. The completion date is the year 2000; costs are estimated at ¥20 to ¥50 billion.

The INS project will supply a wide range of services to both homes and offices, including two-way cable TV and videotexts and teletexts. Given the changes in NTT's status, and the appearance of competition, the scheduling of these and similar developments can be expected to accelerate the debut of INS.

As the telecommunications infrastructure develops it can be expected to give rise to new-media equipment markets (see Table 14).

Factory automation has also moved very rapidly in Japan. The industrial robot is both a good example and a striking symbol of technological changes in manufacturing. The industrial robot was first developed and marketed in the United States in the late 1950's. The U.S. government funded most of the research. The first sale of a robot to Japan took place in 1967. By the end of the 1970's, Japanese companies were the largest producers and users of industrial robots. The Japanese government played no part until the late 1970's, by which time the technology and its applications were well developed and accepted.

The history of the industrial robot illustrates major characteristics of the postwar technological pattern. The United States invented, Japan developed; the U.S. government pushed the technology, the Japanese government showed no more prescience than other governments in fostering the sector; Japan built its position through very high rates of capital investment; the Japanese market grew very rapidly.

The robot industry in Japan is now a substantial one. Output exceeds $500 million. Like many newly emerging industries, it is still highly fragmented. A survey by *Nihon Keizai Shimbun* found that in 1983 a total of 175 companies in Japan produced robots. Ninety of them produced both for in-house use and the open market. As would be expected, a shakeout in the industry appears to be taking place. The 44 largest producers have been increasing sales by 43 percent in 1983 compared to 1982; the industry as a whole grew 21 percent.

The Japanese industry pioneer, Kawasaki Heavy Industries, which entered the market with technology purchased from Unimation in the United States, has between 1981 and 1983 fallen from number one to number four in the industry. The industry leader, Matsushita Electric Industrial Company, had robot sales in 1983 of ¥23.5 billion; they project sales of ¥41 billion in 1985. *Nihon Keizai Shimbun* reports that the greater part of Matsushita's sales consisted of electronic-parts-fitting robots, as would be expected since Matsushita is Japan's largest consumer electronic products company. Matsushita also produces assembly and welding robots to complete its robot line. Matsushita's robot sales are more than twice those of Fanuc, which has the second-highest sales volume, and three times those of Hitachi, which is in third place. The overall market share pattern emerging in the mid-1980's is that of a maturing industry, testimony to the very rapid growth of this sector of the Japanese economy (see Table 15).

Matsushita practices what it proposes to sell. In his book *Bijinesuman Kinmirai* ("The Japanese Business of the Future") Mr. S. Kunimitsu reports, "Matsushita Electric Industrial Company plans to increase the number of robots in use from the present 3,000 to more than 100,000 during the next 10 years. They will bring about a revolution in which the number of robots will exceed the number of workers. Besides Matsushita, Toshiba has a three-year, ¥50 billion plan for superautomation; Hitachi plans to automate 60 percent of its assembly operations by 1985, reducing its number of assembly workers by about 30 percent."

Anticipating the question of the impact of this trend on employee relations, Mr. Kunimitsu quotes a middle manager from

Table 11

RATE OF INTRODUCTION OF OFFICE AUTOMATION EQUIPMENT IN LARGE JAPANESE COMPANIES
(Percent Using)

	General-Purpose Computers	On-Line Terminals	Facsimile	Office Computers	Word Processors
1973	77.5	25.4	9.3	5.8	–
1975	81.2	38.9	17.3	9.5	1.2
1977	83.3	51.2	32.7	14.6	1.9
1979	85.6	67.4	55.5	31.7	4.9
1981	87.1	70.2	60.2	36.1	29.0
1986 (est.)	88.2	76.6	62.1	47.2	42.1

Source: *Maikuroerekutoronikusu no Koyo ni Oyobosu Eikyo ni Tsiute.* Mikuroerekutoronikusu no Koyo ni Oyobosu Eikyo ni kan suru Chosa Kenkyu linkai, Tokyo, February, 1984, p. 80.

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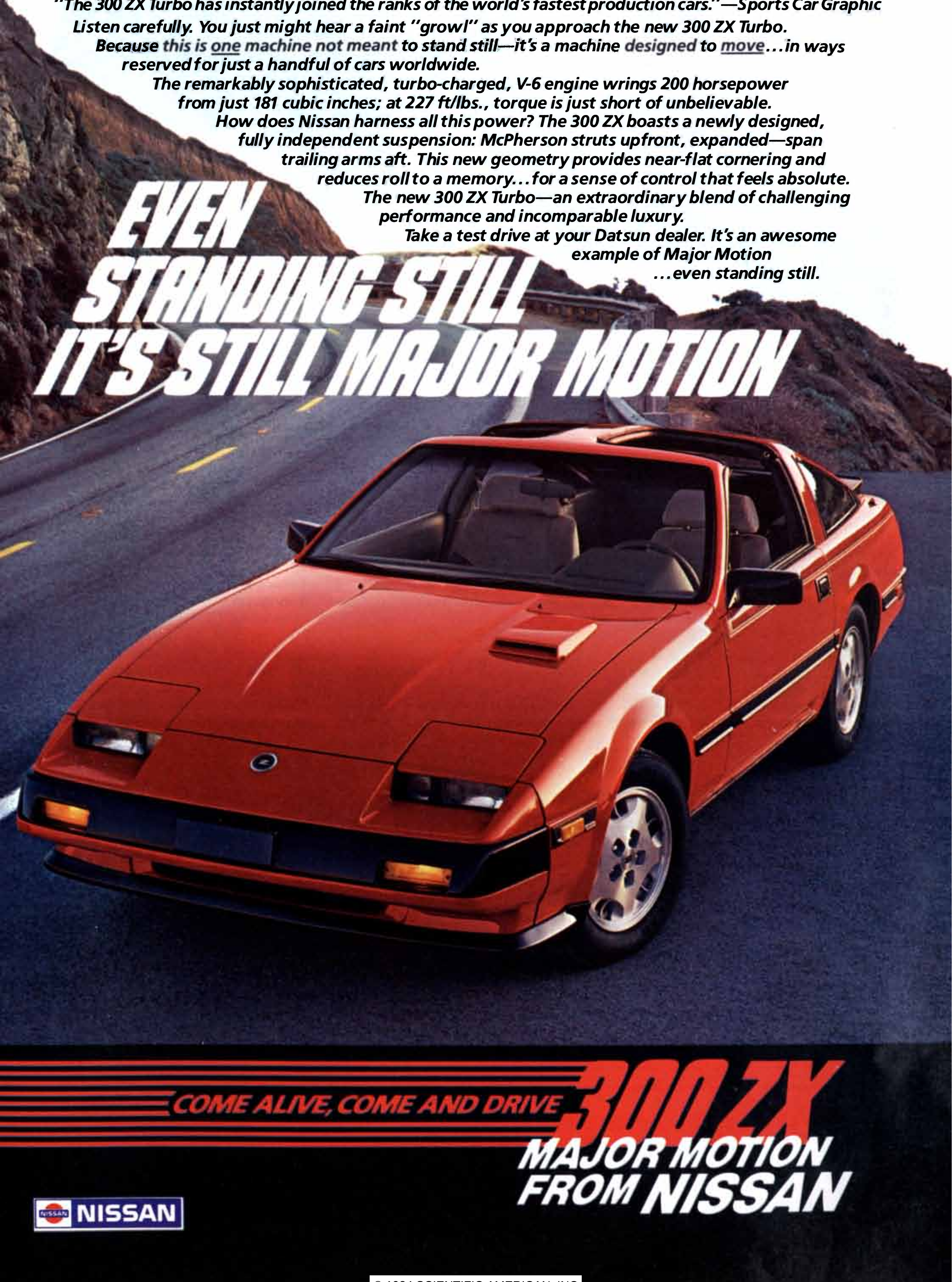

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Table 12

JAPANESE OFFICE AUTOMATION MARKET (PRODUCTION) (¥ bil.)

Calendar Year	1982	% Change	1983*	% Change	1984*	% Change
Copier	415.7	−1.2	480.0	+16	535.0	+12
Electronic Calculator/ Hand-Held Computer	141.6	−3.7	162.0	+35	179.0	+11
Electronic Cash Register	74.0	−7.6	78.0	+5	82.0	+5
Japanese Word Processors	36.0	+94.6	70.0	+94	115.0	+64
Micrographics Equipment	10.8	+9.1	12.0	+11	14.0	+17
Office Computers	400.0	+30.4	432.0	+8	495.0	+15
Personal Computers	231.3	+116.2	285.0	+23	375.0	+32
Facsimile	143.0	+34.9	160.0	+12	190.0	+19
Total	1,452.4	+21.4	1,679.0	+16	1,985.0	+18

Source: Japan Business Machines Association, *Nomura Electronics Handbook 1984,* p. 46.
*Estimates by Nomura.

Matsushita as saying: "We will go from 3,000 to 100,000 robots in 10 years. There will be slightly more robots than employees. There will be a very great increase in productivity not just from the introduction of robots but also from office automation. This means that working hours can be shortened. The union of our company is thinking in terms of halving working hours over the next 10 years."

In the sectors driven by microelectronics it seems likely that government and business in Japan will meet the goals they have set. In these sectors considerable product development has already taken place. Whether the efforts in materials and biotechnology will be as successful is more problematic. In these areas (particularly in biotechnology) current product activity is limited and the future is less clear.

The Long-Term Credit Bank of Japan offers this analysis: "Biotechnology is comparable to new industrial materials technology. This is another promising key technology expected to support growth in the 1980's and the 1990's: both are making advances in technical development and applications, but are not established as full-scale industries. Similar as they are, there is a marked difference between the two in their pattern of industrial growth.

"The new-material industry needs supporting mass-production industries that are constantly seeking better materials. The automobile and the future aerospace industry are examples. New materials embodying advanced technology are used in end products. As demand for the products increases, the market for the new materials expands.

"The bioindustry is different. Biotechnology is capable of replacing less efficient technologies, thereby changing the nature of existing industries. Unlike the new industrial materials, which can establish themselves only when adopted for use in a mass-produced commodity such as automobiles, biotechnology can produce a mass product by the application of a new technique."

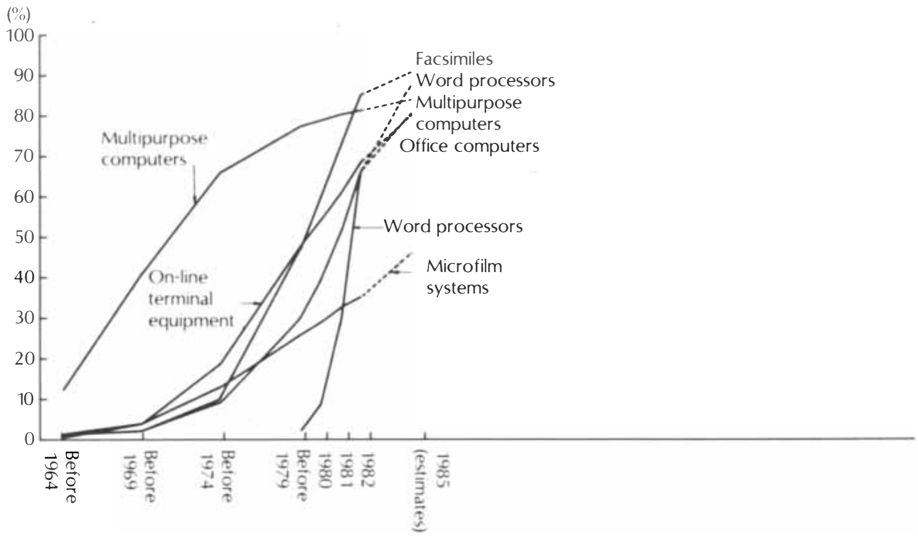
The area of new materials, especially of fine ceramics, is especially important to the Japanese economy: through development in this area Japan sees the opportunity of escaping from exceptional dependence on imported raw materials. This effort is part of the "lightening of Japan," the strategic shift away from iron, copper, zinc and lead toward lighter materials, the production of which requires less energy and a smaller volume of imported metals. Since alumina and silica, the raw materials for ceramics, are in abundant supply everywhere, ceramic substitution for metals in vehicles is extremely attractive. If the economic incentives are there, Japan may well become a leader in this field.

Japanese companies, notably Toray, are now the world's leaders in carbon fiber development and production. In the development of plastics, a field in which Japanese interest is intense, such companies as Du Pont and General Electric lead. The general weakness in the scale and technology of Japan's chemical industry is likely to prove a handicap in this area for some time.

In the field of biotechnology, it has been argued rather widely that Japan lags the West, and the United States in particular, by several years. The Long-Term Credit Bank takes a more optimistic view: "According to a recent survey by the

Table 13

RATE OF OFFICE AUTOMATION EQUIPMENT INTRODUCTION BY YEAR (CUMULATIVE)



Note: Cumulative figures of the rate of introduction by year.
Source: EPA, "Corporate Strategies for Riding Out Hard Times," survey in January, 1983.

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Table 15

ROBOTS IN MAJOR ECONOMIES

	1981	1985	1990
Japan	9,500	36,500	111,000
United States	4,500	15,000	56,000
West Germany	2,300	8,800	27,000
United Kingdom	713	2,700	10,000
France	600	2,300	8,500

Source: OECD.

Ministry of International Trade and Industry, 159 companies are engaged in biotechnological research and development. Seventy-five of them are working on recombinant DNA and 84 are experimenting with cell fusion. The total R&D costs of the 159 companies are estimated at ¥47 billion. There are about 4,000 researchers in this field. The growth rate of R&D costs is 20 percent a year and the growth rate of R&D personnel is 12 percent a year.

"Japanese companies favorably compare with advanced foreign ones in biotechnology except in basic recombinant DNA and bioreactor applications. At first Japanese companies had to introduce basic techniques from U.S. ventures, but since then they have made such remarkable progress that they have little to learn from foreign companies. Japanese companies are well versed in such techniques as fermentation, tissue culture and cell fusion (the basis of which was pioneered in Japan). In the advanced stage of applied biotechnology Japan will in all likelihood acquire an advantageous position in the international arena."

The one high-technology area in which Japan clearly and significantly lags with little prospect of moving toward leadership in the foreseeable future is aerospace. Although Japan has a rocket and satellite program, it is only now proposing to develop a rocket with the lift capability already available in the United States and Europe. The H-2 rocket, as it is called, would not be available until the 1990's. Japan's most recent satellite was reported to be dependent on U.S. sources for half of its technology, including guidance systems.

In its assessment the Long-Term Credit Bank concludes that an independent Japanese position in aerospace is not possible. "Joint international development of aircraft progressed in the late 1970's, and Japan is becoming an important partner. Japan first strengthened its competitiveness in aircraft parts, and in the 1980's it is expected to be competitive in engine development. The development of new aircraft will be beyond its power for at least another 10 years.

"In space development, Japan is said to be 10 years behind the United States. This gap will not be closed for a long time unless Japan turns to the same type of joint international development as in aircraft, abandoning its present policy of depending solely on domestic technology for the exploitation of outer space."

It is on the more amorphous areas of new materials and biotechnology that government support tends to be focused. The Ministry of International Trade and Industry (MITI) began a program in 1981 called Research and Development Project of Basic Technology for the Future (or Next Generation). This is an eight-to-10-year program, with a total cost of ¥100 billion; in other words less than $50 million per year will be spent. Research is contracted to private organizations, and the main programs announced are in fine ceramics, high-efficiency separation materials and bioreactor and genetic recombination utilization technology. Funding tends to be evenly divided among these programs.

These efforts are companions to the much discussed fifth-generation computer project, also MITI led. The fifth-generation computer is meant to be a 10-year program, funded at $15 million per year for the first three years.

Also in 1981 (a year that seems to have been the turning point for much of Japanese thinking and policy regarding future technologies) the Science and Technology Agency of the Government of Japan announced its Program for Exploratory Research for Advanced Technology. Funds of ¥2 billion were announced for each project. A principal goal of the program is the exploration of ways to organize research project teams. The initial projects announced were in the new-materials sector: superfine particles, special-structure substances, fine polymers and perfect crystals.

It will be noted that all of the projects under direct government sponsorship have very limited allocations of government funds, allocations that are almost derisory by the standard of U.S. research funding. The Long-Term Credit Bank fills out the picture: "In addition, there are many private projects in basic and applied research. There are said to be over 70 such research and development projects carried out with private participation under government direction. Japan is particularly good at this type of research, and the United States can profit from studying this kind of arrangement."

This review of national policy sheds some light on the vexing topic of the role

Table 14

NEW-MEDIA EQUIPMENT MARKET

Name of Media	Equipment	Unit Price ($, Est.)	Introduction to Market	Projected Market Size, 1985
Teletext Broadcasting	Teletext Adapter	Approx. 500	Oct. 1983	50,000 units
	Teletext Color TV	1,100–1,400	Oct. 1983	100,000 units
Satellite Broadcasting	Converter-attached Antenna	Approx. 450	Early 1984	150,000 units
	Satellite Broadcasting Tuner	450–680	Early 1984	150,000 units
"CAPTAIN" System	Adapter for "CAPTAIN" System	Approx. 450	Nov. 1984	30,000 units
CATV	Home Terminal	–	Around 1985	100,000 units

Note: "CAPTAIN" system stands for Character and Pattern Telephone Access Information Network System, which is designed to provide pertinent information on banking, shopping, housing, traveling and so on for call up on home TV's from a computer center through telephone lines.

Source: *Nikkei Sangyo Shimbun.*

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of the Japanese government in Japan's technological development. There is widespread agreement in Japan that electronics, new materials and biotechnology are strategic sectors for research and development. This agreement on sectors was not government imposed, but results from long and widespread study and discussion in which several government agencies participated, sometimes from conflicting points of view.

It is also clear that funding and staffing by the Japanese government play a small part in the total technology development effort. The government's largest role appears to be in the research areas that are the most risky and least well defined—new materials and biotechnology. Even in these areas, private organizations are the prime movers in the research effort.

Perhaps the most important role of the Japanese government, or any government, in support of research and development is in ensuring that an adequate infrastructure is in place. Here such efforts as Tsukuba constitute a good example.

Although the construction of a central academic and business focus for research and development at Tsukuba is under way, MITI has launched an effort to make sure that several regions benefit from the growth of high-technology industry. The effort is called the Technopolis programs. The Japan Economic Institute reports: "Perhaps the most widely promoted new central government investment promotion plan is the Technopolis program. Targeting investment by domestic and foreign high-technology companies, the government has approved nine regional development plans that coordinate infrastructure development with tax and financial incentives (five other areas are pending approval). MITI hopes to improve the performance of small- and medium-size firms as well as disperse new industries more evenly around the country. The project involves local authorities who must meet MITI guidelines in terms of location, labor resources, educational facilities and infrastructure. In exchange, MITI provides information and consulting services as well as financial help through the Japan Development Bank and the Hokkaido-Tohoku Development Corporation.

"It is unclear whether or not Japan can support dozens of top-notch biotechnology or electronics firms—the educational system may not be able to supply the skilled labor. Whether so many firms can establish themselves in Japan's market is also a nagging question."

The Japan Economic Institute points out that the supply of skilled labor may also act as a brake on the success of Japan's R&D plans. Efforts have been made to attract scholars from abroad, and these continue, but the hazards of language and differences in social customs and culture are very real obstacles.

The matter is clearly very hard to define or measure. Given the commitment of the Japanese government to providing an adequate infrastructure for the strategic necessity of a major R&D effort, it is difficult to see funds being stinted for university support.

As Japan's business leaders deal with the surge of investment in research and development, especially in enterprises exploiting advances in microelectronics, the utilization of human potential and other facets of personnel management become paramount. Problems of recruiting and training technical personnel and of managing their career progression assume special importance because of the well-established pattern of personnel management in large Japanese companies. It is a traditional, stable pattern that poses problems when companies are confronted with fast-changing technological requirements.

In the large Japanese company, employees are hired directly from school and are expected to remain with the company throughout their careers. The company therefore has a considerable obligation to plan the careers, provide continual training and retraining and make provision for an employee's entire future.

As a result, there is an unusual emphasis in the Japanese company on in-company training programs and on continued personnel evaluation. The system at its best is a remarkably constructive one in terms of human values, but it encounters paradoxes when confronted with the issues of technological change: the obsolete engineer, the technician with inappropriate career ambitions, large numbers of new employees with high career expectations.

As Japan's business leaders discuss some of these issues, one common theme emerges: the sense of company responsibility for research and development personnel and the assumption that the company must take the initiative in dealing in a positive way with career matters.

Senior Managing Director Susumu Aizawa of Epson Corporation is concerned that technological obsolescence will emerge among members of his research and engineering staff, which numbers more than 700 engineers. "I feel that an engineer, like a doctor, should be able to work for a fairly long time. However, we face the challenge of developing a true technological operation. The greatest problem is that of how long we can give full scope to our staff's abilities. Because the technology is gradually changing, most of our specialists will be of little use as it moves to new materials and away from mechanical engineering. In any event, we are already moving past mechatronics. How many of our staff can go beyond the current technology?

"An old example of this difficulty is the vacuum tube specialists. It is not that these people can no longer be used, but they cannot work on the front lines. That kind of technological change seems to be taking place about every 10 years, and the rate is not slowing.

"In trying to deal with this, I feel that the issues of training are hard ones. Although simple cramming is not entirely the answer, without it, nothing will work. One has to build an environment encouraging self-development, with on-the-job training as the focus. Of course, the system must offer scope for the individual while providing training through the company. But education is a difficult subject; even universities fail in education at times. It is a cold way to put it, but trying to bring everyone along is not possible.

"As far as the upper age boundary for adapting to change is concerned, I have the feeling that it is in the mid-40's. After this age, the situation is completely different depending on the person. For a person with very good intuitions and perceptions, it is entirely possible to continue in a management position into the 50's and 60's. Some people, of course, will go into engineering management. We would like as many as possible to do so, but not everyone can make it. For the people who cannot become managers we have no choice but to instruct them to focus deeper and deeper into their specialties, and to remain in that work."

Olympus Optical Co., Ltd., is exploring new approaches to the continuing training and development of its technical staff. Mr. Toshio Nakatsubo, director and manager for research, describes the process. "In terms of developing younger people, we are considering experimenting with what we call career path plans. The aim is to establish standards that must be met at career points one year after university graduation, two years after, three years after. If there is a specific day and month established for the younger people to complete their plan, they can perhaps reach objectives or targets for raising their technical capabilities and improving their efficiency. Therefore, one approach to developing engineers is to set standards of efficiency that must be met after a certain period.

"To give an example of specific standards, five years after university graduation a member of our technical staff should perhaps have presented a paper in English at an academic society outside the company. After three years a person might be expected to have delivered a quality paper to his domestic academic society. These are general standards, but

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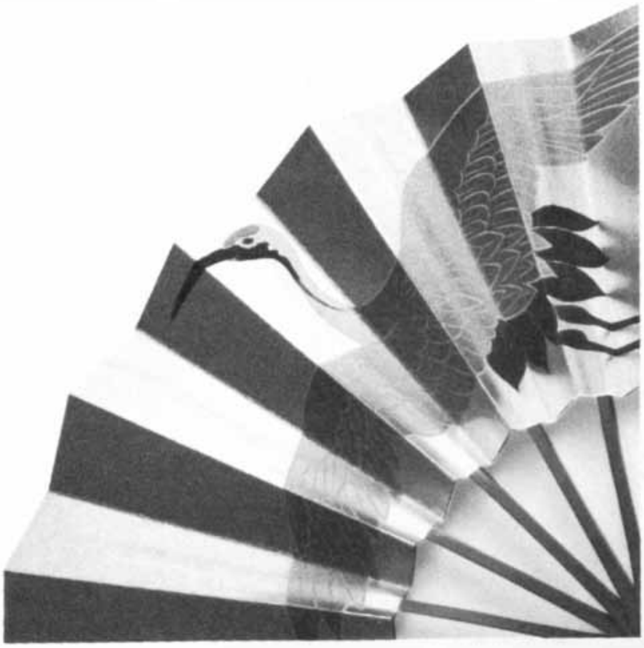

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at minimum our technical staff should be able to read, write and speak one foreign language.

"Specialists must achieve particular ranks of accomplishment. For example, an engineer designing a semiconductor should after a certain number of years be able to handle a variety of designs: after two years a certain number, and after three years he should be able to properly train a first-year man.

"The standards must be applicable in the wider arena of other companies so that an engineer who has met them will know where he stands with regard to the competition. Put another way, if some outsider were seeking an engineer, this should be the sort of person they would want to hire.

"For language training, we have a company English instruction system. It is a specific approach with formal recognition of achievement twice a year. We also have a system for informal study, with foreign instructors available weekly."

Mr. Moriya Shiki, senior managing director of Mitsubishi Electric Corporation, holds quite specific views regarding the training of engineers. "The best training for engineers is on the job: encountering a problem directly, and having another look at it. The best kind of problem for an engineer to deal with is one a bit more difficult than his skill level. If it is well above that level, he will be discouraged halfway through.

"For rapid development of engineers, we have various methods: technical seminars, engineering study units, specialty engineering training systems. The objectives differ. The technical seminars are not only for providing information. They are held at our research institute for six-day periods and have various subjects, including machinery. The attendees are volunteers, and lectures are given by attendees who have been recognized by their seniors as suitable. An advantage to this is that those who have done various difficult things are given a kind of initiation.

"For example, I am an electrical engineer. By attaching a fan in a generator, I have a kind of propeller. In cross section, it measures the same as the wing of a plane. In designing this, a study of hydrodynamics is necessary, and I must study the theory of the plane's wing. Rather than reading several books, I will consult experts, who in turn will recommend special readings.

"The engineering school has a special flavor from the name 'school.' It meets six days a month, for 600 hours a year, at a study center in Kobe. A team of 20 engineers lodge together, and the course director selects 10 experts from the company, who put in hours preparing and teaching well into the night.

"We have still another technical training system. Our work is steadily moving toward information-related equipment and electronics, and these will provide our future growth. Some sectors, however, are not growing, and personnel are excessive. They are happy indeed if they can move to busy sectors, but it is not that simple. Retraining is necessary. In this technical training system we turn nonelectronics engineers into electronics engineers.

"We also have an engineering association, which can be thought of as an intracompany academic society. Consisting of several sections, it publishes papers and sponsors lectures. Some 7,000 engineers at Mitsubishi are in this society out of more than 10,000 total."

Pioneer Electronic Corporation also has a carefully developed training program, as described by Dr. Takeo Yamamoto, senior managing director. "We have a number of development programs, but the basis of all of them is on-the-job training. During the first year in the company the individual is put into what is called a temporary assignment: he is paired off with a person one or two years senior on a one-to-one basis and works on ordinary tasks preparatory to being assigned permanently. In fact, about 95 percent of these employees work out satisfactorily in the initial work assigned.

"After entering the company, however, staff are put through a one-month coordinated training program at the central training center, after which they work in a factory training program. Thus the temporary-assignment status lasts from the summer when they join the company until the end of the following March.

"It is, of course, especially important that much care be taken in placing the person in a suitable assignment, but this can be difficult. The new people express preferences, and some engineers can be divided by specialty, such as electronics or mechanical engineering. However, research experience obtained at the university is not really very deep, and we do not pay overly much attention to that aspect when assigning the new engineers to their posts.

"With respect to the research center, it is not enough that someone expresses a desire to work in research. If he does not have the required quality, he cannot be assigned there. We have on occasion reviewed as many as 200 people for the jobs. It is a difficult task. I personally interview nearly all of the candidates so that I can choose the ones suitable for the research center.

"The best research work seems to be done from age 27 to age 35 or 36. The period of greatest effectiveness seems to be the period in which the individual can take charge of research and development work as a leader or subgroup leader of a team of six or seven researchers."

For all the strengths of the Japanese system of personnel management, Japanese companies are by no means immune to problems of dealing with ambitious and older research specialists who have plateaued. Dr. Bunichi Oguchi, executive director of Fujitsu, Ltd., sees problems in both personnel placement and motivation. "Our technological staff are still young, but as their average age increases problems will arise in managing their careers. Even now, the company has such problems with staff in their 50's. With age, experience becomes the worker's asset. Knowledge increases, but it is for instruction only since older people lack physical strength and have no interest in dirtying their hands. They have leadership capabilities, however, in that they can provide suggestions and some degree of influence. Therefore since they have intuitive skills and experience, they can provide some value in terms of management. However, they are not up to working on the front line.

"They cannot all become managers, and they must be used according to their qualifications. Although they have experience, as the technology becomes more complex there are various areas in which they have no knowledge. Some simply cannot be placed in a job. Others can be placed under someone in specialized work who has deeper knowledge.

"When I was with Nippon Telegraph and Telephone Corporation, I was responsible for the management of a research laboratory. Generally the desire of the technical people to become managers was greater than that of the office personnel. Although the number of people who did not want to manage but rather wanted to focus on research was not zero, leaving out purely academic types, most researchers wanted to be leaders in their world. Perhaps this is because during their university days most technical people did very well. Thus they feel that they are better than their classmates. Even the university professors who focus on research wholeheartedly want to be the head of any committee formed. It is important for people to participate in teamwork, but it is difficult to get them to do so. People's desires are hard to manage.

"We will have a real problem in our industry within 10 years. Fujitsu hired 750 male university graduates this year. Our industry is prospering, and to win in the current competition, we must take in a number of people. However, the question of how to handle these newcomers is a difficult one. When I was starting out, only a handful of people entered the company. If one's health held up, one would be successful. It was an elite training from the

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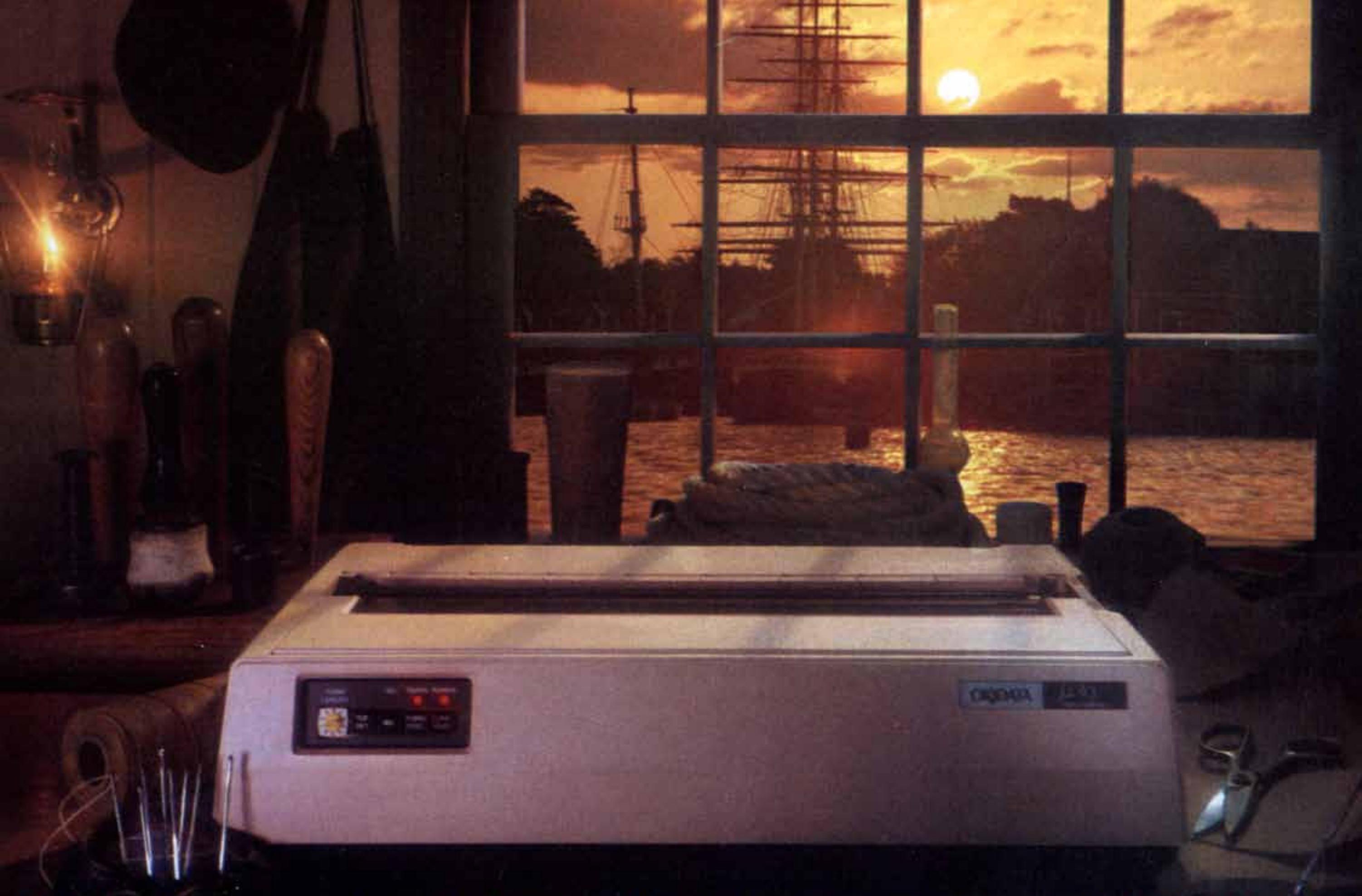

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JAPANESE TECHNOLOGY TODAY

beginning. However, when 700 to 1,000 enter the company together, there is no elite. Therefore competition is naturally keen, and even if they all want to become chiefs, they cannot."

With the surge in investment in research and development, there is an inevitable shortage of certain specialists. Even Japan's strong tradition of school to retirement service shows signs of strain under the tension of personnel needs. Mr. Yoshitomo Nakano, executive vice president of Nippon Kogaku, K. K., discusses his company's policies and experiences in recruiting electrical engineers.

"At present, we generally follow the practices of Japanese-style personnel management. We did begin some years ago efforts at mid-career recruitment. Until then, we had kept to a policy of purism: there were exceptions, but essentially differences in position depended on people's qualifications on entering the company, such as level of education. Now if we find a good man, we give him special treatment.

"Previously, someone recruited in mid-career was seen as a bit lower in position, but this mood has completely changed. A 'pure culture' would no longer work, in part because we needed more staff, but the new factor is technology, more precisely electronics. A great many people in our company did not realize we would need many more electrical engineers, perhaps because having good electrical graduates coming in was not part of our tradition. We did not see the necessity of electronics until the late 1960's, but finally we said, 'Of course we do.' Since then, we have steadily built up the numbers: electrical engineers have made up about half of our recruits, and we now have a considerable capability.

"Still, we were late and so do not have solid ranks of electronics engineers. We have greatly increased negotiations to attract people in mid-career. Even for companies directly in electronics, it is a difficult situation. Some mid-career people come to us to work on a particular project of ours that interests them; others are dissatisfied with the growth opportunities in their present situation."

Mr. Yutaka Kume, executive vice president of Nissan Motor Co., Ltd., reviews his company's requirements for developing engineering talents. "We have 8,000 engineers, although if one includes blue-collar workers in design and research the number is about 9,000. I believe they are highly capable engineers, by world standards. However, not only the individual abilities, but also the research system, give scope to the real engineering capability. In this sort of company, I feel that control arrangements are rather important. However, perhaps now that is not so true. The two most important issues are that the engineering specialists must firmly acquire skills in basic realities, and they must be able to express themselves as freely as possible.

"In a discussion of putting these into practice, I should first note that come boom or depression, we are steadily recruiting engineers, who have various sorts of basic education. Following this, some are sent for further study at home or abroad. Again, we have various ties to universities and research institutions.

"My generation received the old system of education, with divisions into engineering, science, medicine and the like. Engineering included electrical, construction and mechanical. That older division of studies is useless now. We must carry out interdisciplinary training and management. I feel the universities are gradually changing, but companies must carry out educational programs as well.

"It is said that Japan's automobile technology was developed by aeronautical engineers, who were considered the elite of engineers, and that at the war's end they turned to automotive engineering. In fact, the automakers did have outstanding aeronautical engineers during the war. With the war's end and the termination of plane production, I believe many aeronautical engineers turned to autos as the peak of general engineering, but my own group really did not have that view. Rather, we were in difficulties and out of work; the auto industry offered the best opportunity and we took it."

Mr. Sakae Shimizu, senior managing director of Toshiba Corporation, heads that company's research and development activities. "I feel we handle new people better than we handle computers. Our new people are excellent if given direction, but they are perhaps somewhat lacking in initiative, and we see our principal management problem as being how best to handle them. Part of the solution, of course, is to provide the proper environment. In our research center we try to avoid suggesting that an idea will not work. Rather, we ask the young people what subjects they want to research, and we try to be very positive about their interests and wishes.

"We do have a problem in employment, however. There is simply a shortage of available people in all the advanced sectors, such as biotechnology and electronics. I feel the proportion of such people in Japan is rather low compared with that in the United States. Part of the problem is the structure and organization of our universities. They tend to be inflexible, and to maintain older departments at the expense of new fields—large mining departments would be an example. The industry has died, but the departments continue.

"When people enter the company, they receive a month and a half of introductory education. Then their training is carried out largely by moving them between departments. Basically, on-the-job training is critical in developing a first-class company. Therefore manager education is the first priority. Good managers train good engineers. We carry out extensive interviews of individuals after about two years with the company to establish their loyalty to us and the quality of their training. It is of course the manager's responsibility to develop these people, and managers are evaluated on that basis.

"Each year we send about 30 research people to the United States and Europe for training, usually for about a year and a half. These people look like future managers, and they have had about five years of experience. Frankly, we are more concerned about their learning of foreign languages and interactions abroad than about the specific technical content of their training experience.

"We need more training in initiative and in decision making, and more training in such basics as the English language. More training in methods, and more in basic research. We are in any event fortunate in having Japan's fine employment system. It may change, as younger people's attitudes change, but it remains a source of strength."

Japan has begun to critically examine its educational system. Dr. Motokazu Uchida, general manager of the research and development center at Hitachi, Ltd., believes that Japan's technological future depends on new approaches to education. "The high points of our technology are at Western levels, but our base must be broadened. We are too concerned about deviations from the norm; it is important to institute an approach that will allow individuals to change and to develop from the beginning into people who can change.

"It is not a matter of winning or not winning a technological race with the West but of the limits on our capability. We must think of broadening. I am not sure how one measures this, but, for example, we are gradually seeing new products created by Japanese. If broadening means developing more such new things, then the process will take some time. Nobel-prize-class work is still very limited, but slowly increasing.

"How does our output of researchers compare with that of the United States and other nations on a per capita basis? I think very poorly indeed. Is this not the result of differences in ways of thinking? We think that it is very good to do things as other Japanese do them. However, Americans, and especially the French, per-

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haps basically think this way but in fact decide that it is foolish to do the same thing another person is doing and try to do something different. I think that this may also be true in science. In engineering, from a short-term point of view, it is highly efficient to have mass education, with everyone doing the same thing. But doing a different thing, although perhaps less efficient, may well be more effective. Japan has until now paid little attention to this point of view, choosing instead efficiency before all. In the postwar period we carried out the income-doubling plan and went from a poor to an affluent country. We succeeded, however, by focusing on efficiency rather than effectiveness."

Mr. Toshiya Inoue, senior managing director at Victor Company of Japan, Ltd., describes his company's approach to product development issues. "As the men in charge of our laboratories become older, they make their contributions to the company as executives. The men who lead our company remain technical people, and it is they who decide the direction of the company. As others come up in the company there is no change in direction; from top to bottom I feel we work together to develop new products.

"As a result we maintain a sense of being a youthful company. Certainly if younger people are not coming up through the ranks, we will miss our chances. Certainly younger people's interests change and if we do not move fast in developing products to match, we will miss the market. We have to think of technology and software together in combination. As new media come along, we need to package hardware and software. Until recently, hardware was money for the Japanese company, and represented its assets, but although the software business has its difficult aspects, in the future we must be aware of its possibilities. We are in an era in which we cannot depend only on hardware. In the computer business, software is 80 percent of the total. Of course it is a riskier business, but business means taking risks.

"In technology one must always be thinking 10 years ahead; in VHS, even 20 years. With the videodisk, at issue is what demand will be 10 years from now. I believe it is essential while working individually on narrow problems to think clearly from this longer perspective as well. This is true not only for technology but also for the world of production and of office functions.

"Although the center of Japan's research and development effort is in those industries concerned directly with microelectronics and information processing, the technological thrust to new sectors includes more mature industries as well. Both Japan's steel industry and automobile industry are now clearly established as setting the world standard for product quality, technology and production efficiency. Yet in any view of Japan's industrial future, these are now mature industries, relatively slow-growing and with limited technological change occurring. Despite the maturity of these sectors, however, leaders in the steel and automobile industries in Japan see no end to the scope for technological improvement."

The steel industry of Japan remains the standard for the world in efficiency and quality of product. Still, such industry leaders as Mr. Hiroshi Kojima, executive vice president of Sumitomo Metal Industries, Ltd., recognize both the industry's technology requirements and the limits to its future. "In terms of volume, steel production is flat or slightly down, as we see it. There can be no mistaking it. I feel, though, that while tonnage is declining, our sales will increase in value.

"This will be a matter of improving the quality of steel. In order to do this higher purities must be achieved. The higher-quality steel of the future will also have greater tensile strength. We need steel that will not rust, and we are working on that now. Our steel is already very low priced—one gram is only 10 sen. Very cheap.

"Looking toward the 21st century, I do not think that steel will be a leading industry. Until recently, along with petrochemicals, steel was a leader as a raw-material-producing industry, and profitable. Now, however, the leaders are autos and electronics, although they may not grow a great deal more. In the 21st century, biotechnology and the information industry will be the leading industries, and they will be brilliant. We see no role for Sumitomo in biotechnology. Of course in terms of the information industry, we have a subsidiary that is rather advanced in the computer industry.

"In speaking of leading industries, virtually everyone would say what I have, I think. However, I would add energy to the list. The use of energy distinguishes humans from the other animals, and we cannot live without it. I believe the energy problem is a serious one. In the 21st and 22nd centuries, global sources of energy will be drying up.

"By the end of the 21st century, nuclear fusion will be the key source. We are studying it and are manufacturing products and experimental equipment. Nuclear fusion will require new materials and new technology, but we are working on them. This will not be an early or brilliant success, but since the problem is at the foundation of human existence, I feel it is essential that we aim in this direction."

Even so relatively mature an industry as automobiles poses significant technological challenges, according to Mr. Kenichi Yamamoto, senior managing director of Mazda Motor Corporation. "The automobile industry is mature, with an annual growth of at most two percent. As a mature industry, as long as one can produce in it, one can sell. However, research and development competition is really severe. In the current industry, including exports, competition is keen.

"Another issue is high technology, which includes microelectronics and new materials. Many important factors in the automobile industry are influenced by this high technology. In addition, although automobiles are a mature industry, it can be said that the industry is undergoing a great diversification of product concepts. High technology is influencing and accelerating this product diversification. As a result, we are doing things with microelectronics that could not be done before; we are doing things with new materials that could not have been considered before. The influence of high technology is affecting the market life cycle and the diversity of values. In these sectors of high-technology impact, we cannot stand still.

"Key elements in marketing are changing steadily under the influence of technology. Even in a mature industry, a good deal must be spent for research and development programs.

"Automotive technology, I believe, is now connected to the triangle of product concept, high technology and new production methods. For example, semiconductors play a part in advanced technology in terms of product concept, and again in mass production, with cost reduction possibilities. Therefore auto technology is advancing rapidly. Although autos can be called a mature industry, the key elements of progress are very much evident. It is my sense that if one is slow in these matters, or overlooks key issues, the result will be business failure."

Mr. Hideo Sugiura, chairman of Honda Motor Co., Ltd., takes a positive view of the technological changes that the automobile industry has undergone in recent years. "I see automobile technology as having received a kind of sudden purification ritual. It seems to me that automobile technology and the automobile industry received a major awakening from two factors: first, the safety problem, which was posed at an extreme by the Chevrolet Corvair in 1969, and, immediately after, the pollution problem.

"In the transition, engineering came to be recognized as being for humans. It was a fresh start. Until then, the technology of the auto and of mass production had steadily advanced but had developed by itself. As a result, the automobile went on its own. People were only made to ride. Therefore traffic accidents and other problems developed. Again, since the technology was developed in isolation, a mammoth pollution problem arose. It finally became clear that something had to be done, and the reluctance to move was broken. I think it was a good thing.

"The speed with which the problems were overcome is proof of the human ability to develop technology. Of course technology is the result of human applica-

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tions, and when the humans woke up, of course the direction of application was changed. I believe that was good. People are clever, and when they understand a problem, the solution is simple. In fact, the recovery was rapid.

"The automobile was an effective response to people's needs and wishes. There is no question that this was true initially. However, the industry then developed on its own in peculiar ways. The high level and severity of traffic accidents are still problems, but automobile technology is not at issue here. The auto is a tool adopted by humans and these problems are those of economic and social self-control, I believe. In Japan there are now 40 million licensed drivers and some 20 million car owners. If they all were to go out at once, the roads would overflow. In response to this, car owners invent the best solution on their own. There are a great many sleeping cars, which go into action in turns.

"For example, in my case, from Suginami to the company is about eight kilometers. It is about 40 minutes by car, 25 minutes by bike or one hour by bus, train and subway. I make my choice based on my personal values or for economic reasons. Tens of millions of people all do the same, and from these micro decisions a macro balance is maintained. Humans naturally have this sense of balance, and so I do not worry overmuch about issues of traffic conditions."

The center of Japan's current technology effort is the electronics industry. It is in this sector that business leaders are most likely to think about the future on a world scale and are most likely to probe deeply into the significance of technological change for the peoples of the world. Certainly these business executives do not uncritically accept the value of higher technology. Rather, they remain highly sensitive to the issues of human values posed by technological advances.

Dr. Koji Kobayashi, chairman of the board at NEC Corporation, has led his company into a leading position in the field for which he coined the term "C & C," computers and communications. "In modern society, information has become the fourth resource, after capital, labor and technology. This 'information resource' will be used with increasing effectiveness, and the technology for building a true information society will be the C & C one. This technology will have a major impact on all sectors of society. Further, its impact will not be limited to domestic society but will cross national boundaries, with the construction of a worldwide information-related infrastructure, and thus play a role in broadening mutual international understanding.

"One can see examples of C & C technology in the various sectors: in the home, as Japan's CAPTAIN teletext system, cable television and automation; in company, office and factory automation; in society at large, as medical and educational information systems; on a national level, as regional information systems and administrative information systems, and internationally, as science and technology information systems, exchange control systems and trade information systems.

"The main technologies involved in the future are likely to be microelectronics, optoelectronics, voice synthesis and voice recognition, satellite communications and software.

"To make possible the free international flow of information, we must especially overcome the language barriers. The realization of the 'automatic translation system' that we are pushing forward in development now is the key to building a world-scale information society. In this C & C technology development, the most important factor henceforth will be software."

Dr. Shunkichi Kisaka, executive vice president of Matsushita Electric Industrial Co., Ltd., holds firm views on the relation between humans and machines. "For the past 200 years we invented substitutes for the legs and arms of mankind. The train and the airplane were built as substitutes for legs, and the motor substituted for arms. These machines have served as part-time muscles for mankind. From now on, changes in products will come about that concern the functions of the head. Looking at the current power of the computer, I think it is very much an overstatement to say that it can take the place of the human head. Still, people who say that are rather numerous. I tell such people that perhaps this is so in their case, given their kind of thinking, but that there are millions of people in the world whose heads are better than theirs. My real feelings are somewhat different.

"In terms of powers of understanding, in two or three years memory will increase by three or four digits. Thus the various functions of the computer will increase by three or four digits, and processing speed will thereby be increased. For the computer itself functional speed will increase by one digit, and with parallel processing by two or three digits. In combination this can be a four-digit increase.

"Further, impressions of sensor functions will increase by one digit, with reliability increasing by two or three digits. Or response will increase by a single digit, with prices falling by three digits, giving a four-digit result. In any event, various combinations are possible, with the outcome a total of three- or four-digit increases in value. Things that are not used because of their high price—solar batteries might be one example—with a three-digit drop could suddenly be used. I think there is a lot that can be done with this kind of system engineering."

Office automation is relatively new in Japan, but it is progressing very rapidly. Mr. Takao Nawate, managing director of Ricoh Company, Ltd., discusses some of the implications. "Capital goes with the introduction of information equipment, and a key question is whether machines can displace personnel in terms of capital and key elements in the business. Of course if costs are ignored, routine and standard work in the office can be completely changed. In the extreme case, people with a taste for experimentation will go ahead regardless. In any event, there will be a sharp increase in the demand for systems engineers and for programmers. As the volume of such work increases, the number of people becoming specialists will increase, with perhaps no great net change in work force numbers.

"As more information processing with high value-added is done, this may well be the outcome. Factory productivity will increase, and so will information-processing productivity. In a way, because of the improvement in processing standards, the change will be at a similar rate everywhere. Because all the companies will be moving in this direction and therefore using the same competitive weapons, efficiencies will improve and competition will become rather fierce.

"There will, however, be a difference between companies. Those doing work in which profits can be related directly to capital will gradually realize profits as they invest. Their costs will drop as productivity increases. They will have a higher value-added from information and will be able to increase prices. Those that cannot match the capital investment will go under. That kind of rather fierce and somewhat distasteful competition will result. The conclusive factor in differences between firms will be both in creative activity: essentially in deciding what to make, and in information processing: what carries with it the higher value-added.

"Judgment and planning will become very important, and so will technology: research and development capability. Until recently, one might say that the planning and research departments rather reflected profitability. From now on, they are likely to be at the center of management. I feel that with management judgment important in the organization, the importance of these functions will greatly increase. As a result, people now doing standard work will become specialists and people in production activity will seek to become technicians. It is rather like developments in missile manufacture: the

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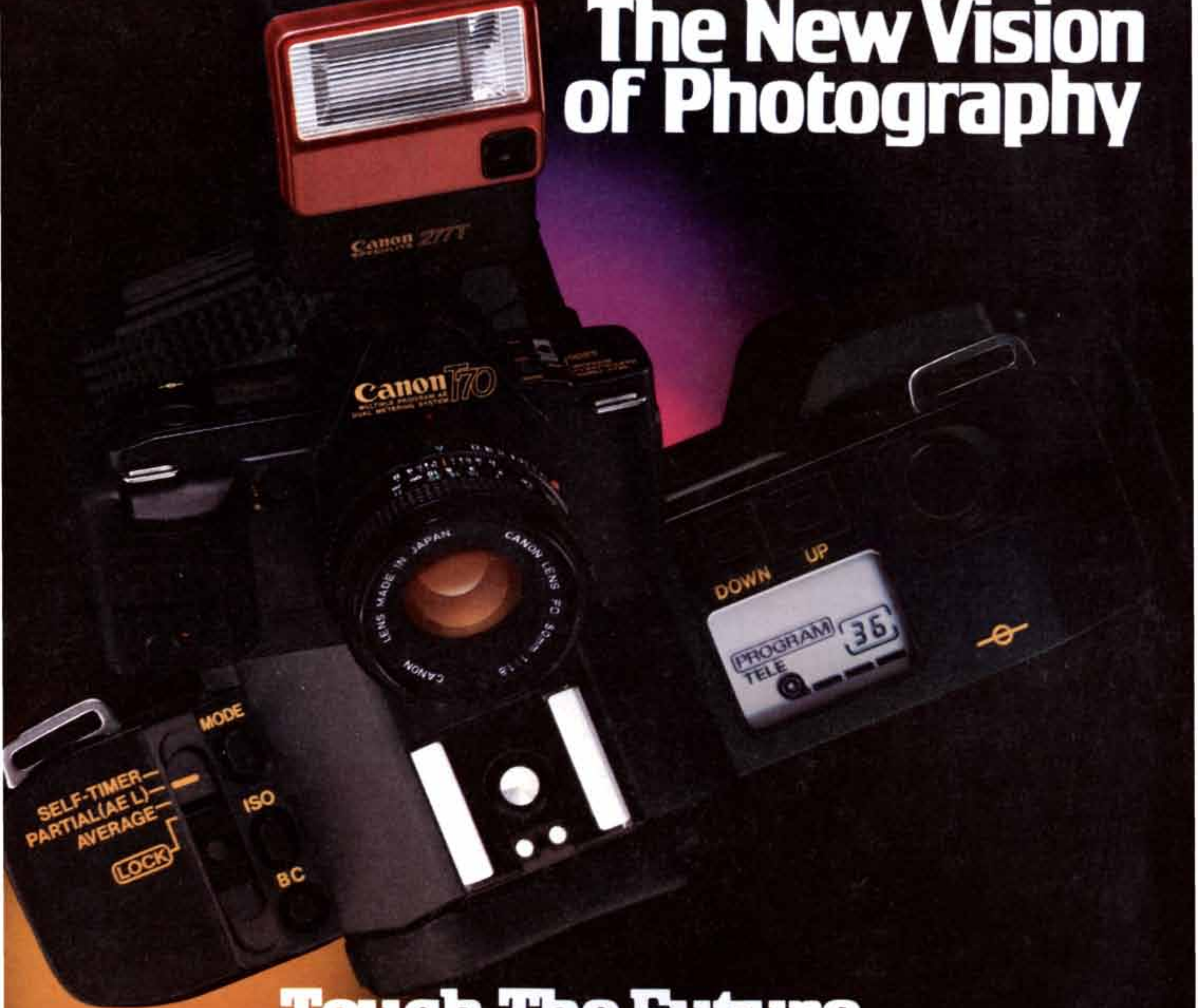

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staff will progress in their work from volume to quality."

Mr. Yoshihiro Mita, president of Mita Industrial Co., Ltd., takes a very positive view of Japan's current technology position. "A nation receives a great many Nobel prizes as it enters into maturity. It is a sign of decline. When the product of a nation's technology is hardware, there is still considerable room for growth, but as it turns to software development, in a sense one must question its strength and the power of its entire technology.

"Thus we find that Western scientists have a special interest in the relations of technology to culture and to humans. It is because they are losing their existence as technologists. Japan's technologists show little interest in these issues, and at present there is ample room for continued healthy growth of Japanese technology.

"There is no room for even questioning the need of humans for technology. Everyone agrees on the need. It can be said that Japan is in a truly healthy phase of its development technologically. If we begin to depart from this view of technology as working for the betterment of the living standards of the people and that sort of negative discussion begins, we will be in trouble."

The question of what direction technology will take is of great interest to Mr. Ichiro Yoshiyama, executive director of the research and development headquarters of Minolta Camera Co., Ltd. "On the plane today, I was reading IBM's *Infinity,* which raises a critical question. Just as a license is required to drive an automobile, so in a high-technology society should there be the matching requirement of a technology license? The idea is an interesting one that closely touches on my experience and feelings.

"Notwithstanding this view, I feel that the goal of engineering must be to bring about a society in which that kind of license is not needed. In thinking about the issue we might consider two groups of people: those over 70 and young children.

"Older people have an untroubled life style based on their long experience and on established standards of cultural values. Even small things must meet these standards and familiar patterns. Young children are extremely responsive even to slight stimuli. If they catch cold, they may die. The danger is the ease with which their course of development can be damaged. Because they are being formed, they are weak. It is rather like a typhoon blowing on a construction site.

"In a way, when children reach their teens, they are formed and can handle small issues. They have pocket money and are a consumer class. It is at this group and the middle-aged group that all of our efforts are aimed in an opportunistic way. I believe we must rethink this. The trouble is that small children cannot answer or speak back to us. And the older people are happy.

"The question is whether, as in preventive medicine, we are not able to offer a guarantee. I believe we must consider how best to carry out proper assessments of technology in terms of the needs of the defenseless, rather than addressing the issue of technology licenses."

Many of Japan's business leaders are convinced of the value of technology, but many of them also hold that ultimate issues regarding technology are better placed in hands other than those of engineers. Mr. Shinji Seki, executive vice president of Mitsubishi Motors Corporation, expresses this view. "I have serious doubts about the wisdom of entrusting leadership regarding technology to those who have only studied the physical sciences or engineering. They do not study human relations or the humanities when becoming engineers. The nuclear problem is a case in point. Fortunately at present the control of atomic power is not in the hands of technical specialists.

"Put another way, there are limits to the advances that technology can make. It could advance to frightening levels and cause the degeneration of the human race. One can imagine pushing a button to make machines do all the work, and saying now we can golf every day. Work is a basic need of humans. There is a variety of such basic needs. In the ancient past, humans grouped together for protection in the wilderness and cooperated with one another. However, as wealth gradually accumulated, we became divided into have and have-nots, and quarrels began. From a primitive communist concept, the world entered into dissension between humans. And now we are in the world of technology. We must find a way, I feel, to avoid humans themselves becoming peculiar in relation to technology. I think it is necessary to closely study humans while controlling as best as possible the future of humanity. We must not be running this way and that, doing daredevil things out of confusion and avoiding our responsibilities."

Dr. Makoto Kikuchi, director of the research center at Sony Corporation, states his thoughts regarding the future of Japanese technology from an initial view of Japan's role in world affairs. "There is no question that the United States and the Soviet Union are superpowers. If Japan were to fight a war in the next five or six years, we simply would not have the weaponry to win. Coming from that view, we need to think of the sphere in which Japan will conduct itself. Japan's great power is its economic power backed by its technology. One fine morning, Japan's apparently meaningless existence will end, and in some sort of international conference, I believe Japan will speak with exceptional authority.

"Present-day characteristics of Japan will not change in a day. For example, if Mondale becomes president, he says he will set a goal of three percent of Japan's GNP for defense expenditures. It is all right to say this, but major military strength will not come into being immediately. Even for some years, Japan will remain decisively weak, I think. The depth of our defense is insufficient; it resembles a plastic cover. Japan must work out a special approach to its affairs.

"This might be expressed in terms of a technology country or a brains country. In reality, I think that things carried out in Japanese society already have that flavor. But this must not become one-sided. For example, in basic research, a list of truly basic work is drawn up, and suddenly money is spent and the national budget is disrupted. We need to discuss whether basic research should be free or not. Again, there are those who urge that priorities in government-funded research be established, but it is companies that worry the most about doing things in terms of priorities.

"Mature technology has its good aspects. You can do a lot with it, and the competition is over features and systems. In its negative aspect, mature technology narrows technical differences. Again, in basic research when you think of immediately using the results, in many cases various developments have already made them useless. Thus even today we are not yet in a period of having exhausted alternative applications of technologies.

"For example, in terms of memories, there are several technologies, and even in just magnetic technologies, there are tapes and also disks, both hard and soft, and among the soft, 3-, 3.5-, 5- and 8-inch types. In the 1950's none of these existed. All the work was done around transistors. An ordinary engineer could not have anticipated devices with a function several times greater. We are at a stage with efficiencies 10 times greater than 30 years ago and costs of one-tenth. It is that rigorous. I feel this is the special feature of technological alternatives. A revolution occurred when the vacuum tube disappeared and the transistor replaced it. Because alternatives are now increasing, we cannot expect the same return on investment as earlier. Thus a call for a technology country is all very well, but objectives have to be established, and we must not abandon all of the other alternatives.

"However, this is well appreciated in Japan. In his novels Natsume Soseki writes of the *Yamatodamashii* (spirit or soul of Japan). All Japanese write symbolically in

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terms of the *Yamatodamashii*. Still, in the 1940's, everyone was shaky about such new things as LSI's, product features and systems. Now everyone talks constantly about new media. Taking a single course, or putting all of our hopes on something, is not an inexpensive approach and is too one-sided. If we approach our work with this understanding, I feel we will be more effective."

In 1985, Japan will stage a science exposition at its new research and development city of Tsukuba. The exposition will symbolize Japan's technological advances and is intended as a spur to further progress. Mr. Yoshinori Ihara is secretary-general of the Japan Association for the International Exposition, Tsukuba, 1985. He explains the planning that has gone into the exposition.

"We are doing this in order to develop a new image for the 21st century. We want to express the basic view that science and technology are not only a function of modern Western research and development but also are non-Western phenomena. Especially because we are holding the exposition in Japan, we seek a rethinking concerning Asian science and technology, and it is with this thought that we are planning the exhibition. Four main points have shaped our planning.

"The first is whether we cannot have a rethinking regarding Asian science and other Asian ideas.

"The second is the impression that science and technology are rather inhuman activities that have a mechanical existence separate from that of humans. In order to provide a real understanding that this is not so, and must not be so, we will tie science and technology to the world of the arts, which are thought of by most people as quite the opposite of science and technology.

"Again, 'science and technology' is a single phrase. However, humans lead widely varying existences, and science and technology should respond to this diversity. Men and women differ; youths and elders differ. We seek an understanding that science and technology have a diversity in accord with the breadth of differences in human existence.

"Finally, within science and technology we want to emphasize the living environment. In thinking of housing for the 21st century, it is essential to address how humans can live under extremely restrictive conditions: in polar environments, in the desert, underground, undersea or in space.

"These are our basic ideas for the exhibition. We also plan to make it an international festival, and so we have incorporated a number of the basic features of one into our program. We will not accomplish our basic purposes if guests do not choose to attend."

The science exposition to be held at Tsukuba in 1985 represents Japan's effort to inform the world of its progress in research and development. Like much else about modern Japan, the country's rate of progress has been so rapid and so great as to have gone largely unappreciated by a world that retains earlier and outdated perceptions of Japan's position. The scale and quality of Japan's research activities now rank with the best available. Not the least of Japan's contributions to the well-being of the world in the coming decades will be its supply to the world of new technology.

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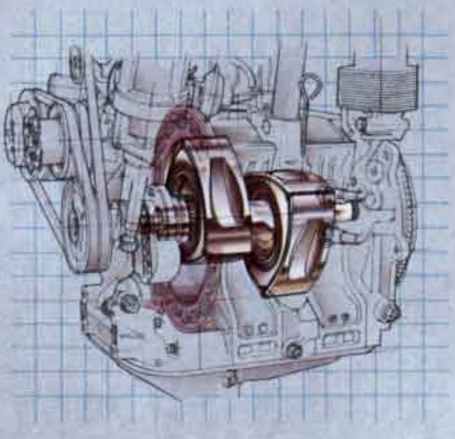

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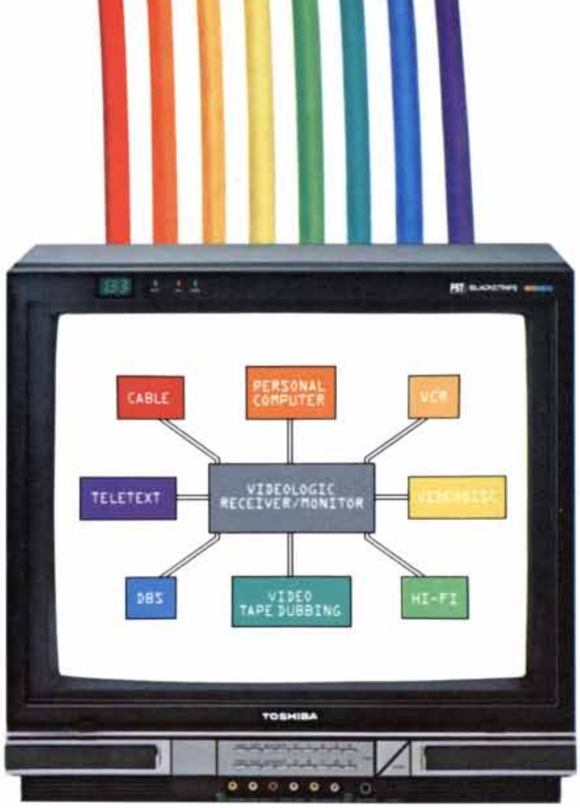

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One quarter of all species of animals and plants on Earth may disappear in the next 30 years because of man's destruction of their habitat. The rate of extinctions is increasing enormously as forests are destroyed and other wild areas are lost. Organisms that evolved over hundreds of millions of years will be gone forever. The complex interdependence of all creatures, from the largest mammals to the smallest plants, is being shattered. It is a crisis with profound implications for the survival of all life. Unfortunately, little is being done to save our planet's natural heritage. Here are some warnings by leading scientists:

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FRESHLY BAKED BREAD is conveyed automatically from the oven to a cooler at the plant of the Charles Freihofer Baking Co. in Albany, N.Y. Loaves have been removed automatically from their pans and are bound for the cooler at a rate of 156 loaves per minute.

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Modern Baking Technology

Rising demand, new markets and the resulting heavy volume of production have forced commercial bakers to do their work increasingly with advanced machinery and automatic processes

by Samuel A. Matz

The 17,000 commercial bakeries of the U.S. turn out some 20 million loaves of bread per day, as well as large quantities of cakes, pies and cookies and such specialized items as pizza crust, bagels, croissants and hallah. The sheer volume has forced bakers increasingly toward advanced machinery and automatic processes. Rising demand (the results of marketing efforts) and new methods of distribution such as the in-store bakery (typically in a supermarket) and the franchised cookie shop have abetted the trend. This year the total size of the market for wholesale, retail and in-store bakers is expected to be $30.1 billion.

Whether the item is a loaf of standard white bread or a loaf of French bread, the basic ingredient is wheat flour. Its most noteworthy component is gluten (the collective name for a group of proteins), which under certain conditions forms a plastic, extensible structure when mixed with water. The physical properties of hydrated gluten allow dough to retain leavening gases during the several steps in baking. It gives bakery products a fine, uniform cell structure and a silky, resilient texture.

Flour made from other cereals such as rye and barley yields dough that is much less elastic and extensible. It does not hold leavening gases well. As a result the finished products are coarser and denser than wheat breads.

Nearly all bakery products are leavened, that is, expanded by gases developed inside the dough. The chief leavening ingredients are yeast and baking powder. Yeast, which is the leavening ingredient for most bread, rolls, pizza crusts, Danish pastry, bagels, pretzels and many other baked goods, works by fermenting sugars such as sucrose, fructose and glucose to generate the carbon dioxide gas that expands the dough. Baking powder contains sodium bicarbonate and a compound that reacts as an acid when the powder is mixed with water. Carbon dioxide is released as a result of the interaction of the bicarbonate and the acidic compound. Baking powder serves as the leavener in most cakes, biscuits and cookies. A few bakery products, such as angel food cake, are leavened primarily by the air trapped in the batter or dough during mixing.

Rich and Lean Formulas

In making bread and rolls bakers generally speak of rich and lean formulas for dough. A rich dough contains substantial amounts of sweeteners, dairy products, shortening and perhaps eggs in addition to flour, yeast, water and salt. As one might expect, such a dough is the substrate for sweet baked goods: pastry, coffee cake, doughnuts, brioche, croissants and many other items. In a lean dough flour, water, yeast and salt constitute from 90 to 95 percent of the ingredients; the remainder is some combination of shortening, sweeteners, milk and malt syrup. White bread and rolls derive from lean formulas; so do pita bread, pizza crusts, English muffins, pretzels, bagels and crackers.

Mixing is the next step in the process. A major objective, particularly with yeast-leavened dough, is known in the trade as development. The term refers to the reactions that take place as dough is mixed, preparing it for further processing and yielding a finished product of good quality.

When the ingredients of dough begin to combine in a mixer, they form a mass that is wet, sticky and weakly coherent: its surface is rough. As it is mixed it becomes smooth, elastic, relatively dry and somewhat resistant to tearing. Many of the physical and chemical reactions that bring about these changes are poorly understood. The predominant change seems to be the orienting and coalescing of gluten fibrils so that they form sheets or strands.

To obtain this effect it is important that the mixer stretch, fold and press the dough rather than tear it or cut it. A dough that has been properly developed can be cut, rounded and molded into loaf form without sticking or tearing in the machinery during the subsequent processing steps. Moreover, it will entrap the carbon dioxide generated by yeast or baking powder to yield bread of low density, a smooth surface and a silky texture. (Pie and cookie dough, cake batter and the like do not ordinarily go through a development step because the dough does not have to be made extensible and elastic.)

Methods of Mixing

Bakers traditionally make yeast-leavened dough by one or the other of two procedures: the sponge-and-dough method and the straight-dough method. Large bakeries turning out white bread usually take the sponge-and-dough approach. In this method most of the flour and water, all of the yeast and some of the other ingredients are blended into a spongy mixture that is fermented for a fairly long time before it is mixed with the remaining components of the dough.

The straight-dough process is simpler but less flexible, that is, it cannot be as readily modified at intermediate stages if something goes wrong during fermentation or in other steps. In this process the water and all the other ingredients are mixed in a single step. (Some of the dry ingredients may be combined before the water is added.) For a small bakery the process may be preferable because the sponge-and-dough method requires holding large amounts of dough under controlled conditions of temperature and humidity and also requires extra equipment, labor and energy to mix some of the ingredients twice.

A mixing and dough-conditioning procedure that is currently receiving attention, particularly in the United Kingdom and Canada, is the no-time method. It takes its name from the fact that the dough is moved directly to the makeup equipment, eliminating the time, equipment and labor involved in bulk fermentation.

Two characteristics of this process differentiate it from the traditional methods. They are a highly intensive mixing stage, during which a large

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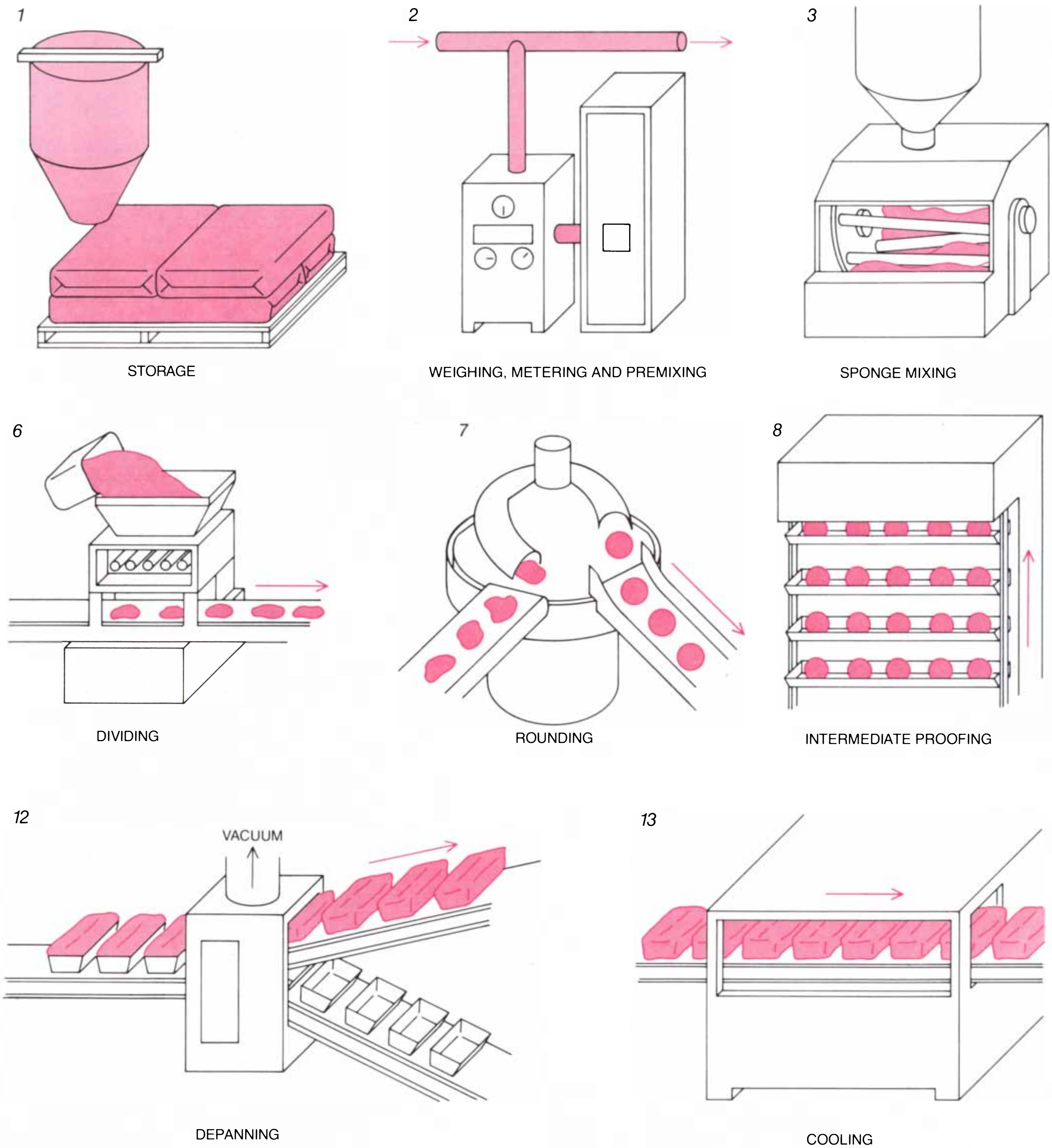
amount of energy is applied to the dough in a short time, and the use of high levels of chemical oxidizers, enzymes and other additives to accelerate the reactions that normally occur during the traditional lengthy mixing period and bulk fermentation. The mixing procedures of the no-time method do little developing of the dough because the equipment tends to shear the strands of gluten. The method replaces the physical developing of the traditional method with high levels of oxidizing chemicals, which cause similar cross-linking of the gluten molecules.

Several attempts have been made to replace the sponge-mixing and fermentation steps with a liquid sponge (sometimes called a brew or a broth) that can be blended, stored and transferred by simpler equipment and less labor. Such methods generally require an initial blend that is fairly high in water and is not developed in a conventional mixer.



AUTOMATED BAKING of white bread on a large scale in a commercial bakery consists of many operations. At each stage of processing the material being worked on is shown in color. The ingredients delivered to the plant in bulk are stored until they are needed (*1*) and then weighed or metered and premixed (*2*). In the mixer (*3*) a sponge dough is formed by mixing most of the flour and water, all of the yeast (for leavening) and certain of the other ingredients. The bulk dough is fermented (*4*), that is, lightened by the leavening action of

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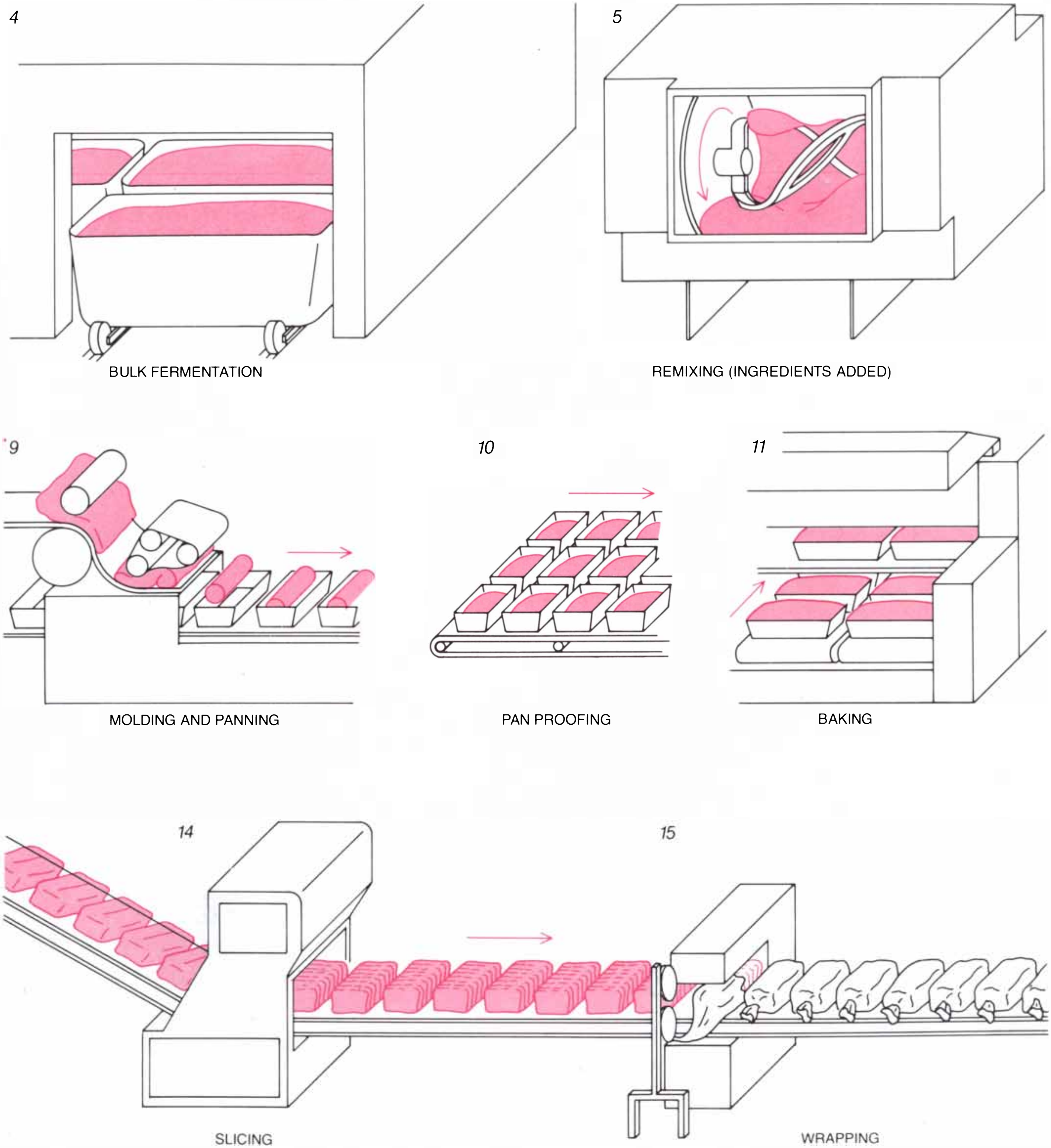
Although some of these processes reserve all the flour for a later mixing stage, the current trend is to put at least 25 percent of the flour in the liquid sponge. In any case the yeast, some of the water and a fermentation substrate (some form of sugar) are included in the first mix. Since the brew is essentially a liquid, it can be blended by simple mixers of low power and can be transferred by pumps.

The brew is normally fermented in large vertical tanks, whereas traditional sponges are fermented in "troughs" with a capacity of about 1,000 pounds that must be moved to and from the fermentation room manually or by special conveying systems. After the initial fermentation the brew is mixed with the remaining ingredients.

Once the dough has been mixed it is ready for what is termed the makeup stage. It passes successively through a divider, a rounder, a proofing cabinet



the yeast, which ferments sugars in the dough. After the addition of the remaining ingredients (*5*) the dough goes to the makeup stage (*6–10*), in which it is divided into chunks, rounded into spheroids, proofed (fermented again briefly), molded into loaf shape and deposited in baking pans. It is then ready for final proofing, baking, depanning, cooling, slicing and wrapping (*11–15*). To make clear what is happening, the machines are not drawn to the same scale. A modern bakery of this type can make about 10,000 loaves of bread per hour.

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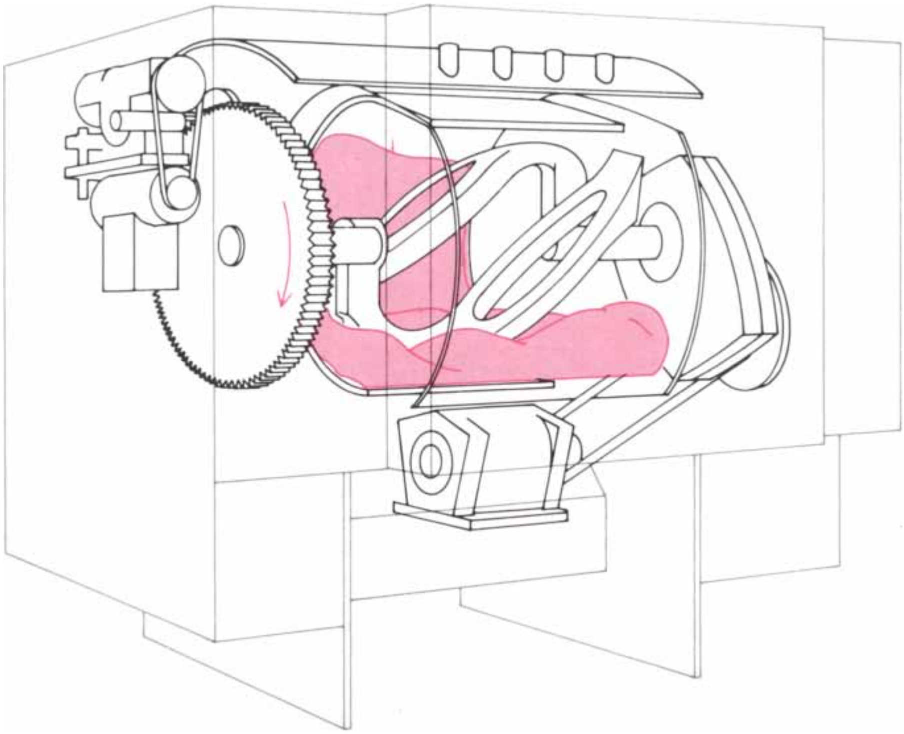
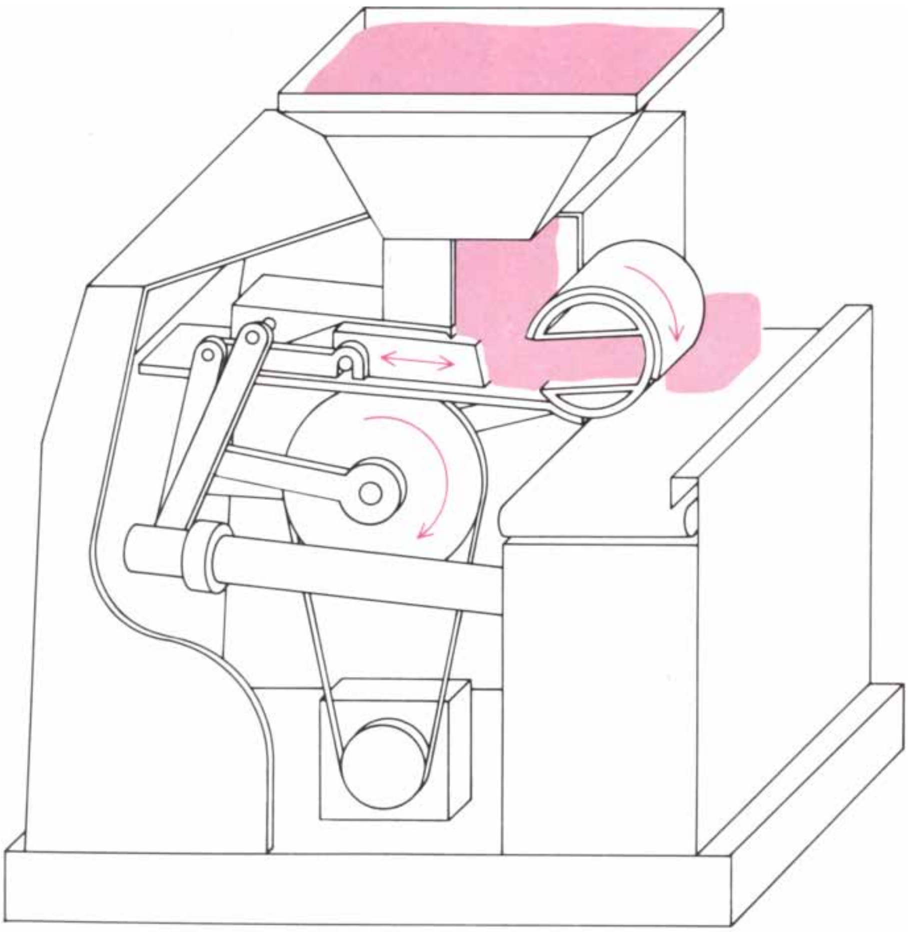


BAKERY MIXER prepares the sponge for further processing. One objective of the mixing step is to develop the dough, transforming it from a sticky and loosely aggregated mass into a material that is smooth, elastic and much drier so that it will be resistant to tearing and sticking during subsequent steps. A typical mixer can process about 1,000 pounds of dough at a time.



ROLE OF DIVIDER is to cut the large sheet of dough that comes from the mixer into chunks of a certain volume. For a standard one-pound loaf of bread the volume of each chunk represents a weight of about 18 ounces. The excess allows for losses in subsequent processing steps.

and a molder. This group of machines takes a large, shapeless mass of dough and forms it into pieces of the appropriate size and shape for baking.

The divider slices the dough into chunks of predetermined weight. (It actually cuts pieces of a certain volume, but that volume represents a consistent weight, usually about 18 ounces for a one-pound loaf of bread. The excess allows for losses in subsequent steps, notably baking.)

The rounder takes the rough, irregularly shaped chunks of dough from the divider and forms them into smooth spheroids with a relatively thick skin. The skin forms as gas is forced out of the chunk and most of the vesicles near the surface collapse. The skin is reinforced by a dusting of flour applied during the rounding process and by the loss of some moisture from the surface. The skin serves to inhibit the further diffusion of gas from the dough during the next, or proofing, stage.

The term intermediate proofing is so entrenched in baking jargon that even many bakers are not aware of its origins. Originally "proof" in baking meant to bring dough to a certain condition of lightness; it now means the fermentation step that achieves that result. The step is intermediate between the fermentation at the sponge stage and the final fermentation just before baking.

The Intermediate Proofer

The intermediate proofer is a room or a cabinet maintained at a warm temperature. There the rounded pieces of dough proof, or ferment, for a period that lasts for from three to 12 minutes. The dough from the rounder, having lost much of the gas it accumulated during bulk fermentation, stretches poorly and tears easily. It is also rubbery and would not mold satisfactorily. During intermediate proofing the dough recovers its extensible and elastic properties. The physical and chemical changes other than the accumulation of gas that take place in the proofer are not well understood, but the pieces of dough leaving the apparatus are larger, softer and more pliable and the skin is firmer and more elastic.

The principal distinction between different kinds of intermediate proofer is in the method of transporting the pieces of dough. One method is by means of several endless belts arranged horizontally. Pieces of dough travel to the end of one belt and then drop onto the next-lower belt, which moves in the opposite direction, and so on until the balls leave the proofer. Another kind of proofer, the tray type, has segmented compartments for carrying the balls.

The molder takes in the pieces of proofed dough and forms them into loaf or roll shapes before depositing them in

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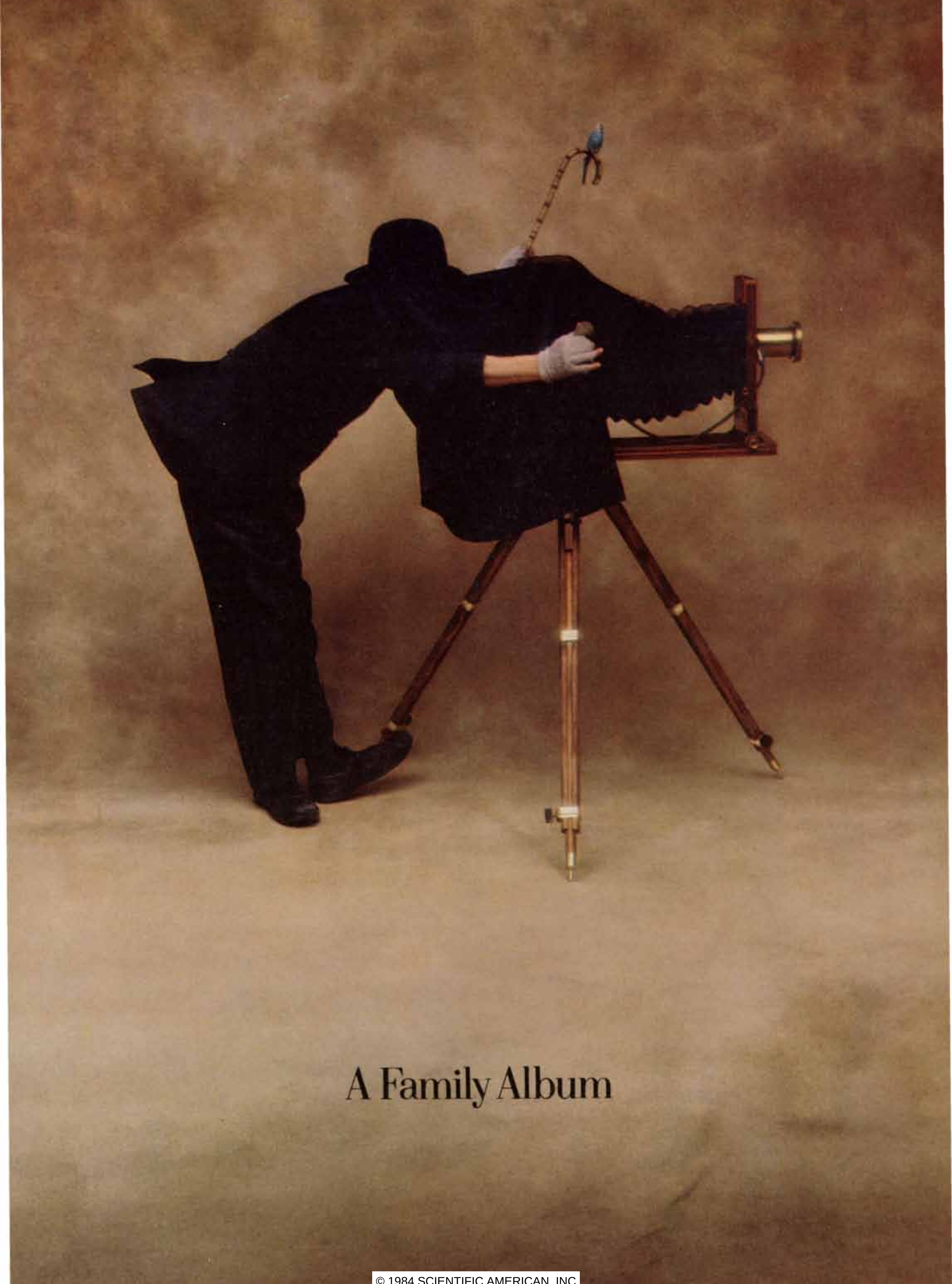

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GM

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baking pans. There are several different types of molder, but they all have four functions in common: sheeting, curling, rolling and sealing. (Rolling and sealing are usually done simultaneously.)

Four Operations

The dough as it comes from the intermediate proofer is essentially spherical. The first operation of the molder is to flatten the spheroid into a thick sheet that can be appropriately manipulated at later stages in the machine. This effect is achieved by two or more (often three) consecutive pairs of rollers, each pair set closer together than the preceding pair.

Next the sheeted dough is curled into a loose cylinder (spiral in cross section). This operation is often done by a special set of rollers that pick up the front end of the dough sheet and reverse its direction. In other models the effect is obtained with a pair of belts. A lower conveyor belt moves the dough forward until the upper curling belt engages the front end of the sheet, brings it back and curls it into a loose cylinder.

A more advanced design substitutes a short length of a woven-metal mat or linked bars of thin metal for the upper curling belt. In such a machine the curling device is affixed just above the conveyor, with one end resting on the belt. As the dough piece passes under the curler the weight of the curler creates enough drag to pull the end of the dough piece upward and delay it while the conveyor belt rolls it into a cylinder.

The layers of the cylinder are quite loosely assembled when the cylinder leaves the curling section. The next function of the molder is to thoroughly seal together the layers of dough so that when the cylinder is baked, it will not uncurl but will expand into the typical loaf shape. In addition the cylinder is lengthened so that its axial dimension is slightly less than that of the baking pan and air trapped between the layers of dough is expelled.

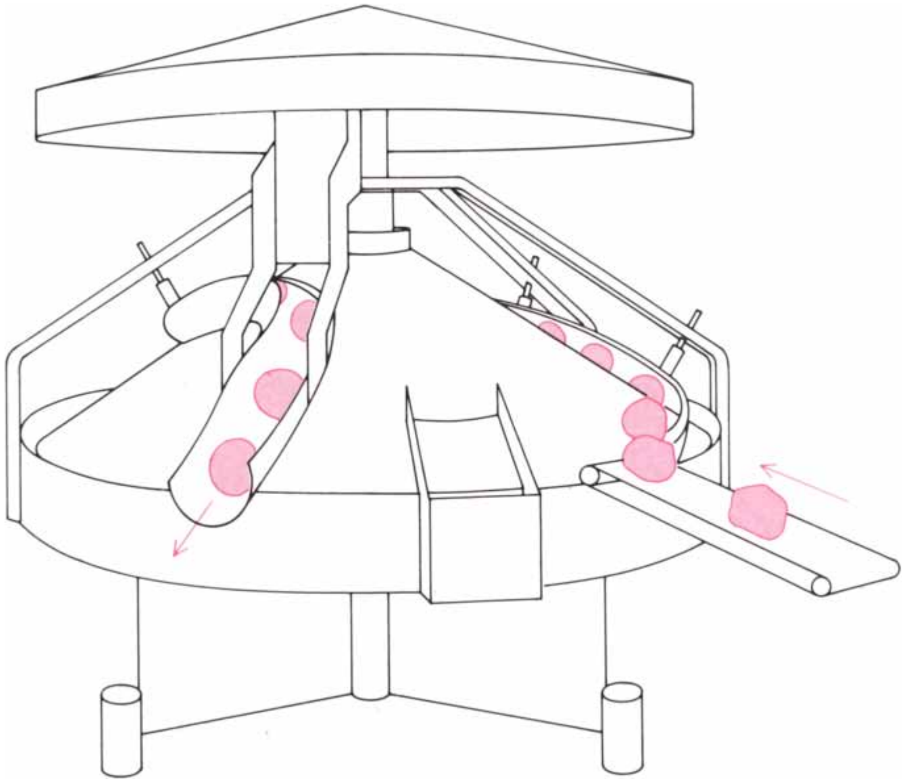
Conventional molders achieve these results by rolling the cylinder of dough between a large drum covered with canvas and a semicircular compression board with a smooth surface. The clearance between the drum and the board is gradually reduced along the route of travel of the dough so that the dough is kept constantly in contact with both surfaces and is gradually compressed. An alternate arrangement consists of a flat pressure board and a powered belt; they squeeze the cylinder into shape as it passes through the gradually narrowing channel.

As the dough travels through the sheeting rolls in the molder the moisture content of the trailing edge tends to increase at the expense of the preceding portion. This redistribution of moisture results from the compression of the dough. In conventional operations this edge becomes the outside layer of the loaf of bread.

For many years it was thought it would be better if the wetter portion of the dough sheet were folded into the center of the loaf. The dough would respond better, it was thought, to proofing in the baking pan and to baking. Recent modifications in the design of molders have aimed either at making the distribution of moisture in the cylinder of dough more uniform or at changing the final position of the wet end of the sheet.

New designs that have been adopted by many bakers include the cross-grain molder and the reverse-sheeting molder. The cross-grain machine curls the dough sheet at a right angle to its direction of travel. As a result the wetter edge of the dough forms one end of the loaf rather than the outside layer.

The reverse-sheeting molder switches the direction of travel of the dough between the second or third set of rollers, thus placing the original trailing end in the leading position. Still another type of molder was developed primarily to give loaves a more uniform cell structure by twisting the pieces of dough after they have been rolled into cylinders. The cylinder falls into a pair of U-shaped cups that then rotate in opposite directions to impart a twist to the loaf. The result is twist bread.



DETAILS OF ROUNDER indicate how it forms the irregular chunks of dough from the divider into smooth spheroids. One purpose of rounding is to develop a relatively thick skin on the spheroid in order to inhibit the escape of gas at the proofing stage. The skin forms because the surface of the dough piece dries out from the evaporation of water and the accumulation of dusting flour and becomes denser as a result of the collapse of gas vesicles near the surface.

Most modern molders include an automatic panning device. Conveyors carry empty pans past the end of the molder, and the loaves are deposited in them by an apparatus that is operated by compressed air.

Ovens and Baking

The oven is a bakery's most conspicuous and characteristic piece of equipment. With its associated loaders, unloaders, depanners, coolers and conveyors it dominates the layout and determines in large part the placement of most of the other pieces of equipment in the production line. The capacity of the oven is the factor that limits the output of most bread plants. For these reasons selecting an oven, maintaining it properly and operating it at its maximum rate are key elements in the successful operation of a bakery.

The oven has an important influence on the quality of the product. Although it cannot compensate for errors made earlier in the manufacturing process, a well-designed and properly operated oven can bring out the full potential of a well-processed piece of dough. The mechanical details of an oven's construction are important because they determine efficiency, fuel consumption and other factors. Perhaps more fundamental (and certainly less well understood)

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are the effects of its heat-transfer mechanisms on the quality of the product.

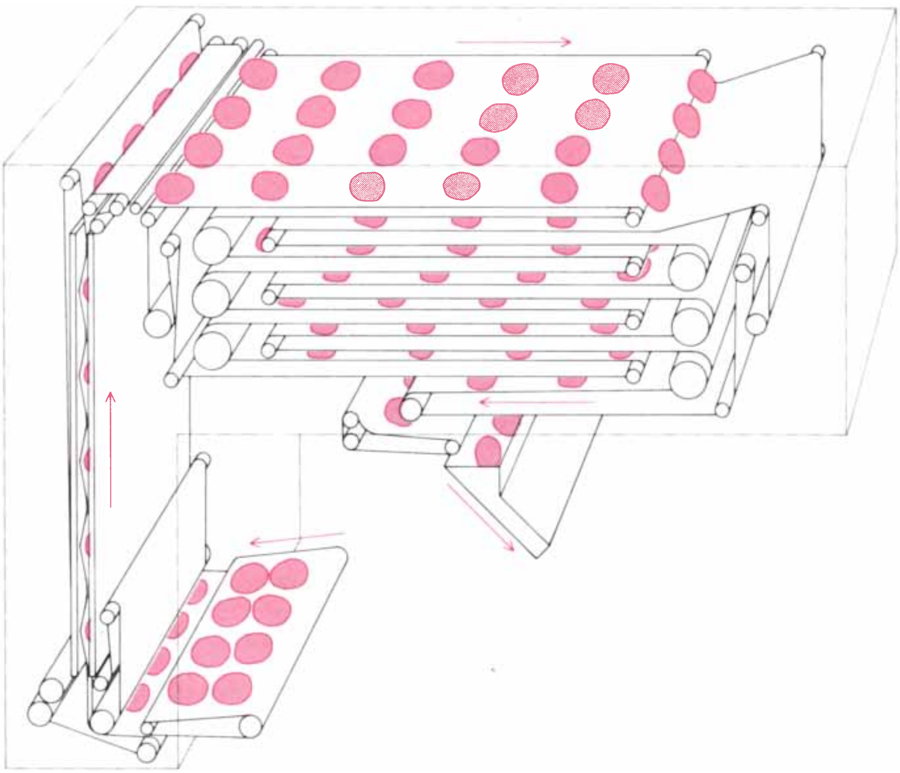
Heat Transfer

All ovens transfer heat by conduction, convection and radiation. The difference in the percentage of heat transferred by each mechanism accounts for most of the variation between one oven and another in the results of baking.

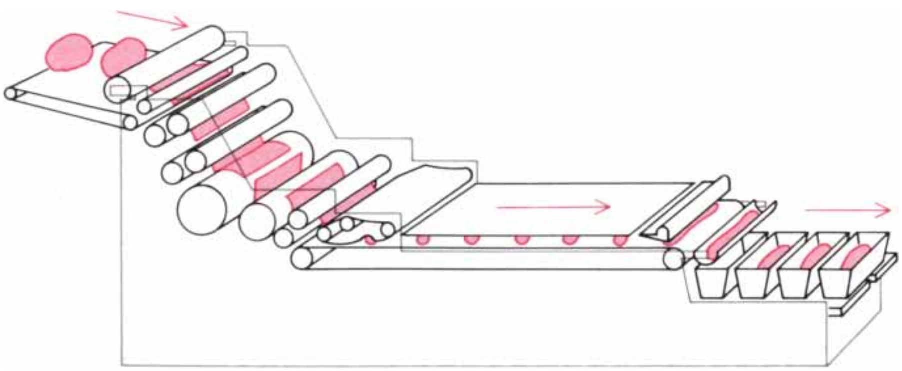
Conduction, in which heat is transmitted through an object, takes place in baking through the pan and its supporting structures. Because of the localized nature of conductive heat transfer, steep temperature gradients are set up in the dough. The hottest areas are the ones in contact with the pan. Unwanted differences in the rate of heat-catalyzed reactions can arise unless these inputs are carefully controlled. If they are not controlled, the bread (or whatever is being baked) comes out burned on the bottom.

Convection, in which heat is transmitted through the air or some other fluid medium, is enhanced in many ovens by the turbulent currents of hot gas surging through the baking area. They originate mainly from the burners, but the movement of the product and of its conveying device also increases the effectiveness of this type of heat transfer. Within and around pieces of dough convection smooths and blurs temperature differentials. Convection affects only exposed areas of dough. Pans with holes or traveling bands made of a mesh are sometimes employed to heighten the effect.

Radiation, which is the emission of energy by a heated surface, has two characteristics significant in baking that are different from the other modes of heat transfer. One is that its influence is subject to shadowing, which results when radiation is intercepted by some object other than the dough (such as the pan or parts of the oven). It leads to uneven darkening of rough surfaces on the dough. The other characteristic is that radiation is highly responsive to the absorptive capacity of the dough. With infrared radiation that means changes in color; with microwave radiation it means changes in water content. As a piece of dough darkens owing to chemical changes induced by heat, more radiant energy is absorbed and the change in color tends to accelerate.



INTERMEDIATE PROOFER is a room or a cabinet the interior of which is maintained at a warm temperature to encourage fermentation. The yeast ferments such sugars as sucrose, fructose and glucose in the flour to generate carbon dioxide. The result is leavening, the expansion and lightening of the dough by the gas. The term "proof" originally meant to bring dough to a certain condition of lightness; it now refers to the fermentation steps that achieve the lightness.



FUNCTION OF MOLDER is to take the balls of dough formed by the rounder and fermented in the intermediate proofer and shape each one into a loaf (or a roll if rolls are being made). By means of a series of rollers and belts the molder flattens the ball into a sheet, curls the sheet into a loose cylinder and seals the layers of the sheet so that they will cohere as the loaf is baked. At the end of the operation the molder deposits the loaves in baking pans automatically.

Oven Variations

The predominant type of oven in large commercial cake bakeries is the tunnel oven, in which the baking chamber is a long (perhaps 300 feet) but relatively narrow and low enclosure. Through it runs either a continuous band of steel or a device for conveying pans. A variant commonly seen in bread-baking lines is a traveling-tray oven. Each tray is permanently attached to a chain that pulls it from the front of the oven to the back. There it is transferred to a lower track that returns it to the front of the oven, where the bread is unloaded.

A traveling-hearth oven has a baking surface made of steel segments that move through the baking chamber on conveyor chains. Loading and discharge are at opposite ends of the tunnel—an arrangement that is often preferable because it allows more flexibility in positioning auxiliary equipment. Individual pans, straps of several joined pans or even unpanned pieces of dough can be placed on the hearth.

A band oven carries the concept of continuous processing a step further by making the hearth an uninterrupted strip of metal. The band can be made out of solid steel, perforated steel or woven wire mesh. Dough can be put directly on the hearth (as with cookies, crackers and hearth bread) or in pans set on the band.

Heating devices vary. Often they con-

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sist of gas-fired burners extending into the oven cavity above and below the conveyor carrying the dough. The burners are arranged in groups to form control zones for regulating the temperature in different parts of the oven. Some or all of the burners are made so that the intensity of the flame can be varied along their length in order to adjust the heat balance across the chamber.

Indirect heating is also used. A heating unit (or more than one unit) outside the oven chamber feeds hot gas to fans that force it into the oven. Commercial bakeries have also made limited use of microwave heating, mostly to reduce the amount of moisture in crackers after they have been almost fully baked in a conventional oven.

At one time loaves were removed from the baking containers by inverting the pan and tapping it sharply. The jolt released the bread, which dropped onto a conveyor that carried it to the slicing or packaging equipment. Originally it was a laborer's hand that delivered the tap, but now in large plants the task is done mechanically.

As one might expect, mechanical depanning damages a considerable number of loaves. Many modern bakeries avoid this hazard by gently lifting the loaves from the pan with machines that grasp the bread with vacuum cups. Some models also incorporate air jets to loosen the loaves before they are lifted from the pan. Vacuum depanning is quieter than other methods are; it also is less damaging and requires less labor. It serves for depanning rolls, buns and many other shapes in addition to loaves.

Other Baked Goods

Mechanization has also come to the manufacture of other bakery products. An example is provided by croissants and Danish pastry.

The traditional hand methods, still widely employed in small bakeries, consist of sheeting out a rich yeast-leavened dough, applying a layer of butter or margarine, folding the combination to make multiple layers of dough and shortening, rolling the folded dough to make a thinner sheet, folding it again and repeating the steps of folding and thinning until a sheet with the desired number of fat layers has been obtained. Usually the dough is refrigerated between sheeting steps to allow it to "relax" (to dissipate the stresses) so that it does not tear during the subsequent handling. Cooling also hardens the fat so that it does not melt and become absorbed by the layers of dough.

The resulting interim dough product, rolled to the desired thickness, is cut to shape, adjuncts such as fruit filling or chocolate are applied and the final form is established by hand or machine before the item is baked. It is the

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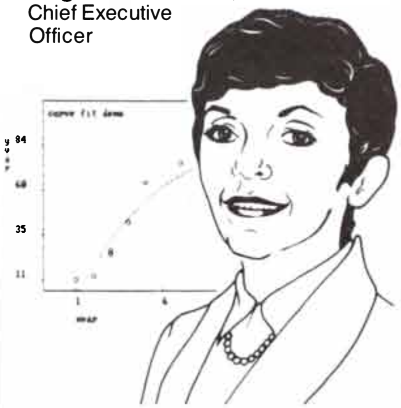

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alternating layers of fat and dough that give the final product its characteristic texture and the flaky, glossy crust.

The most advanced machines for making these products perform a long, complicated series of steps. Such a machine extrudes the dough onto a continuous sheet, extrudes a layer of shortening on the dough, automatically rolls the combination into a cylinder so that the fat and dough twist into a spiral (in cross section), reduces the cylinder to a continuous flat sheet and then folds and sheets the combination as many times as is necessary to create the desired number of layers. Before the final forming steps, roller blades cut the finished sheet to shape.

Ethnic Breads

Bagels are made from tough, lean dough that is first formed into balls, each one with a weight appropriate for a single bagel. The ball is proofed briefly and then formed into a doughnut shape by rolling it around a vertical rod coated with nylon. After a second proofing for one hour at a temperature of 100 degrees Fahrenheit and a relative humidity of 75 percent the bagels are cooked in boiling water for about two minutes, washed with cold water and dried on the surface in preparation for baking, cooling and packaging. A modern plant does all these steps mechanically and continuously.

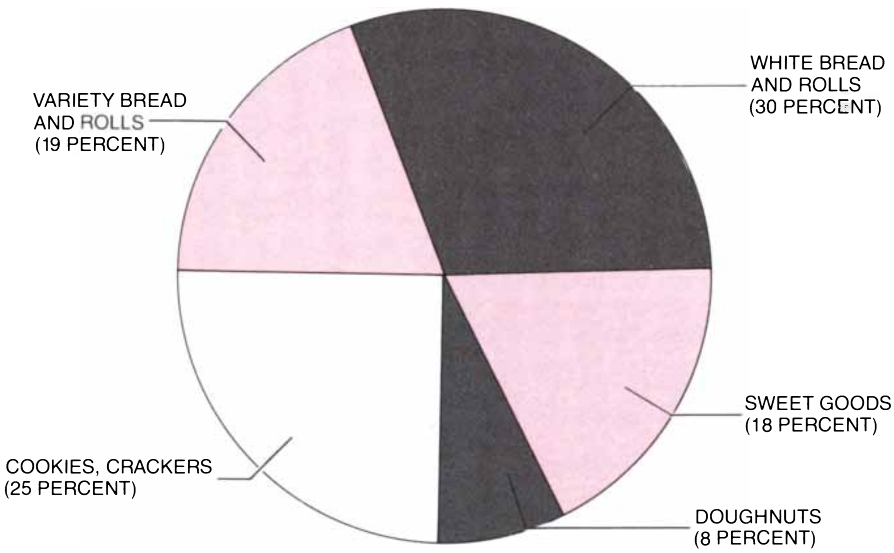
Pizza crust is made from lean dough. The period of fermentation ranges from minutes to hours depending on the type of crust wanted. After the dough is mixed it is divided and formed into disks either by pressing balls of dough flat or by sheeting a mass of dough and cutting circles from it. A few manufacturers have introduced a laminating, or layering, step to make the crust more crackerlike. Pizza crusts prepared for immediate retail sale are baked, but a large proportion of frozen pizza is made with crusts fried in deep fat.

For English muffins the dough is lean, but it must also be soft and extensible in order to conform to the shape of the griddle in which it is baked. The effect is achieved by putting in more water than would be added to bread dough and by using softening additives.

The dough as it comes from the mixer is divided into pieces that are coated with corn flour (to minimize sticking) and deposited in proofer cups. The proofed piece of dough is deposited automatically in the griddle, which travels on a steel conveyor belt that passes through a tunnel oven. A "top flight plate" moves along above the griddle, limiting the upward expansion of the muffin as well as causing additional color to develop on the top crust. At the end the muffins are dumped, cooled and packed.

What can one expect in the future? Increases are probable in the number and diversity of retail specialty shops such as the franchised cookie bakeries and the fresh-roll bakeries now often seen in shopping centers. Multiproduct bakeries in supermarkets will continue to increase in number and size and in the variety of products. More restaurants will make their own pizza crusts, pita bread, pies, biscuits and tortillas.

To service these outlets manufacturers will produce more partially prepared bakery products such as dry mixes, refrigerated dough and frozen dough. They will refine their formulas, processes and methods of distribution with the objective of making what the consumer buys closer to the ideal of fresh, homemade baked goods.



PROPORTIONS OF MARKET for main kinds of baked goods are projected for 1984 on the basis of data assembled by *Bakery Production and Marketing*. Chief changes from 1981 are in white bread and rolls (down from 33 percent) and in sweet goods (up from 15 percent).

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SCIENCE/SCOPE

A redesigned equipment rack for the F/A-18 strike fighter's radar will allow the U.S. Navy and Marine Corps to save millions of dollars on new radars over the life of the program. The original rack consisted of many honeycombed sections bonded together. The Value-Engineered rack is a single piece fabricated by an automatic, numerically controlled machine center. The changes stem from technology that was not available at the time the original contract was signed. Hughes Aircraft Company will share some of the savings with the Navy through the Department of Defense Value Engineering program. This program is designed to encourage employees to look at the functions of a product and develop alternatives that cost less, perform better, and are more reliable.

The first U.S. facility for making gallium arsenide solar cells on a standard production line is now under construction at Spectrolab, Inc., a Hughes subsidiary. Gallium arsenide cells, which are now being made on a prototype line at Hughes Research Laboratories, will help satellites and spacecraft become more efficient in converting sunlight into electricity. Compared to conventional silicon cells, gallium arsenide cells generate up to 30% more power and operate at much higher temperatures. The first cells are expected to come off the production line in mid-1985. Full-scale mass production at rates to 15,000 cells per year is scheduled for January 1986.

Two high-power communications satellites have been ordered by Advanced Business Communications Inc. (ABCI). The satellites are widebody HS 393 models, now being developed at Hughes for launch from the space shuttle. The drum-shaped spacecraft are designed to fill the width of the space shuttle's cargo bay in order to take advantage of launch pricing policies. Each satellite will operate over the Ku band and carry 16 channels designed for business communications, video distribution, and teleconferencing. The spacecraft's higher power will let users receive signals through small, low-cost earth terminals. Hughes Communications Inc., a Hughes subsidiary, will provide launch, tracking, telemetry, and control services for the Ku band system. Hughes Communications Galaxy Inc. will market 16 transponders.

A microwave/millimeter-wave radar cross-section measurement system, designed to take automated measurements on full-size or scale-model targets, joins the solid-state millimeter-wave product line at Hughes. The new Model 42260H system, originally built for Boeing Military Airplane Co., is the latest in coherent short-pulse instrumentation measurement systems. It is suitable for indoor and outdoor ranges as close as 50 feet and as far away as beyond 4,000 feet. The system uses a modular design concept that accommodates up to six separate radio-frequency transceivers.

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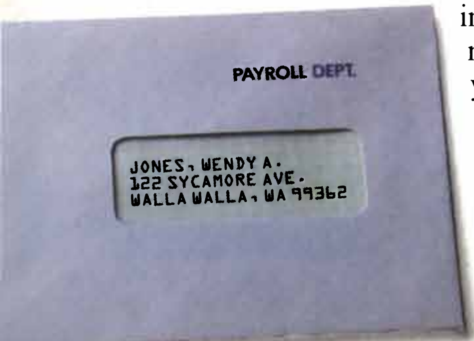

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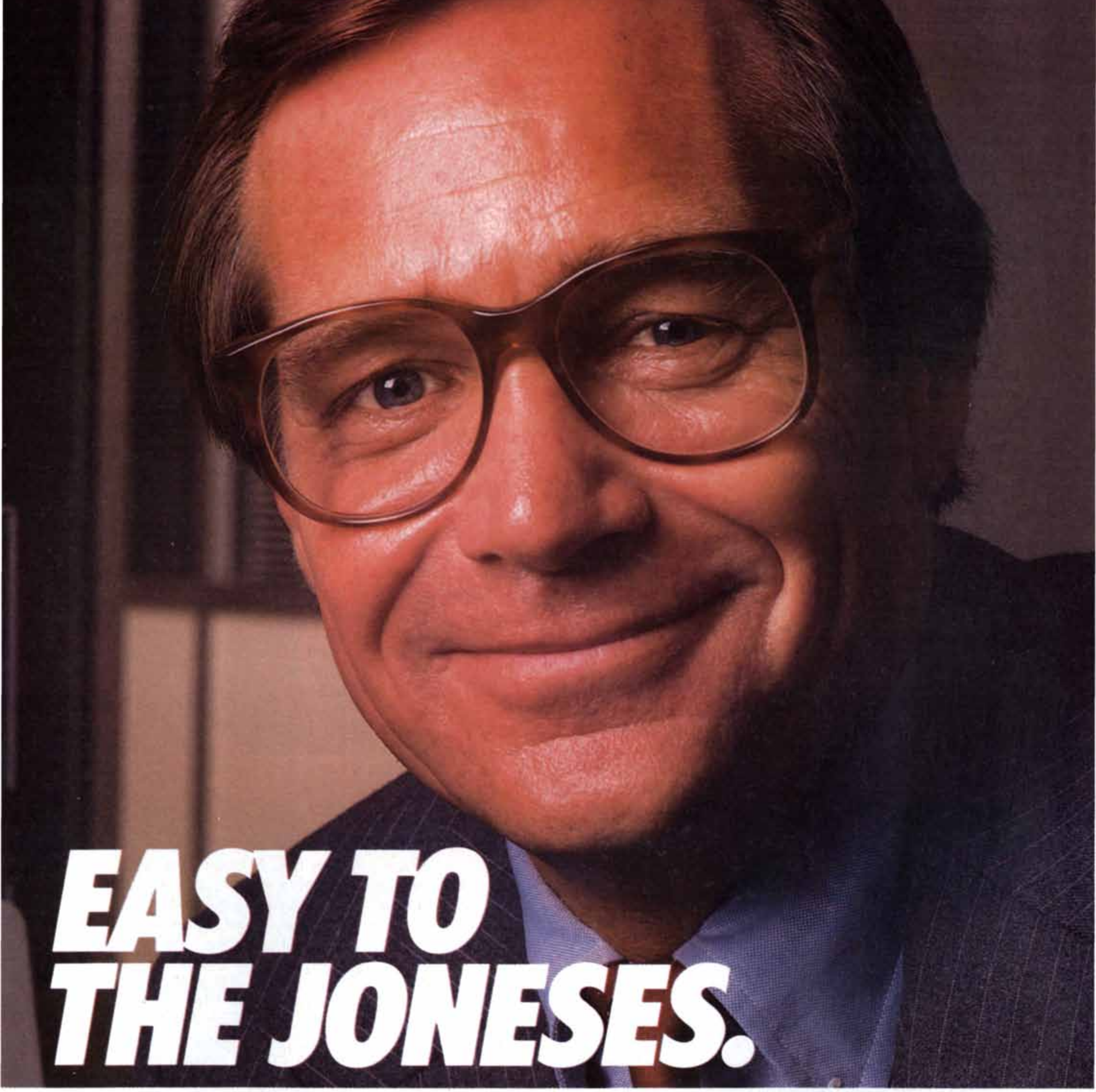

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The Canopy of the Tropical Rain Forest

Largely unexplored, it is home to one of the most diverse plant and animal communities on the earth. A new way of reaching the canopy allows close observation of its ecology

by Donald R. Perry

"Yet another continent of life remains to be discovered, not upon earth but one to two hundred feet above it," wrote the British naturalist William Beebe at the turn of the century. He was speaking of the canopy of the tropical rain forest, a treetop region where abundant light and moisture foster, by one estimate, 40 percent of this planet's species of plants and animals. Some 80 years later Beebe's words still hold true. The canopy is difficult to observe from the ground because of obscuring vegetation; it is hard to reach because tropical trees often rise 25 meters or more from the forest floor without branching and host an abundance of snakes, scorpions and noxious insects.

In the lowland rain forest of Costa Rica I have devised a means of circumventing these barriers, enabling my colleagues and me to observe the ecology of a tropical canopy in unprecedented detail. We have suspended a rope web 30 meters above the ground, between three tall trees that tower over the surrounding rain forest. By means of clamps and pulleys an investigator can scale a rock-climbing rope to reach the web, traverse it and descend from it into the canopy at any point.

Our approach owes much to similar efforts by earlier investigators. In his book *A Naturalist in the Guiana Forest* R. W. G. Hingston describes one such attempt. On a 1929 expedition to South America he and his colleagues from the University of Oxford used a naval line-throwing gun to fire a climbing rope into the treetops. The line, however, became hopelessly entangled among lianas, the woody vines that drape the rain-forest canopy. The naturalists then hired native climbers to scale the trees directly and build platforms, but the scientific results were disappointing. Hingston concluded: "If the upper regions of the forest are to be explored systematically, the work will have to be done with more elaborate apparatus."

In the following decades naturalists continued to set up fixed observation posts in the upper stories of rain forests around the world, in the form of either towers or platforms, accessible by means of rope ladders, or belts and foot spikes such as those used to climb telephone poles. Among the most notable was a 40-meter-high treetop base constructed in 1960 by H. Elliott McClure, working with the Walter Reed Army Institute of Research in the rain forest near Kuala Lumpur. The effort to observe canopy communities from fixed vantages, however, was a frustrating exercise. An altogether different set of species, for example, might inhabit an adjacent tree, in view but beyond the reach of a platform-bound observer.

During the summer of 1974 I traveled to Finca la Selva, a rain-forest reserve in Costa Rica owned and operated by the Organization for Tropical Studies of the University of Costa Rica, to test a technique that promised greater mobility. The necessary equipment was simple and easily portable. To climb a tree that seemed to offer an interesting vantage, I used a crossbow to shoot a weighted arrow over a high branch; a fishing line trailed from the arrow. I then tied a braided nylon cord to the line and threaded it over the limb, and finally replaced the cord with a rock-climbing rope. I scaled the rope using two jumars, Swiss-made clamps that grip a rope tightly when they are under tension, then release when they are relieved of weight. They were introduced to treetop research by William C. Denison of Oregon State University in his studies of Temperate Zone forests [see "Life in Tall Trees," by William C. Denison; SCIENTIFIC AMERICAN, June, 1973]. I fastened stirrups to the lower ascender and a harness to the upper one; I climbed by alternately resting my weight in the stirrups while raising the harness and sitting back in the harness while raising the stirrups. It took about 15 minutes to climb the 30 meters or so of rope to the canopy, where the harness served as a comfortable seat, the height of which could be continuously varied as observation demanded.

The method has proved useful, but it requires a sturdy limb from which to suspend the rope. As tall as tropical trees are, it is surprising how few of them have branches sound enough to support a climber. In the intense competition for space in the sunny canopy many species have traded strength for rapid growth. The balsa tree, well known for the fragility of its wood, is one example; other weak-limbed trees at Finca la Selva include legumes, kapok trees, wild nutmeg and the dominant tree of that forest, *Pentaclethra macroloba,* commonly known as *gavilán.* More than half of the tall trees at the Finca la Selva reserve are off limits to my rope-climbing method.

A solution suggested itself in 1978 as I was studying the role of herbivorous bats in dispersing the seeds of the monkey-pot tree, *Lecythis ampla.* The monkey pot is noted for its strong wood as well as for its edible nuts, and so I built a platform 34 meters up in the crown of a monkey pot at Finca la Selva. Some 100 meters away in two directions two almendros, *Dipteryx panamensis,* towered above the surrounding forest. This species of legume has wood so hard that it resists nails. It seemed possible that together with the monkey-pot tree the two almendros might serve as sturdy support towers for a system of ropes allowing unrestricted movement across the intervening canopy of weak trees.

In March, 1979, I returned to Finca la Selva with John Williams, an engineer. Using double loops of 3,210-kilogram test sailboat rope, we fastened pulleys to limbs of the three support trees, then threaded 350 meters of the rope through the pulleys and joined the ends to make a continuous, triangular loop. We com-

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CLIMBER IN THE TREETOPS hovers 40 meters above the ground. Below are the crowns of other trees in the tropical rain forest at Finca la Selva in Costa Rica. The system of ropes and pulleys has made possible extensive exploration of the canopy, an ecosystem that is home to distinctive varieties of plants. Several are visible on the tree limbs, including a woody vine, or liana (*left*), and two bromeliads (*right*).

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EPIPHYTES burden the limb of a kapok tree. The tree itself is temporarily leafless; epiphytes account for all its verdure. Nonparasitic and entirely independent of the ground, epiphytes include vascular plants of 65 families, mosses, lichens and algae. Dispersed by the wind and animals, their seeds and spores germinate on any hospitable trunk or limb surface in the canopy.

LIANA, *Gnetum leyboldii*, festoons a tree. Liana stems can reach a diameter of 23 centimeters; the author estimated that the weight of one liana exceeded 2,800 pounds. In the rain forest, where wood is often fragile and roots are shallow, such a burden can break or topple a tree.

pleted the web by rigging a second rope between the platform and an attachment point on the far side of the loop of perimeter rope. From the platform we could rotate the perimeter rope through the pulleys, sweeping the internal rope across the area of forest enclosed by the loop until the rope was positioned directly above the stretch of canopy we wanted to observe.

The investigator could then coast out from the platform along the internal rope by means of a pulley attached to it, connect a vertical descent rope to the web and, using the jumars, descend inchworm fashion into the canopy. For subsequent observations the temporary vertical rope could also be climbed from the ground. The combination of the web and the descent ropes gave us unrestricted movement through a volume of forest an acre in area and 30 meters in depth, opening great biological wealth to observation.

The upper story of the forest, which we investigated, incorporates two-thirds of its volume. This region can be divided arbitrarily into a lower canopy, extending from 10 to 25 meters above the ground, an upper canopy, reaching a height of 35 meters, and an emergent zone that encompasses the tops of the tallest trees, which commonly grow to heights of more than 50 meters. The canopy is well lighted, in contrast to the forest understory, which because of thick vegetation above receives only about 1 percent of the sunlight that falls on the treetops. In the canopy all but the smallest of the rain-forest trees put forth their leaves, flowers and fruit. It also contains many plants that exist entirely within its compass, forming vegetative communities that in number of species and complexity of interactions surpass any others on the earth.

Among the most conspicuous features of vegetation in the canopy are epiphytes. About 28,000 species in 65 families are known worldwide, 15,500 of them in Central and South America; they include species of orchids, bromeliads and arboreal cacti as well as lower plants such as lichens, mosses and ferns. Thousands more epiphyte varieties remain unidentified.

The Greek meaning of the word epiphyte is "plant that grows on a plant," and they carpet tree trunks and branches. Epiphytes sprout from seeds borne by the wind or deposited by animals, their roots holding tight to the interstices of the bark. Yet they are nonparasitic; their hosts provide them with nothing more than a favorable position in the brightly lighted canopy. For nourishment epiphytes depend on soil particles and dissolved minerals carried in rainwater, and on aerial deposits of humus. The deposits are the product of organic debris, such as dead leaves from

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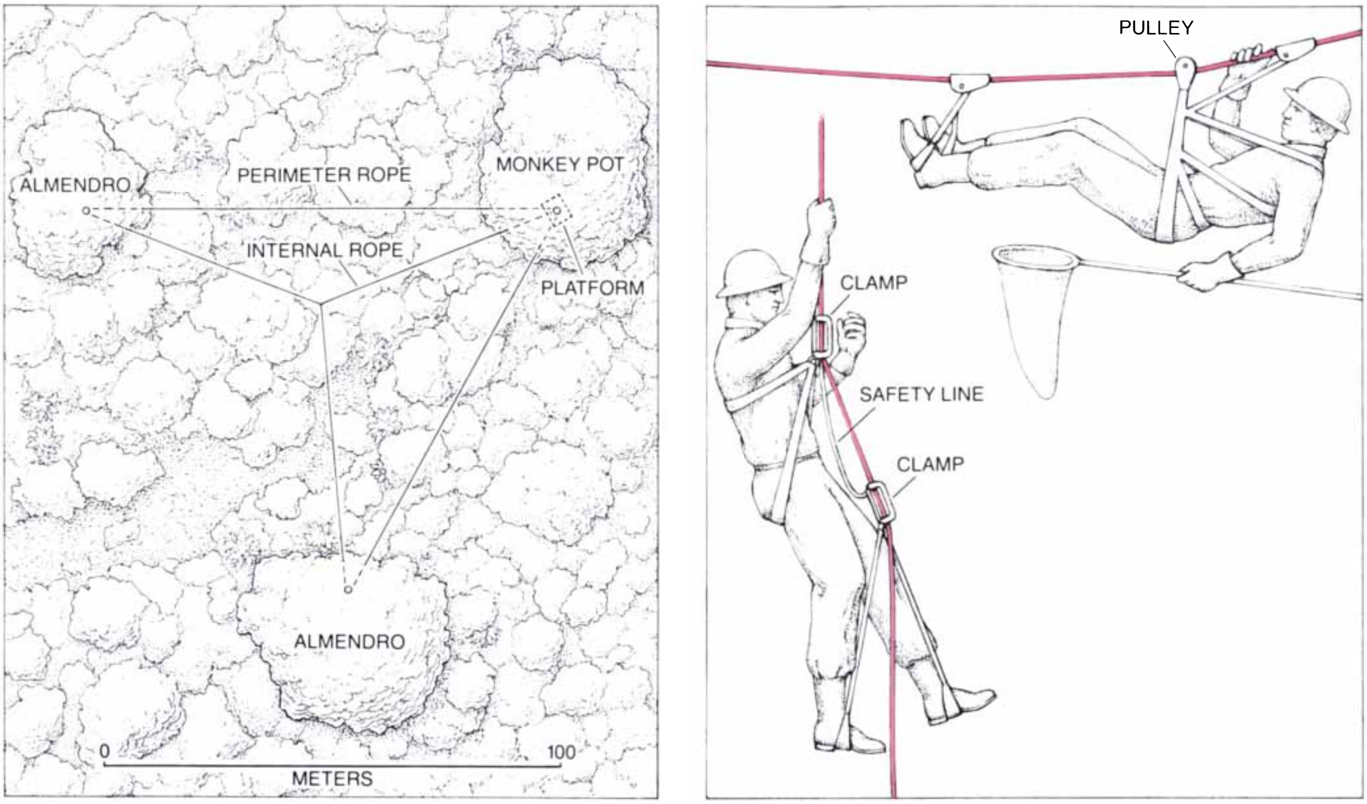

METHOD OF EXPLORING THE CANOPY enables an investigator to move freely through the treetops. An overview of the study plot at Finca la Selva shows the tall trees that support a triangular span of rope above an acre of rain forest. Pulleys at the attachment points allow the span to be rotated, shifting the position of an internal rope. By means of a pulley attached to a parachute harness a worker can ride the internal or perimeter ropes to a study site in the canopy; clamps attached to the harness and to foot stirrups add support and serve as brakes. To descend from the web into the canopy or to reach the web from the ground the investigator uses the two clamps to move stepwise up or down a vertical rope, alternately locking the stirrups while loosening and moving the harness, then reversing the process.

epiphytes and other plants, that lodges among epiphyte roots.

Water is directly available to epiphytes only when it rains; other plants have continuous access to moisture trapped in the soil. As a result many epiphytes have developed features that collect and retain rainwater. Some, including orchids and arboreal cacti, have succulent stems and leaves, with spongy tissues that store water, as well as waxy leaf coatings that reduce the loss of moisture through transpiration. Many orchids have bulbous stem bases; other families of epiphytes impound water in tanks formed by tight rosettes of leaves or in cups shaped by the junctions of broadened petioles and stems. Some species possess absorbent, spongelike root masses that soak up and hold water. Bromeliads, a Central and South American family, can hold reserves of several gallons within their cisternlike bases, forming "arboreal swamps" that attract insects of many species, earthworms, spiders, sow bugs, scorpions, tree frogs and insect-eating birds.

In the favorable conditions at Finca la Selva the density of epiphyte growth can be considerable. The annual rainfall exceeds 120 inches, the humidity rarely falls below 80 percent and the dry season is not severe. The grooved bark of the monkey-pot tree that supported our platform aids epiphyte attachment, and its crevices retain rainwater within reach of the roots of epiphytes. On this favorable substrate Michael H. Grayum of the University of Massachusetts at Amherst and I tagged close to 50 species of epiphytes, the roots and stems forming mats up to 25 centimeters thick; perhaps 50 more remain to be identified. Such thick growths of epiphytes, sodden with stored rainwater, can weigh several thousand pounds per tree, severely straining fragile rain-forest limbs.

When nutrients locked in trunks and limbs and therefore largely unavailable are excluded from a calculation of forest biomass, epiphytes represent a substantial portion of the total. In the mountainside rain forests, known as cloud forests, conditions of almost constant mist and drizzle are even more conducive to epiphyte growth than the environment at Finca la Selva. In the cloud-forest reserve at Monteverde in Costa Rica, Nalini Nadkarni of the University of Washington found that epiphytes account for 40 percent of the nutrients stored in foliage.

Until recently it was thought those nutrients could be recycled into other plants only when dead epiphyte material fell to the forest floor. It now appears that certain nutrient cycles may be played out entirely within the treetops. In the cloud forest at Monteverde, Nadkarni used my rope-climbing method to reach the treetops. She found that 12 species of trees develop adventitious roots that grow from high limbs directly into encrusting mats of epiphytes. The roots apparently absorb nutrients from the humus that collects in the epiphyte root mats.

Many species of epiphytes are most numerous in the lower canopy, where they escape the drying effect of direct sunlight. Higher in the tree crowns, where humidity varies most sharply over the course of the day, drought-resistant epiphytes and another group of canopy plants, the hemiepiphytes, are commoner. Hemiepiphytes begin life as epiphytes, sprouting from seeds lodged in bark crevices and in branch crotches. Later they send aerial roots to the ground, where they gain a reliable supply of moisture. The supply of nutrients they take from the soil enables hemiepiphytes to become much more massive than epiphytes, and the combined weight of the foliage and the cascade of roots of a single plant is sometimes enough to break the limb that supports the hemiepiphyte.

Some hemiepiphytes of the genera *Clusia* and *Ficus,* among them the strangling figs, inflict another kind of damage

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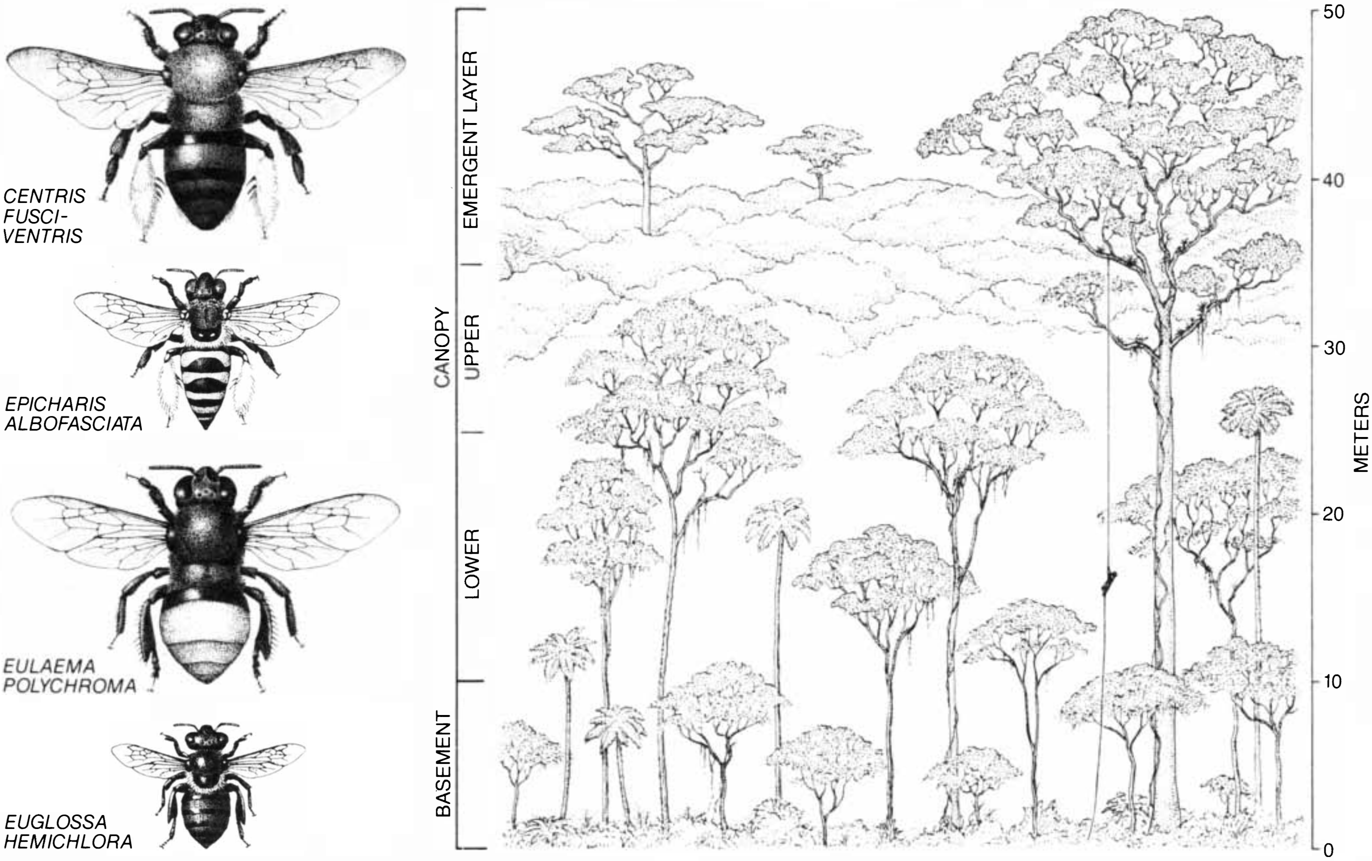
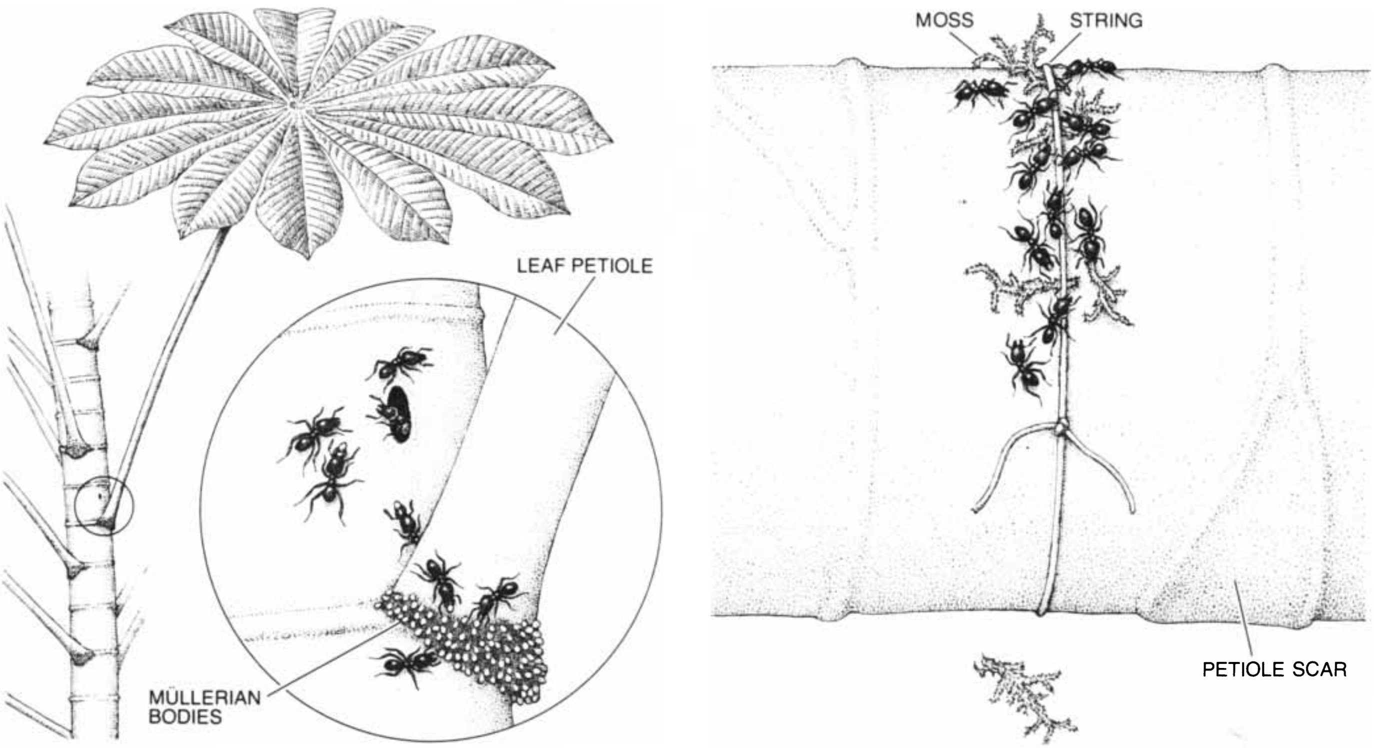


LAYERING OF ENVIRONMENTS in the rain forest fosters species diversity. In the understory, or basement, light is dim, humidity rarely drops below 95 percent and temperature varies little. In the canopy sunlight is abundant and humidity and temperature fluctuate. Each level of the forest has its own array of plants and animals, including pollinating insects. The two bee species at the top left were found only at the upper margin of the canopy, the lower two species only in the forest below. Such stratification may further increase the diversity of the forest by impeding pollen exchange, isolating plant groups genetically and leading to the development of new species.



SYMBIOTIC INTERACTION OF ANTS AND TREES benefits the ant genus *Azteca* and the tree genus *Cecropia*. Within a hairy cushion at the base of each leaf petiole the trees produce white nodules about a millimeter long that are rich in glycogen, a form of starch usually found in animal tissues. The ants feed on the nodules, known as Müllerian bodies; they also benefit from the structure of *Cecropia* stems, which are hollow and easy for the ants to penetrate and use as an enclosed nesting space. The ants in turn protect their host by preventing epiphytes from taking root on the trees' fragile limbs, which might break under the load. When the author tied moss and other small epiphytes to *Cecropia* limbs, the ants swarmed onto the plants (*right*), tearing off small bits of plant matter to remove the epiphytes.

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on their host: their roots snake down the trunk and anastomose, or fuse, forming a shell within which the host tree dies and rots away. By that time the parasite's roots have strengthened enough to support it as a full-fledged tree, occupying the space in the canopy left by its former host. Conventional wisdom about stranglers contends that they kill their victims by choking them. More recently investigators have suggested they compete successfully against host trees for light, spreading their foliage so luxuriantly that it shades the trees to death.

A final group of arboreal plants consists of the hanging vines, an ad hoc division that includes true vines such as the philodendron, whose stems contain little woody material, and the lianas. Hanging vines germinate on the forest floor and grow upward. Like hemiepiphytes and dense epiphyte mats, their weight sometimes snaps limbs and perhaps pulls down entire trees, opening gaps in the canopy.

Such gaps play an important part in forest growth. Many tree species can germinate only where light is abundant; they persist only because of occasional breaks in the canopy. By creating openings, arboreal plants are indirect agents in maintaining the diversity of the rain-forest flora.

The ecological factors leading to the distribution of flora in the canopy and the consequences of distribution for the plants' breeding strategies were major focuses of my research. It is a significant fact that for all the luxuriance of the canopy, no single species is present in a dense and uniform growth throughout the forest. Among the trees whose foliage defines the canopy, individuals of most species are widely scattered. Epiphytes grow in patches on individual trees and in the forest as a whole.

A number of factors are known to influence the distribution of epiphytes. Older and thicker limbs often bear heavier epiphyte burdens because they are more likely to have been colonized. A tree with rough bark offers superior purchase to the grasping roots and tendrils of epiphytes, and individual epiphyte species tend to cluster on shady or sunnier limbs according to adaptation. Epiphytes also are likely to be commoner on branches that lie under routes regularly followed through the treetops by birds, bats, monkeys, squirrels and other mammals that carry epiphyte seeds in coats, claws or beaks or release them in their excrement. For the same reason, epiphytes often grow profusely on trees that bear attractive fruit and therefore are frequently visited by fruit-eating animals. Epiphytes are less abundant directly along the routes that arboreal mammals follow on limbs and trunks; these arboreal highways are sparsely vegetated just as cowpaths are.

Because thick mats of epiphytes can be the downfall of a fragile tree, many tree species have evolved active defenses against epiphyte colonization. One strategy is the frequent sloughing of bark, in which young epiphytes are shed with the cast-off bark layers. It has been suggested that the alkaloids present in the bark of many rain-forest trees represent another defense against the attachment of epiphytes or vines. Alkaloids may act as allelopathic chemicals, plant-synthesized substances that inhibit the growth of other plants.

Where conditions are favorable, epiphyte colonization proceeds with startling speed. I have often returned to my study site at Finca la Selva to find that ropes and platforms abandoned a few months before have sprouted a layer of young epiphytes, much as boat hulls accumulate barnacles. Yet some trees whose bark neither sloughs frequently nor contains allelopathic chemicals are free of epiphytes. How do such trees gain immunity?

My research supports the view, advanced by Daniel H. Janzen of the University of Pennsylvania, that the answer lies in mutualistic relations between the trees and certain species of canopy ants. Janzen speculated that the *Azteca* ants found in trees of the genus *Cecropia* scour germinating epiphytes from the limbs, thereby protecting the trees, the limbs of which are particularly fragile, from becoming overburdened with growth. The aggressive ants also swarm to attack other insects and mammals, many of them herbivores that might damage the tree. The ants may be said to have an interest in preserving their arboreal home; certainly *Cecropia* trees have evolved features that benefit the ants. At the base of the leaf petioles the trees produce starch-rich nodules on which the ants feed. The hollow, bamboolike stems of *Cecropia* shelter the ants as they nest and farm aphids.

Confirming the hypothesis has proved difficult; the aggressive behavior of *Azteca* ants has hampered efforts to observe their behavior. The rope web at Finca la Selva, however, made it possible to observe *Cecropia* limbs closely while remaining out of reach of the swarming ants. Using lengths of dental floss, I tied to several limbs small mats of epiphytes bearing plants of varying size. Immediately the ants swarmed onto the mats and began pulling loose small bits of material. They hauled the fragments away and dropped them off the limbs. The mat containing the smallest epiphytes—mosses and seedlings only a few millimeters high—was stripped away within a few days; larger epiphytes remained untouched. It appears that the ants do protect *Cecropia* from burdens of epiphytes, but they must do their prophylactic work while the epiphytes are small.

Other rain-forest trees that harbor ants also seem to remain free of epiphytes. Ants may play a role much larger than has been thought in the forest-wide distribution of epiphytes.

Another aspect of the distribution of life in the forest's upper story is the wide spacing of trees of the same species. It is thought to result from two factors. The first is the sheer number of species that coexist in the forest. The rain forest harbors a vast accumulation of life forms that reflects the 65 million years or more during which the forest has existed as an undisturbed ecosystem, its inhabitants continually diversifying. More than 200 species of trees have been identified in a single five-acre plot in the lowland forest of the Malay Peninsula. The other factor thought to account for the scattering is the pressure of herbivores. The concentration of insects, birds and mammals eager to devour seeds and seedlings is greatest near the parent tree; the farther from the parent tree a seed takes root the greater its chance of survival is. Distance is advantageous to seedlings, but it hinders the cross-pollination of mature trees. The canopy is the site of flowering and pollination for the most important species, and observations made there show how the trees overcome their reproductive difficulties.

Because of the distances between individuals of a given species and because early observations revealed few animals capable of acting as long-distance pollinators, many workers speculated that tropical trees generally are self-pollinators, capable of producing seeds with their own pollen. But many tropical species are dioecious: their sexes are separate, and so self-pollination is impossible. Moreover, recent observations at canopy level and below have shown an abundance of long-distance foragers, including butterflies, moths, birds, bats and various species of bees, capable of carrying pollen between the dispersed members of a single species. The presence of a community of pollinators would seem to preclude selection for self-pollination.

Many of the canopy pollinators are species never seen on the ground; both the butterflies and the bees of the rain forest, like its birds, reptiles and mammals, are stratified into canopy and understory communities. The fact that upper-level pollinators rarely descend to the understory may explain why they went virtually undetected in the past; it also has important evolutionary implications. The existence of separate pollinator communities means there is little pollen exchange between the different levels of the forest. The effect on the transfer of genetic material is much the same as that of a geographic barrier, and like a mountain range or a strait the

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GREENBONED TREE FROG clings to an orchid; the plant grows epiphytically 34 meters above the ground. The permanent reserves of rainwater stored in some epiphytes enable tree frogs to hatch, pass their larval stages and lay their eggs without descending from the treetops.

CENTIPEDE patrols a tree limb 33 meters up. This specimen is 15 centimeters long and capable of inflicting painful stings with its two poisoned claws. The presence of such noxious animals on trunks and limbs in the rain forest hampered earlier efforts to explore the canopy.

stratification of pollinators may foster speciation. A single species of plant with members in both the canopy and the understory might well differentiate into two new varieties because of the genetic isolation of the two groups. The stratification of pollinators thus could account for much of the diversity of the tropical rain forest.

Investigators who have explored the reproductive strategies of rain-forest flora have confirmed that cross-pollination is the rule among trees. (Epiphytes, which receive few visits from pollinating insects, probably are self-pollinators.) Kamaljit S. Bawa of the University of Massachusetts at Boston found that 79 percent of the trees in a Costa Rican dry forest depended on cross-pollination to produce seeds; Bawa, James H. Beach of the University of Massachusetts at Amherst and I extended the study to the moist forest at Finca la Selva with the same results.

In exchanging pollen over great distances, the trees are aided by certain kinds of foraging behavior among the bee species of the canopy. One foraging style was first noted by Janzen, who called it "traplining"; it is most often seen in the lower reaches of the canopy. Certain species of bees memorize and repeatedly follow a route, often several kilometers in length, that takes them to a number of flowers yielding large quantities of pollen. This strategy enables them to take advantage of trees that produce only a few highly rewarding blossoms. The large number of trees along the bees' route often include several of the same species, making the bees likely agents of pollen transfer. Traplining contrasts with opportunistic foraging, in which bees are attracted to trees bearing many blossoms and spend a large part of their foraging day at a single tree.

At Finca la Selva I noted another foraging style that seems to aid cross-pollination: group foraging. Up to 11 bee species, and possibly more, routinely fly from tree to tree in groups of tens or hundreds of individuals. The mixed character of the groups may make their foraging more efficient: one of the species may be particularly good at finding flowers, another at operating the floral mechanisms that expose the pollen, still another at driving away competing foragers. The heterogeneity also seems to promote frequent movement and consequent pollen transfer.

The trees themselves may in some instances have evolved strategies to encourage the movement of pollinators and promote cross-pollination. Andrew Starrett of California State University at Northridge and I have found that almendros (one of the species that support the web) display a cross-pollination strategy. Unlike many other tropical trees in which every individual in

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an area blooms more or less simultaneously, almendros flower slightly out of phase with one another. The trees' blooming period stretches over two to three months, during which time each tree is in flower for several weeks. The result of the asynchrony is a forced movement of foraging bees from tree to tree, fostering the transfer of pollen.

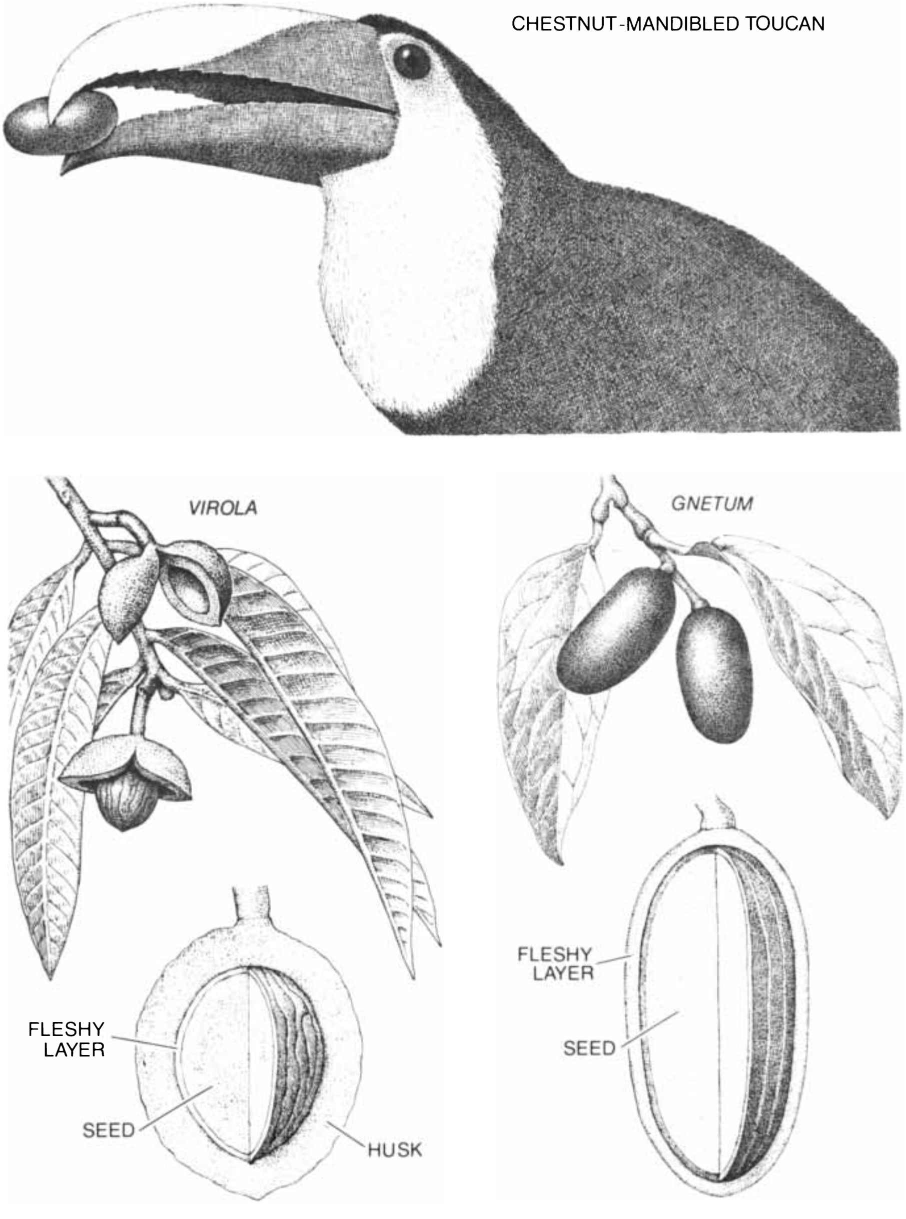
Such blooming strategies may well be common among the trees of the canopy. Gordon W. Frankie and William A. Haber of the University of California at Berkeley think that even species whose flowering appears highly synchronous show enough asynchrony to encourage the movement of pollinators. So far no one has ventured to explain how such asynchrony might be regulated. It is easy to imagine how trees, responding to an environmental cue, might flower simultaneously or how a lack of coordination among individuals might result in a completely random pattern of blooming. It is harder to imagine how a species achieves just the right degree of asynchrony to foster cross-fertilization.

The tropical rain forest is largely made up of angiosperms, the division of plants distinguished by flowers and by seeds that are enclosed in the ovary of the parent plant, which in many species develops into a fleshy fruit. Gymnosperms, which in the form of conifers are the dominant tree variety of many temperate and arctic forests, are rare in the rain forest. Yet until the late Cretaceous, about 65 million years ago, the Tropics were dominated by gymnosperms: cycads, gingkos and conifers. Charles Darwin termed their sudden eclipse by angiosperms an "abominable mystery." What accounts for the decline of gymnosperms in tropical forests? What selective advantages do the distinctive features of angiosperms confer? Observations made in the canopy suggest an answer.

In the present diverse forest of angiosperms, with its wide spacing between individuals of the same species, the reliance of gymnosperms on the wind to transfer pollen would place them at a clear disadvantage. That method is effective only in more homogeneous forests, where distances between conspecific individuals are small. But Philip J. Regal of the University of Minnesota believes their inefficient pollination method is not enough to explain the decline of the gymnosperms. Before windborne pollination became a hindrance, angiosperms would have had to become numerous enough to isolate individual gymnosperms. Other factors, Regal speculates, must have given angiosperms their original edge.

Regal suggests that the crucial development was the evolution of fruit-eating birds, capable of carrying seeds to great distances, an event that took place in the late Cretaceous. The presence of birds enabled the fruits in which angiosperm seeds are enclosed to show their full evolutionary value. In the tropical forest the ability of a tree to disperse its seeds is a selective advantage for two reasons: it foils the herbivores that cluster near the parent tree and destroy seeds and seedlings, and it enables the species to spread its seeds to well-lighted gaps in the canopy. In the case of a gymnosperm, whose seeds all fall near the parent tree, the chance of one of them reaching the favorable environment of a forest gap is much less than it is in the case of an angiosperm, whose seeds are scattered over a broad area of forest.

It is thus possible to imagine how the combination of the fruit and the flower enabled angiosperms to gain a toehold in the gymnosperm forest. Long-range seed dispersal by excretion or regurgitation from the digestive tract of birds, from which seeds emerge undamaged, gave rise to a population of isolated individuals. The flower, by enticing long-distance foragers to transfer pollen among those scattered pioneers, ensured their reproductive success. The angiosperms' superiority in eluding seed pred-



EVOLUTIONARY MIMICRY is suggested by a comparison of the liana *Gnetum leyboldii*, a species of gymnosperm, with an angiosperm of the genus *Virola*. Like the true fruit of *Virola*, and unlike most gymnosperm seeds, the seeds of *Gnetum* are sheathed in a layer of sweet, juicy flesh. This pseudofruit attracts a fruit-eating bird, the chestnut-mandibled toucan, which also feeds on *Virola* fruit. In both cases the bird removes the flesh within its muscular crop and regurgitates the seed, in the process often carrying it far from the parent tree. Seed dispersal increases the reproductive success of tropical trees. The leaves of *Gnetum* display a pattern of intersecting venation, also a common characteristic of flowering plants and rare in gymnosperms. It may be that *Gnetum* was able to survive in the tropical forest, which has been dominated by flowering plants for more than 60 million years, only by imitating features of angiosperms.

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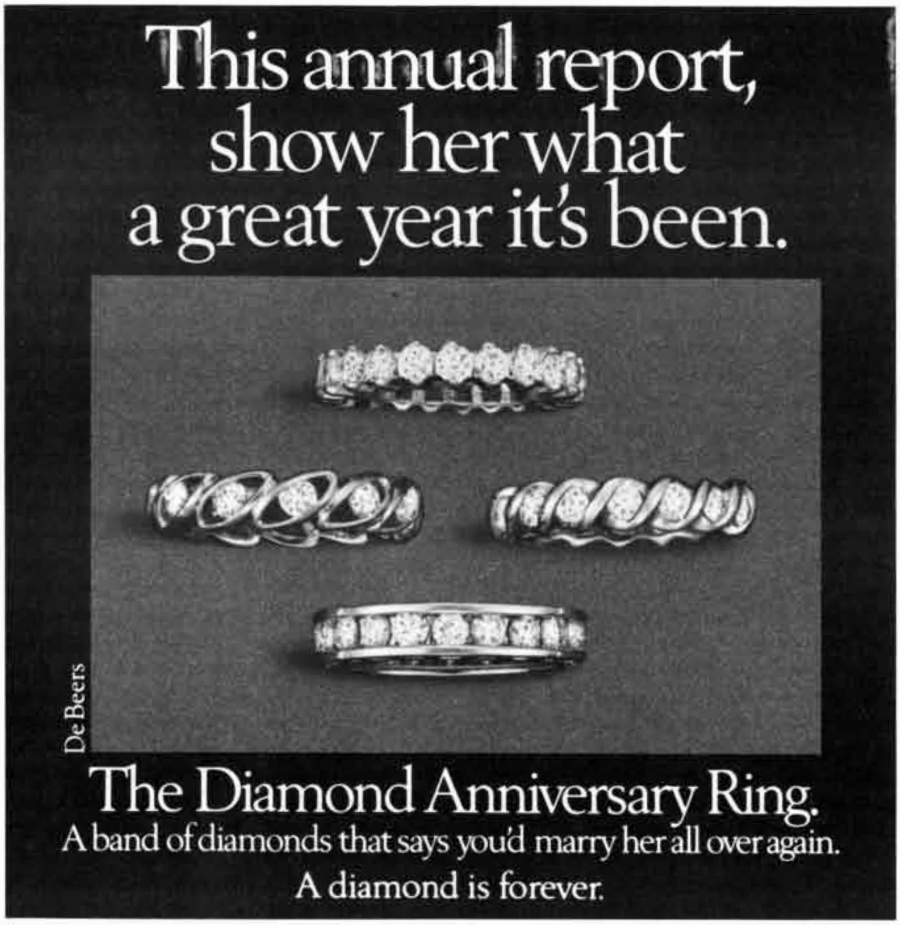

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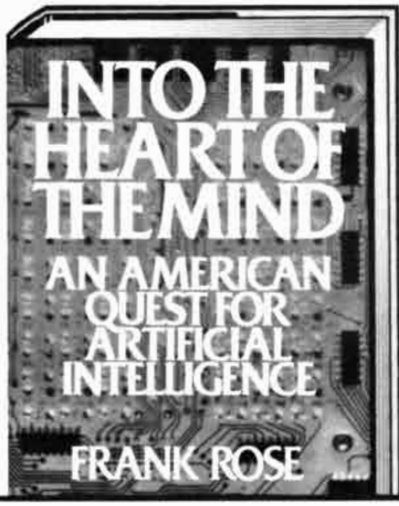

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ators and colonizing canopy openings allowed their numbers to increase. The gymnosperms' wind-pollination system soon became unreliable and their fate in the evolutionary game was sealed.

The few gymnosperms that remain in the lowland rain forest of Costa Rica yield evidence supporting Regal's theory. They seem to have survived by mimicking angiosperm features in order to benefit from the same synergism of long-distance seed dispersal and animal-mediated pollination. *Gnetum leyboldii,* one of the lianas that drape the canopy at Finca la Selva, is a species of gymnosperm. Most gymnosperms, true to the Greek sense of their name, produce naked seeds. Observations I made within the crown of a 52-meter-tall legume, however, show that *Gnetum*'s seeds function as what might be called an ecological fruit. Its seeds are enclosed in a fleshy layer about two millimeters thick that contains a sweet juice. I found that the chestnut-mandibled toucan feeds on *Gnetum* seeds in the same way as it does on angiosperm fruit: by devouring the fleshy seed whole and regurgitating the kernel, often far from the parent plant. Because *Gnetum* survives as a population of widely spaced individuals in which the sexes of the plants are separate, it is likely that it imitates angiosperms in a second crucial way: by coopting insects to carry its pollen. (It is not clear what enticements it offers to pollinators, since it produces nothing resembling a flower or nectar.) According to David and Debbie Clark of the Organization for Tropical Studies, the other gymnosperm surviving at Finca la Selva, a palmlike cycad of the genus *Zamia,* also seems to be dispersed and pollinated by animals.

It is ironical that just as the intricacies of the ecology of the tropical rain forest—and in particular of the canopy—are being revealed, the forest itself is vanishing. In *Conversion of Tropical Moist Forests,* published four years ago by the National Academy Press, specialists warned that little will remain of Central America's moist forests by the end of the decade. The global situation is only slightly less dire. Each year about 210,000 square kilometers of primary forest are cleared, and Paul W. Richards' prediction [see "The Tropical Rain Forest," by Paul W. Richards; SCIENTIFIC AMERICAN, December, 1973] that most tropical rain forests will have vanished by the year 2000 is proving to be correct. Since deforestation results largely from the need of growing Third World populations for farmland, pasture and firewood, a reversal of the trend seems unlikely.

With the disappearance of the rain forest the planet will lose many of its species and much of its genetic diversity.

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The National Research Council predicts that more than half of the species of plants and animals existing today will become extinct by the year 2100, and new knowledge about the diversity of the canopy suggests that the number may be even higher. The greatest wave of extinction since the late Cretaceous, driven by human need, seems to be approaching. It will take with it not only life forms of fascination and beauty but also many species as yet unidentified that might have proved boons to agriculture and medicine.

Important insights into the past of our planet and our species may also be at stake. It now appears that the canopy of the tropical forest may have been the setting of several epochal evolutionary events. They may include the development of flight in the precursors of birds and, in our treetop-dwelling primate forebears, the appearance of stereoscopic vision and a high degree of intelligence and physical coordination, traits valuable in the complex environment of the canopy. Stereoscopic vision may have encouraged the evolution of sociality: as the eyes moved together, field of view diminished and with it the ability of a solitary animal to detect predators. The chance to examine the environment that brought forth these biological innovations is slipping away year by year.

In order to hasten the study of the dwindling forest and realize at least some of its potential benefits to mankind more elaborate means of canopy exploration are needed. John Williams and I are developing a system called the Automated Web for Canopy Exploration (AWCE) that will make 20 acres of forest accessible from ground level to the tops of the tallest trees. Three stout trees will support a triangular loop of stainless-steel cable, traversed by a cable analogous to the internal rope of the original web. An investigator will travel in a suspended chair; he will control his position by actuating remote-controlled electric winches. Mounted in a hilltop control shed behind one of the support trees, the winches will rotate the perimeter cable and move the chair along the internal rope. Diesel generators will supply power to the facility. A site for the AWCE has been tentatively arranged: it will span a small valley near Braulio Carrillo National Park in Costa Rica.

The study of tropical rain forests is a matter of great urgency. Some research money has materialized through the Rolex Awards for Enterprise and a fellowship from the Institute of Current World Affairs but more funds are needed. Only a tick of the cosmic clock remains in which to study what are perhaps the most fascinating communities of life in the universe.

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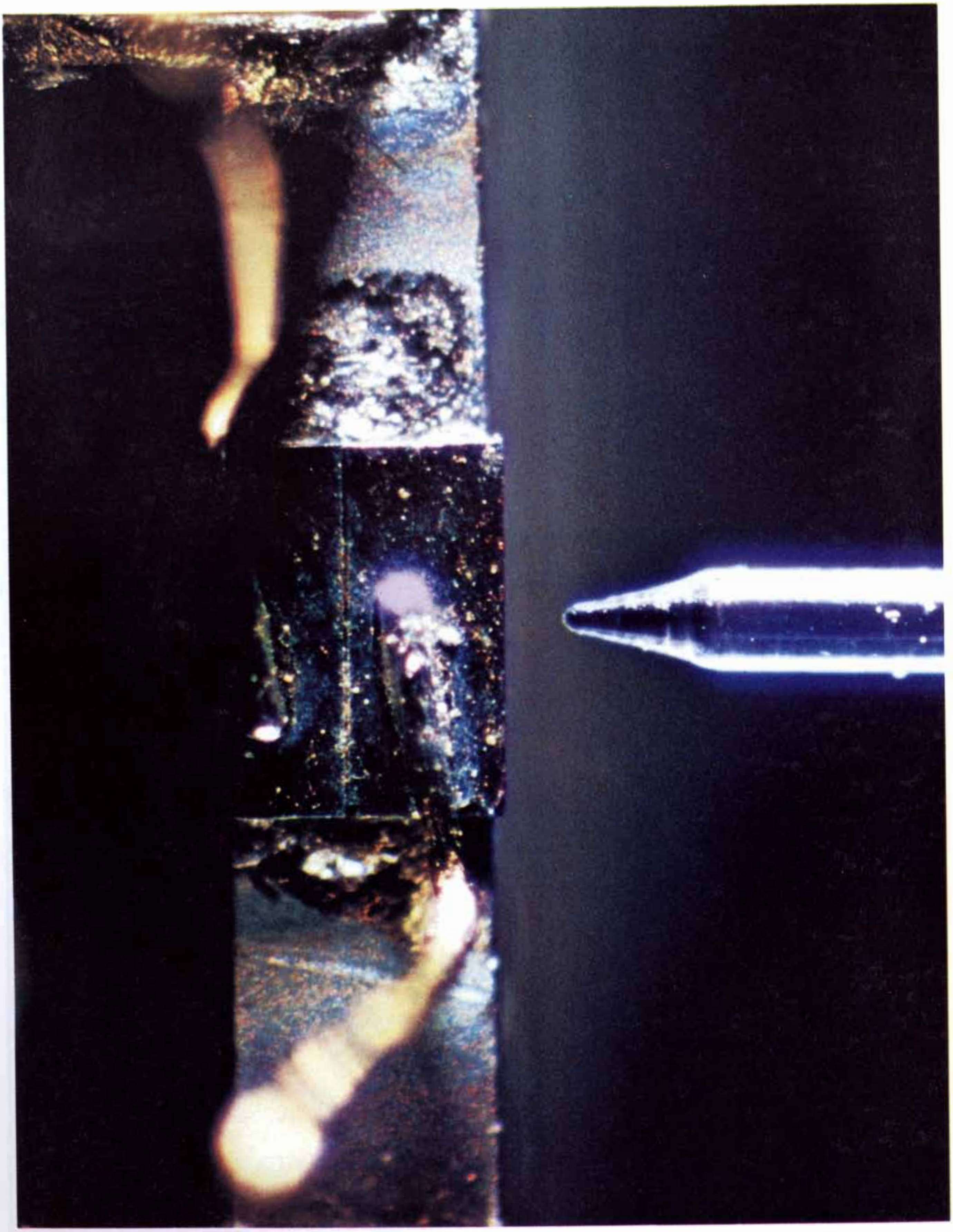

CLEAVED-COUPLED-CAVITY LASER developed by the author and his colleagues at AT&T Bell Laboratories was photographed under a microscope there. At the right is an optical fiber roughly 100 micrometers in diameter. Its end is lensed, that is, shaped to capture laser light. The tip of the fiber confronts the laser (the rectangular object at the left). The thin vertical line on its surface is a gap between two half lasers; the cleaved-coupled-cavity, or C^3, laser consists of two lasers with a space between them. The C^3 laser emits light at the invisible wavelength of 1.55 micrometers. At that wavelength a fiber made of silica glass is most nearly transparent to light.

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The C^3 Laser

The alignment of two conventional semiconductor lasers yields a beam of almost perfect purity that enables communication systems to send signals at rates as great as billions of bits, or binary digits, per second

by W. T. Tsang

When American Indians transmitted messages by means of smoke signals, they were exploiting concepts at the heart of modern optical communication. The intermittent puffs of smoke they released from a mountaintop were digital signals. Indeed, the signals were binary: they encoded information in the form of puffs of smoke or the absence of puffs of smoke. Light was the information carrier; air was the transmission medium; the human eye was the photodetector. The duplication of the signal at a second mountaintop for transmission to a third served as signal reamplification.

Today the digital signals are pulses of light produced by a semiconductor laser; the transmission medium is fiber optics. Indeed, it is the simultaneous achievement of reliable semiconductor lasers and low-loss optical fibers that will enable communication systems to carry the increases in information traffic expected for the balance of the century. The superiority of an optical system over an electrical system is measured by criteria including information-carrying capacity (four orders of magnitude greater for an optical system), energy loss in signal transmission (two orders of magnitude lower) and error rate (one order of magnitude lower). In the U.S. the American Telephone and Telegraph Company had some 20 million circuit miles of optical communication lines in operation or being installed at the end of last year. An undersea optical line between North America and Europe is planned for service beginning in 1988.

Nevertheless, no conventional semiconductor laser manufactured today is ideal for optical communication. For one thing the lasers in the system cannot exploit the full carrying capacity of the optical fibers. The available semiconductor lasers—contrary to the popular understanding—do not emit light at a single wavelength. They emit instead at a family of wavelengths, and different wavelengths are transmitted at different velocities in optical fibers. The result can be the blurring of a signal.

Here I shall describe a new laser that my colleagues and I have developed at AT&T Bell Laboratories. We call it the cleaved-coupled-cavity, or C^3 laser. In essence it is no more than the alignment of two conventional semiconductor lasers that can interact optically but are electrically independent. By means of this alignment the laser becomes capable of purifying its own output, so that what emerges is a beam of electromagnetic radiation at a single wavelength. In addition the laser becomes tunable, so that the output can be switched with great rapidity from one wavelength to another. The C^3 laser promises great improvements in the information-carrying capacity of optical communication systems. Moreover, the laser's tunability will open new applications beyond those in optical communication. For example, the laser can serve as an optical-electronic logic element processing information at a rate of gigabits (10^9 operations) per second.

Since the central technologies of optical communication—the laser, or signal producer, and the optical fiber, or signal transmission medium—are intimately related, an explanation of the usefulness of the C^3 laser begins not with the laser but with the fiber.

An optical fiber carries light along its length because light cannot escape from it. The light cannot escape because the refractive index of the core of the fiber is higher than the refractive index of the cladding that surrounds the core. (The refractive index is simply the ratio between the speed of light in a vacuum and its speed in a material.) Because of the gradient in refractive index between the core and the cladding, the light is trapped; it follows a zigzag path down the length of the fiber.

The number of possible paths (or modes of propagation) in any given fiber is determined by the diameter of the core, by the gradient in refractive index from the core to the cladding and by the wavelength of the light. When the diameter or the gradient is large, many paths are available; such fibers are multimode. When the diameter or the gradient is reduced, fewer modes can be accommodated. Eventually only a single, axial mode is allowed.

In a multimode fiber a pulse of monochromatic light travels by all the modes, that is, by all the possible zigzag paths. Each path has a different length, and so each mode entails a different transmission time. As a result the pulse broadens, or smears out, over time. Since information is encoded by patterns of pulses, the smearing limits the rate of information transmission (expressed as bits, or binary digits, per second) and also the spacing of repeaters (signal reamplifiers). The problem can be avoided by employing a single-mode fiber.

Now suppose a pulse of light includes a range of wavelengths. Light at different wavelengths travels at different velocities in a given material. Again, therefore, the pulse of light broadens—even in a single-mode fiber. The phenomenon is called chromatic dispersion. Remarkably, the pattern of dispersion reverses itself (in present-day fibers, which are based on silica) at a wavelength of about 1.33 micrometers in the infrared part of the electromagnetic spectrum. Wavelengths near 1.33 micrometers all travel at much the same speed. But for wavelengths shorter than 1.33 micrometers the relatively "blue" part of the light travels slower than the relatively "red" part and so arrives later at the end of an optical fiber. For wavelengths longer than 1.33 micrometers the "blue" part arrives sooner than the "red."

A further problem limits the performance of an optical fiber. It is the optical loss in the fiber, that is, the loss of signal energy. The loss occurs when impurities in the material scatter light or absorb it. Silica glass, for example, shows a marked loss at a wavelength of about 1.25 micrometers and another at about 1.39 micrometers. Both are due to the absorption of light by hydroxyl (OH^-) ions trapped in the glass during its manufacture. Aside from these sharp losses, silica shows a broad-scale loss that ris-

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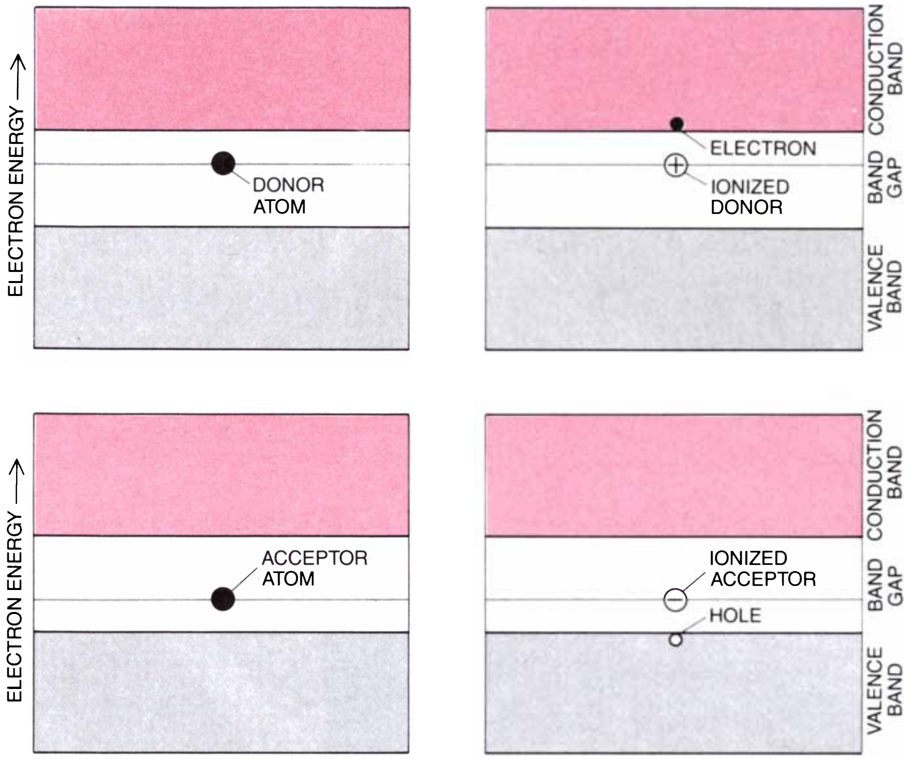
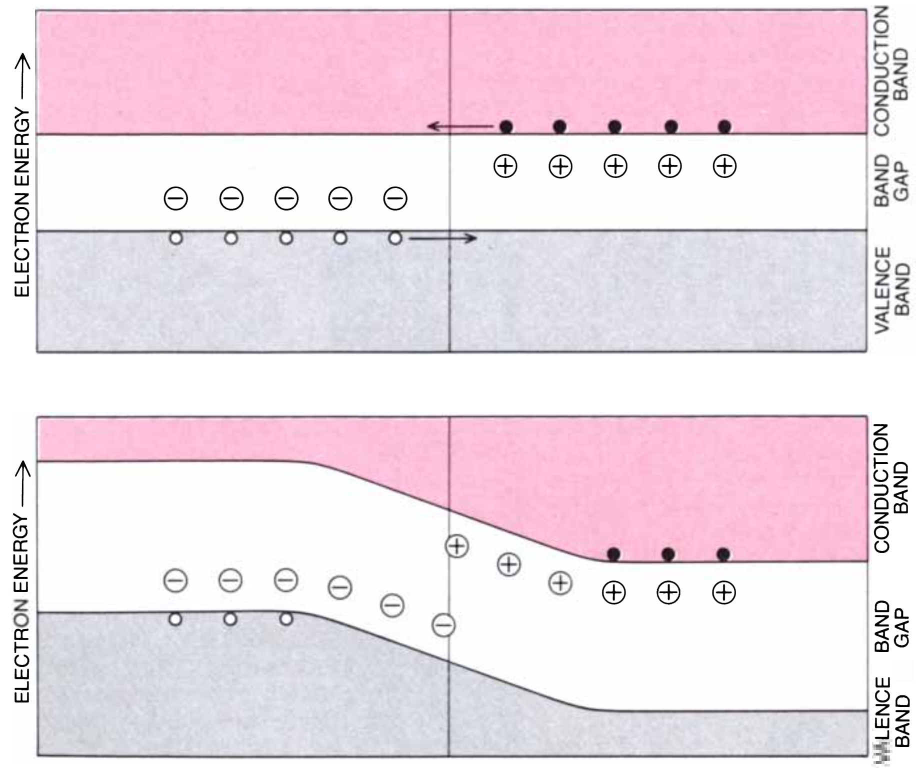


SEMICONDUCTORS are materials in which a small amount of energy promotes electrons from a valence band (*gray*), in which electrons are bound to atoms, to a conduction band (*color*), in which electrons move freely. Two types of semiconductor are made by introducing impurities into an intrinsic semiconductor such as silicon. In *n*-type semiconductor (*top charts*) impurity atoms called donors each give up an electron to the conduction band. The donors themselves become positive ions. In *p*-type semiconductor (*bottom charts*) impurity atoms called acceptors each capture an electron from the valence band, leaving a "hole." The hole, or absence of an electron, is in effect a positive charge. The donors themselves become negative ions.



P-N JUNCTION is the alteration of a semiconductor material from *p*-type to *n*-type in a narrow zone. At the time the junction first arises (*top drawing*) the *n* side has an excess of electrons, the *p* side an excess of holes. Electrons and holes thus tend to diffuse. When an electron meets a hole (in an ideal semiconductor), they recombine. What remains (*bottom drawing*) are the ionized impurity atoms, which produce an electric field at and around the junction. This built-in electric field makes the *p-n* junction the central element in semiconductor electronics.

es rapidly with decreasing wavelength.

If these problems are to be minimized, the light must be carefully chosen. To avoid chromatic dispersion a wavelength of 1.33 micrometers is best. To avoid optical loss a wavelength of 1.55 micrometers is preferable: single-mode silica fibers are most transparent at that wavelength. One strategy would be to employ an utterly monochromatic source producing light at a wavelength of 1.55 micrometers; chromatic dispersion would cease to be a problem because the light consists of one wavelength, and the fiber would be at its most nearly transparent. Unfortunately no conventional semiconductor laser currently in use emits light at a single wavelength. The pulsed output of a conventional semiconductor laser has a spread in wavelength of from five to 10 nanometers.

The lasers now serving optical communication systems are semiconductor lasers. Such devices are small (about the size of a grain of salt); they produce pulses of light from pulses of electric current; their electrical requirements are modest (a few milliamperes at one or two volts); they can generate light at the infrared wavelengths where optical fibers are most nearly transparent; unlike, say, a gas laser, they are mechanically stable and reliable.

In order to see how the C^3 laser promises major improvements in the performance of semiconductor lasers, it is worth exploring in some detail how semiconductor lasers work. Fundamentally a semiconductor, as its name suggests, is a material whose electrical properties are intermediate between those of an insulator (in which electrons are tightly bound to atoms) and those of a conductor such as a metal (in which certain electrons—the outermost ones in the metal atoms—are free to move throughout the volume of the material). In a semiconductor the outermost electrons are bound but can be freed by means of a small amount of energy.

One way to characterize these differences is to note that in an isolated atom the amount of energy allotted to each electron (the energy "level" of the electron) is sharply delimited. In a solid, however, the atoms are arranged in a periodic lattice structure; consequently the individual levels merge into broad bands of allowable energies separated by forbidden zones called band gaps. In a metal the outermost occupied band is only partially filled by electrons. Thus there are vacancies available for free, or charge-carrying, electrons. In an insulator the outermost occupied band is completely filled and a wide band gap intervenes between it and the next-higher band, which is empty. In a semiconductor the outermost occupied band is also completely filled (this band is called the

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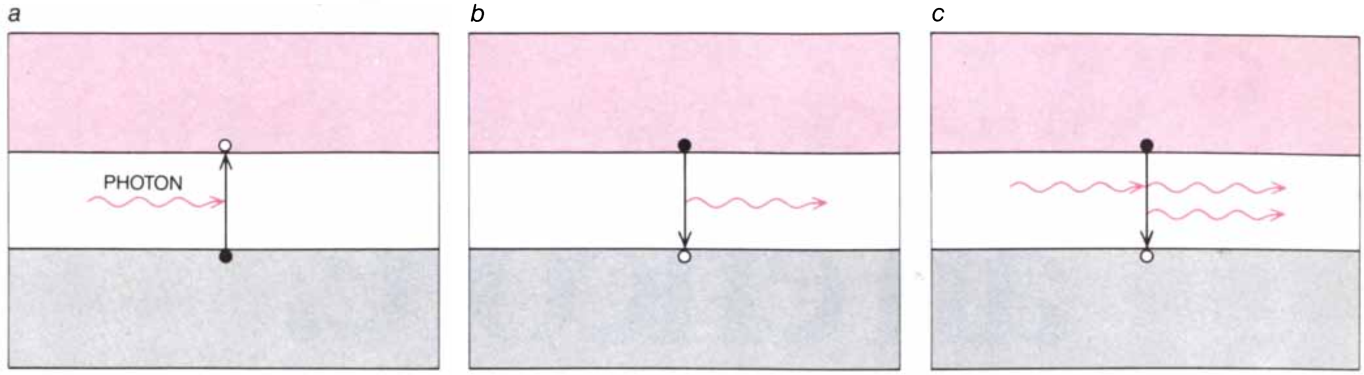

EMISSION OF LIGHT by a semiconductor occurs in two ways: either spontaneously or under stimulation. In the spontaneous process electrons in the valence band have been excited into the conduction band by absorbing photons (quanta of light) whose energy exceeds the band gap: the energy difference between the bands (*a*). The excited electrons are unstable: after a short time they spontaneously "drop" to the valence band, annihilating a hole and releasing a photon whose energy equals the band gap (*b*). In stimulated emission, photons whose energy equals the band gap induce excited electrons to make their "drop" to the valence band. The photons produced by stimulated emission match the incident photons in both energy and phase, that is, the alignment of the waveform of the photons (*c*).

valence band), but the next-higher band (called the conduction band) is only a small band gap away.

Some materials, such as the chemical elements silicon and germanium or mixtures of two different elements (say indium and phosphorus) or three elements (say indium, gallium and arsenic) or more, are intrinsic semiconductors. Often, however, impurities are added to intrinsic semiconductors in order to modify their electrical and optical properties. The resulting materials are termed extrinsic semiconductors. There are two kinds. In the first, termed an *n*-type semiconductor, impurity atoms called donors each contribute one of their electrons to the conduction band [*see top illustration on opposite page*]. The amount of energy required to free and "promote" this electron is quite small compared with the band-gap energy. Since the donor loses an electron, it acquires a positive charge.

In the second variety, termed a *p*-type semiconductor, impurity atoms called acceptors each capture an electron from the valence band, thereby leaving that band with a "hole": the absence of an electron. The hole acts in every respect as if it were a positive charge. Meanwhile the acceptor has acquired a negative charge.

The material at the heart of modern solid-state electronics is the *p-n* junction, that is, the alteration of a semiconductor from *p*-type to *n*-type material over an extremely small distance. A transistor, for example, is either a *p-n-p* material or an *n-p-n* material. In order to understand how a junction works it is useful to imagine an instant of time in which *p* material and *n* material first come in contact [*see bottom illustration on opposite page*]. At that instant the *n* side has an excess of free electrons; the *p* side has an excess of holes. Driven, therefore, by a concentration gradient, electrons tend to diffuse toward the *p* side; holes tend to diffuse toward the *n* side.

When an electron meets a hole in an ideal semiconductor, the two recombine. As a result charge carriers (electrons and holes) tend to disappear from the vicinity of the junction. The *p* side is left with an excess of acceptor atoms; their positions—and negative charges—are fixed in the semiconductor crystal lattice. The *n* side is left with an excess of donor atoms, whose positive charges are likewise fixed in the lattice. In this way an electric field becomes established in the vicinity of the junction, a field that opposes the further diffusion of electrons or holes.

Such a device can be designed to serve as a laser. The crucial point is that three basic optical processes can occur in a semiconductor: spontaneous absorption, spontaneous emission and stimulated emission [*see illustration above*]. In the spontaneous processes a charge carrier (an electron or a hole) absorbs or emits a photon as it moves from one band to another. The energy of this photon equals that of the band gap. The wavelength of a photon is a measure of its energy; hence the wavelength of the radiation absorbed or emitted by a semiconductor depends on the choice of a particular semiconducting material. Suppose an electron in the valence band absorbs a photon whose energy is greater than the band gap. The electron will be excited into the conduction band, leaving a hole in the valence band. Conversely, suppose an electron is in the conduction band. It is in an excited state; in a word, it is unstable. After a short time, and without any external stimulus, it will make a transition into the valence band, where it will annihilate a hole and release a photon whose energy precisely equals that of the band gap.

The third basic process—stimulated emission—is essential to laser action. It takes place when a photon whose energy precisely equals that of the band gap impinges on electrons in the conduction band. In this situation a conduction-band electron will be induced to make its transition to the valence band and so emit a photon. Remarkably, the incident photon and the photon emitted by the electron will match each other not only in energy but also in phase. That is, the crests and troughs of their waves will align. It should be said that photon emission can arise from transitions between a band and the energy level occupied by an impurity atom, and even from transitions between two impurity levels. Moreover, the energies of charge carriers in the conduction band and valence band obey a statistical distribution. Further still, the energy levels of impurity atoms form narrow energy bands. For all these reasons the electromagnetic radiation emitted by a semiconductor includes a narrow range of wavelengths rather than the single wavelength defined by the band gap.

A *p-n* junction can be an excellent light emitter; one need only connect the junction to a supply of electric current. The current places a voltage across the junction—a voltage that partially counters the electric field intrinsic to the junction. In this way the energy barrier raised against the flow of electrons and holes is reduced [*see upper illustration page 154*]; hence electrons move from the *n* side to the *p* side, where they recombine with holes, emitting a photon by spontaneous emission. A similar process produces photons when holes move from the *p* side to the *n* side and recombine with electrons there. If the applied voltage is almost large enough to flatten the energy barrier, great numbers of charge carriers become capable of surmounting the barrier; the resulting flow of carriers leads to a carrier distribution called a population inversion. More important, the number of photons emitted in the vicinity of the junction, in what is called the active layer of

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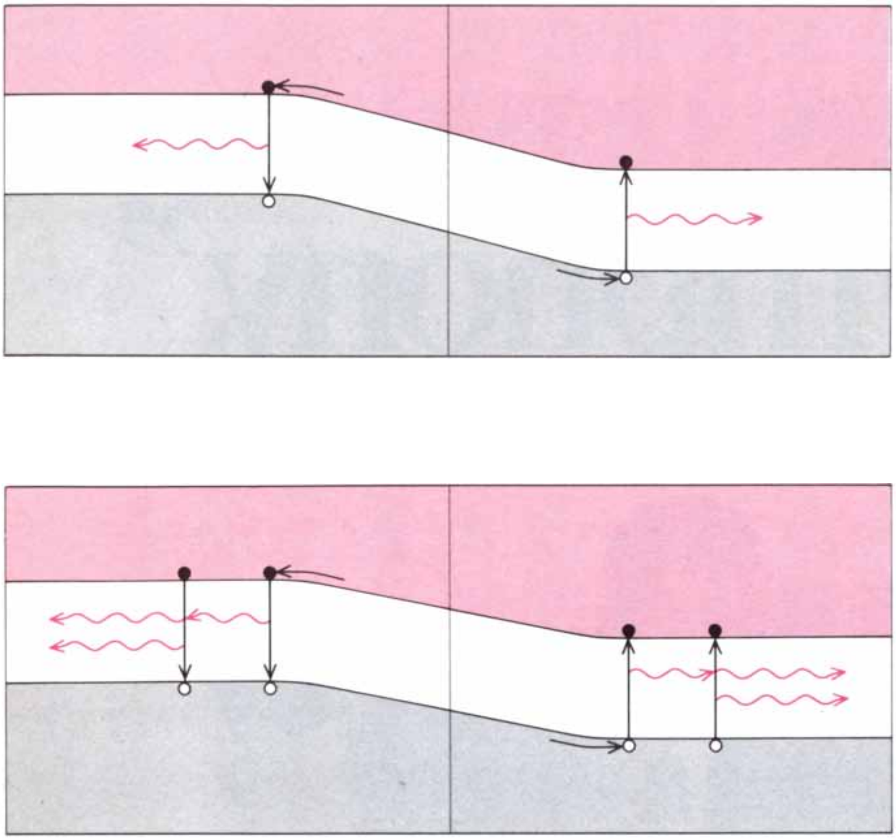
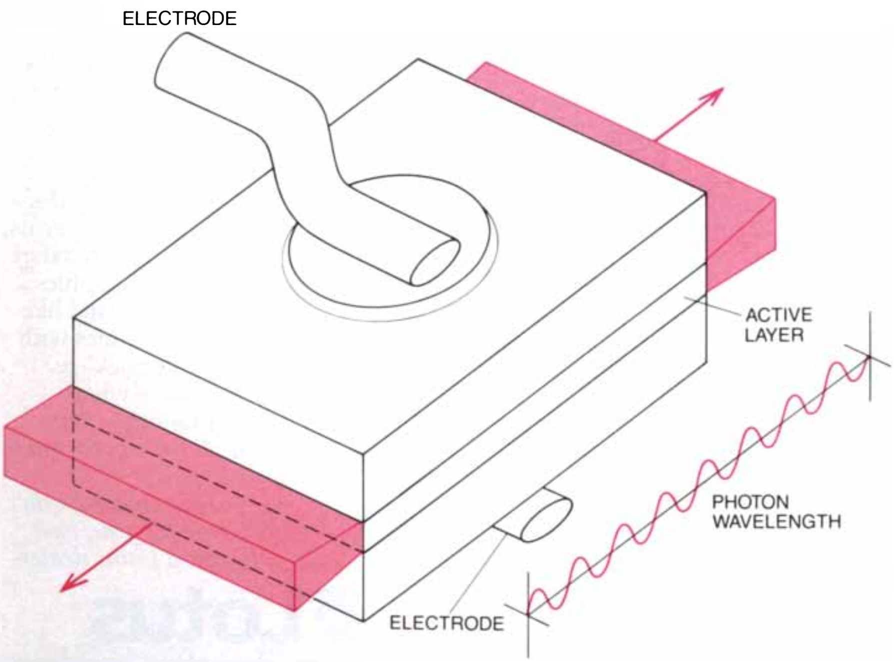


P-N JUNCTION EMITS LIGHT under the influence of a voltage applied to the junction. Basically the voltage counters the electric field at the junction. As a result electrons and holes diffuse across the junction and recombine, emitting photons by spontaneous emission (*top drawing*). If the applied voltage is almost large enough to nullify the electric field, stimulated emission can occur (*bottom drawing*) when electrons have been excited in sufficient number.



SIMPLEST SEMICONDUCTOR LASER is a *p-n* junction in a semiconductor crystal whose end faces are flat and perfectly parallel. The faces then form a pair of semireflecting mirrors bouncing photons back and forth through the "active layer" of the crystal. When current is injected, photons arise by spontaneous emission. The ones traversing the semiconductor bring on an avalanche of stimulated emission. Reflections at the mirrors are self-reinforcing if the wavelength of the photon fits evenly into the length of the laser. An example is at the right.

the semiconductor crystal, becomes so great that stimulated emission occurs. When the current is turned off, the emission of photons stops. Hence the semiconductor emits pulses of light in response to pulses of current: it is a transducer, or converter, of electrical signals into optical signals.

One further condition must be fulfilled for the device to be a laser: two end faces of the crystal perpendicular to the *p-n* junction must be flat and perfectly parallel to each other [*see lower illustration at left*]. The faces then form a pair of semireflecting mirrors that bounce photons generated at the junction back into the active layer. As the photons traverse the region they induce an avalanche of stimulated emission. In short, they amplify the light. (The word laser is an acronym for "light amplification by stimulated emission of radiation.") Photons escaping the semiconductor through the semireflecting mirrors form the laser beam.

The semireflecting mirrors are really a modern version of an optical apparatus invented in 1896 by the French physicists Charles Fabry and Alfred Perot. Hence the limitations that apply to the apparatus (now called a Fabry-Perot resonant cavity) also apply to the laser. In particular the light reflected by the mirrors can reinforce itself only if the light and its reflection are in phase. To put it another way, the wavelength of the light must fit evenly into the length of the laser—or rather the effective length: the measured length multiplied by the refractive index of the material between the mirrors. Wavelengths that satisfy the condition are called resonant wavelengths. All other wavelengths are suppressed. In principle the resonant wavelengths are infinite in number. But since a particular *p-n* junction generates light in only a narrow range of wavelengths (usually called the gain profile of the laser), the beam emitted by the laser will consist of resonant wavelengths that fall within the range. The end faces of a semiconductor laser are typically 200 to 400 micrometers apart. If the laser is designed to emit light at a wavelength of 1.55 micrometers, it will actually emit a number of resonant wavelengths that differ by "mode spacings" of about one to two nanometers. Once the material of the active layer has been chosen, the wavelengths are unchangeable.

Physics alone does not govern the nature of semiconductor lasers. Some engineering practicalities also influence the design. For one thing, the useful life of a semiconductor laser depends on limiting the amount of current applied to the device. Several methods are employed. In one method further chemical elements are introduced into the crystal so that the active layer of the laser is between regions where the band gap is

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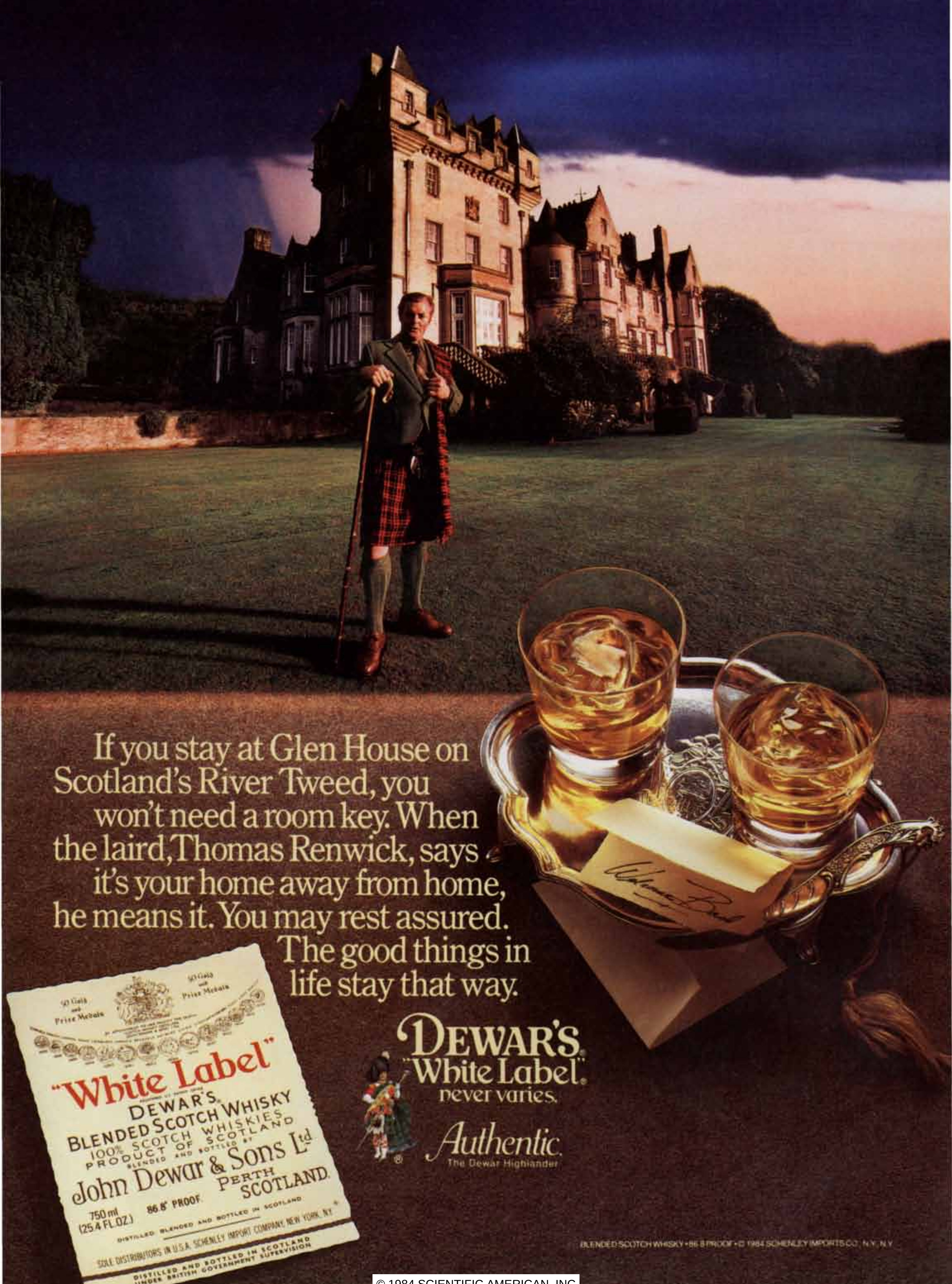

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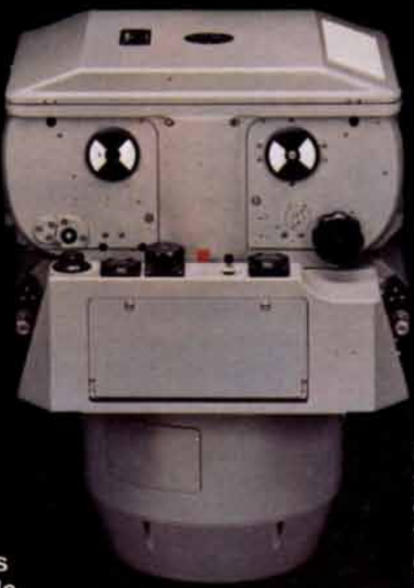

This spectacular photograph of the Horn of Africa was taken aboard the Space Shuttle *Columbia* in late 1983 from a height of 150 miles. The instrument: a precision aerial survey camera from Zeiss, suitably modified for use under conditions of weightlessness.

In this particular case, each frame, 9 in. square, represents an area of 13,800 sq. mi. The scale is 1: 820,000. The remarkable resolution of 65-100 feet provides pictures that are extremely rich in detail despite the enormous distance between lens and subject. Consecutive, overlapping photographs create sets of stereo photos for subsequent evaluation in three dimensions. On the Columbia flight, the Zeiss aerial survey camera recorded over 1,000 black & white and infrared photographs of astonishing quality and detail. They will form excellent bases for mapping and for evaluation in diverse disciplines such as geology, resources planning, agriculture, oceanography and meteorology.

Zeiss plays a key role in satellite photography, too; and Zeiss lenses and instrumentation are invaluable aids in astronomy, the search for new energy sources, and in other areas that require superb photographs as a basis for interpretation.

Zeiss equipment can be found in earthbound applications in sister sciences. Zeiss photogrammetric plotters convert photographic data quickly and accurately to map form. In surveying, Zeiss introduced the first automatic level in 1950, the first fully-computerized Total Station in 1978, the first "software" program for certain surveying routines in 1981, and many other innovations that have helped make civil engineering an ever more exact science.

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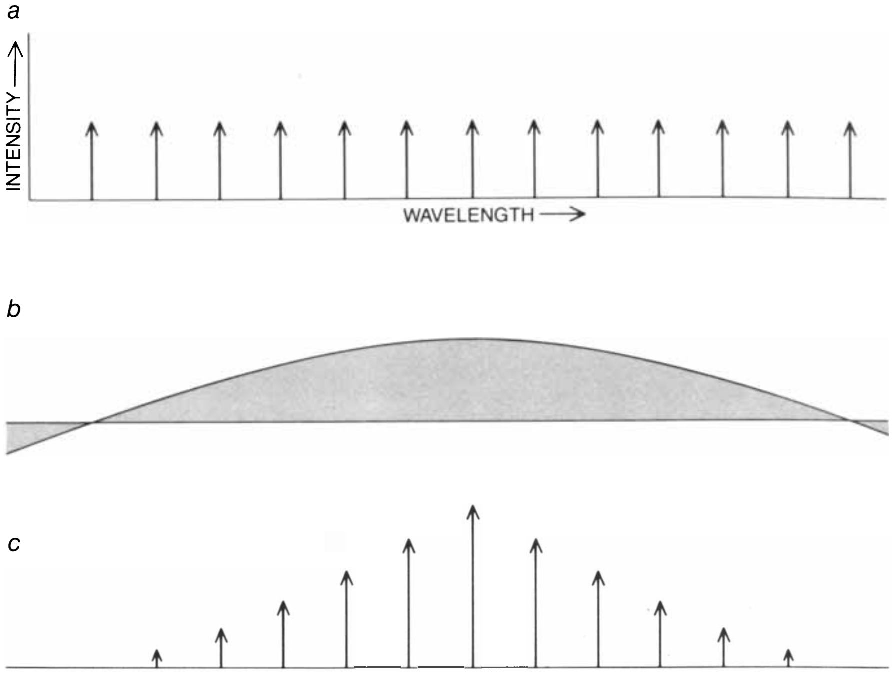
particularly wide. The resulting "heterostructure" has built-in energy barriers that help to prevent the diffusion of charge carriers out of the active layer. Stimulated emission can then be attained at relatively low values of applied current. The active layer can in fact be made a narrow tube surrounded on all sides by wide-band-gap materials. The resulting devices are called buried-heterostructure lasers.

Nature has been kind: the refractive index in the active layer turns out to be greater than that of the surrounding wide-band-gap material. As a result the tubelike active layer in a buried-heterostructure laser acts like the core of an optical fiber: light generated in the active layer is guided along the tube. The guiding is valuable because the process of stimulated emission requires the interaction of photons and excited charge carriers. Together the advances in the design of semiconductor lasers and the development of excellent crystal growth and fabrication techniques now yield lasers that can operate at room temperature for more than a million hours on currents as low as 2.5 milliamperes at one or two volts.

This is not to say the buried-heterostructure laser is ideal for optical communication. For one thing the beam of even a buried-heterostructure laser jumps randomly among the available resonant wavelengths. The jumping, called mode partition, is particularly troublesome when the laser is turned on and off rapidly in an effort to code information as pulses of light. The jumping cannot be neglected in a modern optical-communication system, where the tolerable error rate is one bit in 10^9, or even one in 10^{11}. Suppose two pulses of light emitted by a laser designed to operate at about 1.55 micrometers (1,550 nanometers) actually differ in wavelength by two nanometers (the mode spacing for a laser cavity length of 250 micrometers). The pulses travel 100 kilometers in a single-mode optical fiber whose core is made of silica. Owing to chromatic dispersion the transmission time for the relatively "blue" pulse (the one at 1,548 nanometers) will be 3.5 nanoseconds less than the transmission time for the relatively "red" pulse (the one at 1,552 nanometers). As a result the information-carrying capacity of the system will be limited to a maximum of 150 million bits per second; otherwise the pulses would smear over one another. Hundreds of millions of bits per second may seem to be a large number. Actually the goal for modern optical-communication lines lies well within the billion-bit-per-second range.



ENERGY DIAGRAM for the simplest semiconductor laser shows why its output beam jumps randomly among several wavelengths. In principle the laser resonates at the infinite number of wavelengths that fit evenly into the length of the laser (*a*). The *p-n* junction, however, produces photons only in a narrow range of wavelengths called the gain profile (*b*). Thus the beam emitted by the laser includes only the resonant wavelengths positioned within the profile (*c*).

It was the pursuit of ultrahigh-capacity, long-distance optical-communication systems that led to the C^3 laser, a device that not only emits the purest known laser beam when the device is being pulsed at rates as high as two billion pulses per second but also is the first single-wavelength laser that can be tuned electronically over a wide range of output wavelengths.

The C^3 laser consists of two semiconductor lasers that differ slightly in length, say by 20 percent. Because they differ in length, the spacing of their resonant wavelengths differs. The two lasers are positioned close to each other, with their active layers aligned, so that the beam emitted by each laser enters the other [*see lower illustration on next page*]. The light emitted by one is then suppressed by the other, unless the wavelength is resonant in both. In general the wavelengths will not match; indeed, the output beam will be confined almost perfectly (nothing in quantum mechanics is absolutely certain) to a single wavelength: a matching resonance near the peak of the lasers' gain profile [*see top illustration on page 161*]. In this way mode partition is eliminated.

How is the C^3 laser tuned? By injecting current into one of the individual lasers. A central point about the C^3 laser is that the two lasers in it are optically coupled but electrically isolated: each receives its own electric current. Suppose, then, one of the lasers is given a current that places it above its lasing threshold (the minimum current that produces a population inversion and stimulated emission). The positions of its resonant modes will then be fixed. Meanwhile the second laser is given a current that keeps it below its threshold. Under this condition the second current serves exclusively to control the density of charge carriers in the active layer of the second laser. (If the second laser were lasing, the application of electric current would serve only to increase the stimulated emission of photons.) The density of charge carriers turns out to govern the refractive index of the laser. In turn the refractive index governs the effective length of the laser, and the effective length governs the resonant wavelengths. In sum, the varying current applied to the second laser serves to shift the resonant wavelengths of the second laser with respect to those of the first. As a result the resonances that matched will fall out of alignment and other matches will take their place.

At Bell Laboratories we have tuned a 1.55-micrometer C^3 laser to 15 different infrared wavelengths in a range of 30 nanometers. Each successive tuning required a change in current to the subthreshold laser amounting to little more than a milliampere; the amount of time the switching required was about a billionth of a second. Mode partition was virtually absent: it occurred less than once in 10 billion samplings of the beam. (Modern ultrahigh-capacity, very-long-distance optical-communication systems require an error rate of less than one incorrect bit in a billion bits of transmitted information.) The laser was maintained at any of its wavelengths by holding constant the current applied to the second laser. To generate optical

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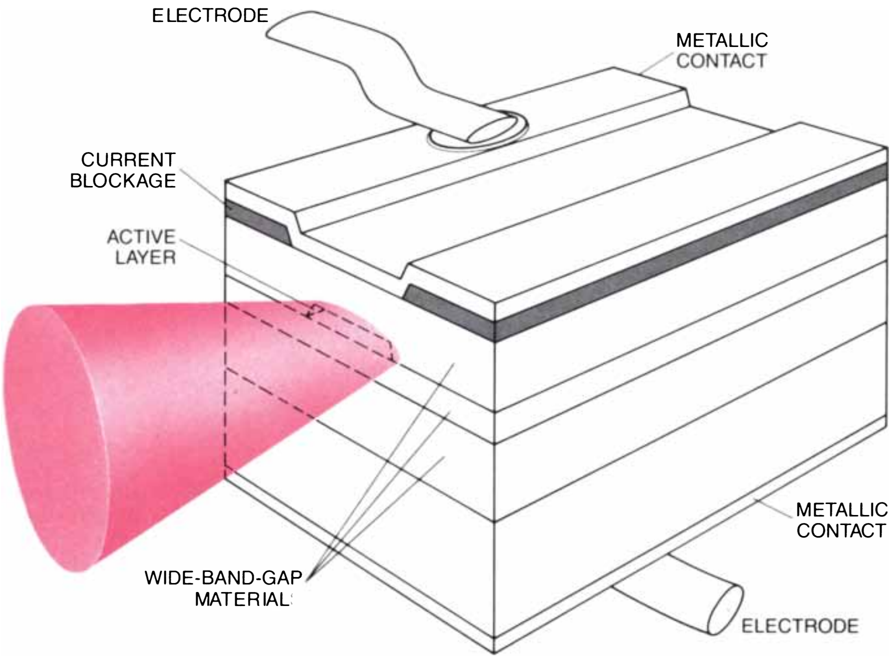
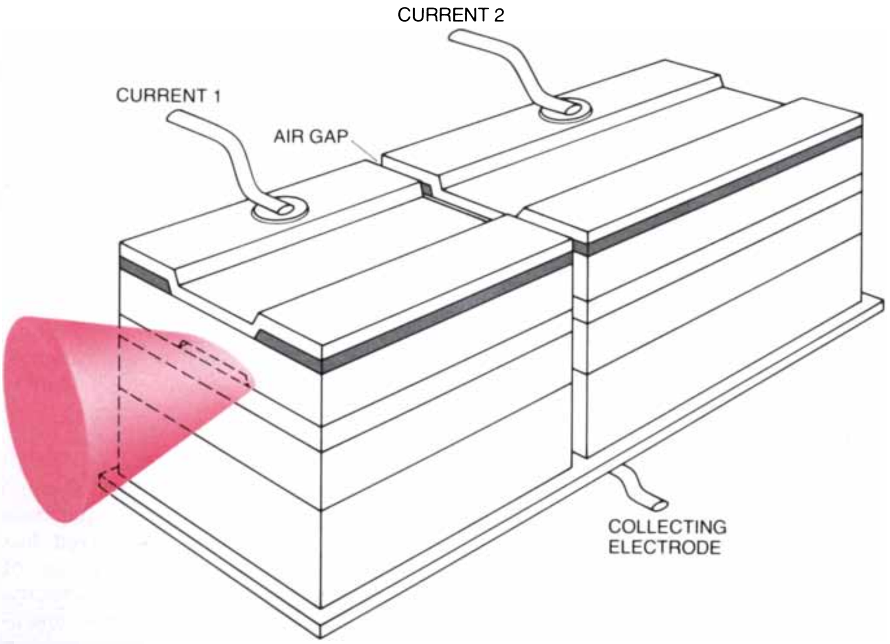
pulses the first laser was maintained above lasing threshold and given trains of electric pulses. At a certain strength the application of electric current to the second laser placed it above its lasing threshold. As a result the tunability ceased. The C^3 laser then functions at a single wavelength in spite of further increases in the applied electric current.

A C^3 laser is made by cleaving a conventional semiconductor laser along a crystal plane parallel to its end faces. The result is two shorter lasers. In isolation each of the latter would be a conventional laser. In fact the two lasers are not isolated. One of the surfaces of the parent laser, a surface parallel to the *p-n* junction, is coated with a gold pad about three micrometers thick. The pad resists the cleaving; thus it serves as a hinge holding the half lasers together with their active layers in precise alignment and an air gap a few micrometers wide between them. Contrary to the reservations expressed when the technique was tried, the width of the air gap and the precise difference in length between the two half lasers turn out not to affect the performance of the device in any critical way. The technique is applicable to the manufacture of lasers made from a wide range of materials emitting at wavelengths from the visible (at about .7 micrometer) to the far infrared (at about 30 micrometers).



BURIED-HETEROSTRUCTURE LASER resulted from efforts to improve the performance of the basic semiconductor laser. It reduces the *p-n* junction to a "tube" running the length of the semiconductor crystal. Then it surrounds the tube with layers of semiconductor whose wide band gap raises an electrical barrier confining charge carriers within the tube. The wide-band-gap material also confines the photons produced at the junction. The laser beam spreads because of diffraction occurring where the beam emerges from the face of the device.



ALIGNMENT OF TWO LASERS composes the C^3 laser. The half lasers have different lengths; hence their resonant wavelengths are differently spaced and only a few of them match. The mismatches are suppressed. Among the matches, moreover, only one is near the peak gain. Thus the beam of a C^3 laser consists of that wavelength almost exclusively. The probability of the beam's jumping to another wavelength is less than one in 10 billion beam samplings.

Among the potential uses for the C^3 laser, three forms of optical communication strike me as having particular promise. First, the extraordinarily monochromatic output of a C^3 laser eliminates the problem of chromatic dispersion in optical fibers and so facilitates the transmission of digital information in a single-mode fiber at a wavelength of 1.55 micrometers: the wavelength at which a silica fiber is most nearly transparent to electromagnetic radiation. In one test of the laser's ability at 1.55 micrometers Bell Laboratories has transmitted digital information in an optical fiber more than 120 kilometers long at a rate of one gigabit (10^9 bits) per second without reamplification along the way. The frequency of error was less than two bits in 10^{10}. At such a rate one could transmit the text of the Encyclopaedia Britannica in less than half a second, and the text would be received virtually without error (one letter or punctuation mark might be a misprint). In a further test, also done at Bell Laboratories, digital information was transmitted 160 kilometers at a rate of 420 megabits (420×10^6 bits) per second without reamplification. The error rate was less than five bits in 10^{10}.

The second application for C^3 lasers in optical communication lies in wavelength-division multiplexing. Here the output beams of several C^3 lasers, each laser tuned to a different wavelength, are coupled to a single optical fiber. The fiber can then carry several independent messages.

The third application enhances still further the information-carrying capacity of a single optical fiber. At rates on the order of a billion switchings per second one can shunt the output wavelength of a C^3 laser among as many as 15 modes spaced about two nanometers apart. Thus the single-wavelength transmission of information, with high-power and low-power pulses representing the binary digits 1 and 0 respectively,

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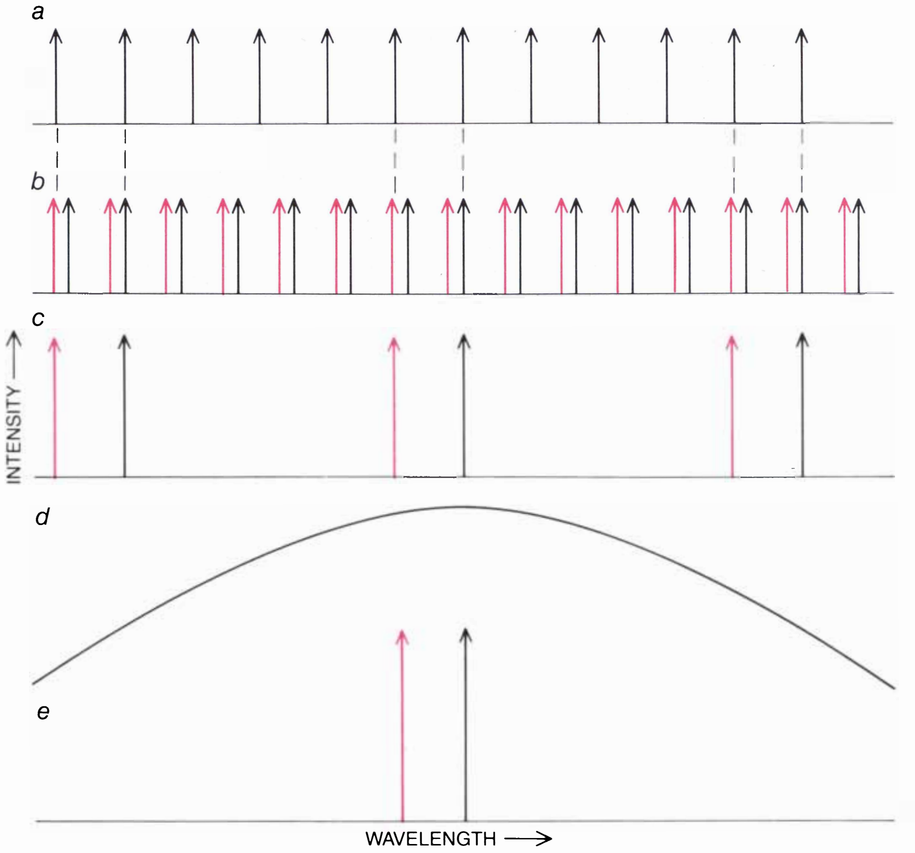
yields to multiwavelength transmission. In the simplest possibility two different wavelengths are employed to represent 1 and 0. A more complex scheme calls for switching between four different wavelengths. A single pulse would then signify the binary data 00, 01, 11 or 10, depending on the wavelength. In this way each pulse would carry two bits of information. Switching among eight wavelengths would enable a single pulse to carry three bits of information.

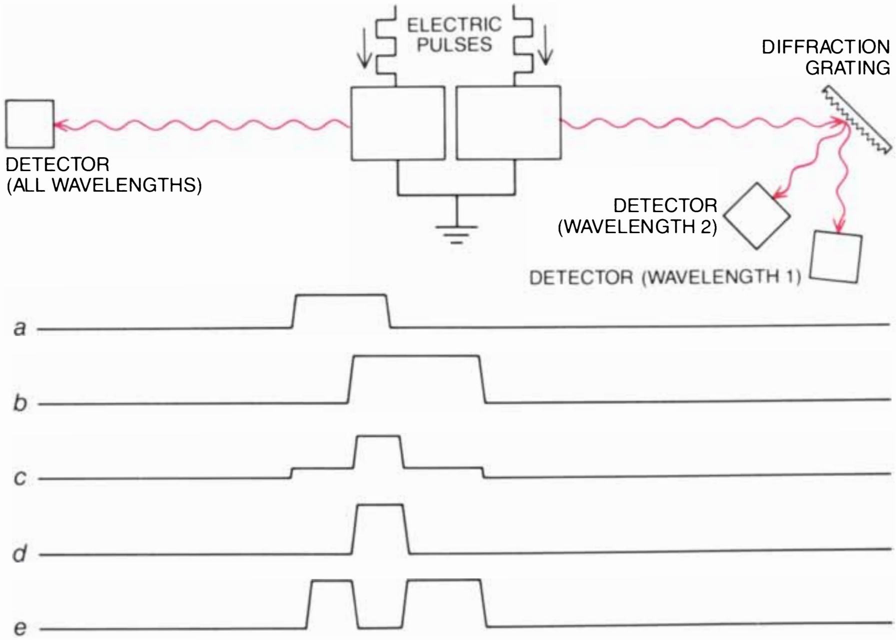
Beyond the possibilities in optical communication are further possibilities in which C^3 lasers perform the switching and logic operations now done by electronic means. The scheme relies on the electrical isolation of the two half lasers composing a C^3 laser. Each half laser receives a train of electric pulses [*see bottom illustration at right*]. If a pulse of current arrives simultaneously at each half laser, the C^3 laser emits a pulse of light at a certain wavelength; call it wavelength 1. If a pulse of current arrives at one half laser but not at the other, the C^3 laser emits a pulse of light at a different wavelength, wavelength 2. If no pulses of current arrive, no pulses of light are produced.

The pulsed beam of light emerging from one end of the C^3 laser is directed into a photodetector sensitive to all wavelengths. Accordingly the photodetector signals whenever one half laser or both half lasers receive a pulse of electric current. The detector is performing the logic operation known as *or*. Meanwhile the pulsed beam emerging from the other end of the C^3 laser is directed into a diffraction grating, which splits light into a fan of wavelengths. A pair of photodetectors can then detect wavelength 1 and wavelength 2 independently. The presence of wavelength 1 signals that both half lasers are receiving a pulse of electric current; thus the wavelength-1 detector performs the logic operation *and*. The presence of wavelength 2 signals that one half laser or the other—but not both—is receiving a pulse of electric current. This is the logic operation *exclusive or*.

The scheme has several advantages. It produces multiple logic outputs for a single pair of electrical inputs. It is fast: the switching time for a C^3 laser is as short as a nanosecond, so that information processing in the gigabit-per-second range is conceivable. Finally, the scheme yields optical output from electrical input; hence it can serve as an electronic-optical transducer. Applications for optical logic and switching may lie some time ahead. Still, it is clear that semiconductor optics can serve in that capacity. The C^3 laser is a straightforward extension of the conventional semiconductor laser, yet its characteristics and capabilities may prove to be important in many different ways.



TUNABILITY OF A C^3 LASER by current injection is shown by means of the laser's energy diagram. The current to one of the half lasers puts it above its lasing threshold, so that its resonant modes are fixed (*a*). The second half laser is kept below lasing threshold. Still, it has resonant modes (*black lines in* b), and some of them (*black lines in* c) match the modes of the light-emitting half laser. The match at the peak of the laser's gain profile (*d*) determines the wavelength of the C^3 laser's output (*e*). Now the current applied to the second half laser is changed. The change alters its resonant modes (*colored lines in* b). Hence a new set of matching resonances is established (*colored lines in* c) and with it a new output wavelength (*colored line in* e).



OPTICAL LOGIC CIRCUIT may be a future application for the C^3 laser. The circuit arises from the laser's tunability and from the electrical isolation of the two half lasers composing a C^3 laser. Independent trains of electric pulses (*a, b*) are applied to the half lasers. Simultaneous pulses cause the emission of light at wavelength *1*. A pulse to one of the half lasers causes the emission of light at wavelength *2*. The detection of light at both wavelengths amounts to the logic operation designated *or* (*c*). The detection of wavelength *1* amounts to the logic operation *and* (*d*). The detection of wavelength *2* amounts to the logic operation *exclusive or* (*e*).

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Mammoth-Bone Dwellings on the Russian Plain

They were built 15,000 years ago by hunting-and-gathering bands. Their complexity and permanence suggest that a profound social change was taking place on the steppe at the end of the great Ice Age

by Mikhail I. Gladkih, Ninelj L. Kornietz and Olga Soffer

In 1871 G. S. Kiryakov, who was a member of the local gentry in the village of Gontsy in what is now the Ukrainian Republic of the U.S.S.R., ordered an excavation to be carried out on a piece of property he owned near the village. When the workmen began to dig, they uncovered some unusual large bones. The bones proved to be from the mammoth, an animal that has been extinct in the Ukraine for 10,000 years, and Kiryakov gave them to the local high school as a curiosity.

The history teacher at the high school was excited by the bones and, enlisting the aid of a geologist from Kiev, he began to dig. At the spot where the bones had been unearthed the two amateur archaeologists found the remains of a Paleolithic community. Because of the crudeness of the available excavating techniques, it appeared the bones were simply refuse: a Paleolithic garbage heap left by hunters who had stripped the meat from mammoth carcasses and left the bones on the ground.

It was not until the 1920's that better methods for opening up mammoth-bone sites were developed. Among the innovations was that of excavating the entire occupied area of a community, rather than working in narrow trenches as earlier workers had done. When the new techniques were applied at Gontsy and other sites, it became clear that the mammoth bones were not merely refuse. On the contrary, the bone was the structural material for an extraordinary style of building. The mammoth-bone structures were generally round or oval in plan. Skulls, mandibles, scapulas and other bones formed the foundations. The superstructure was probably a wood frame covered with hides or sod.

About a dozen sites in the Ukraine are now known to include mammoth-bone dwellings. In the late 1960's one of the most intriguing mammoth-bone sites was found near the town of Mezhirich. Ivan Pidoplichko of the U.S.S.R. Academy of Sciences worked at the site from the time of its discovery until his death in 1975; since then we have worked there. We conclude that the site was the winter camp for a prosperous Paleolithic hunting-and-gathering band. The hunters came to Mezhirich in about 15,000 B.P. (before the present) and built at least five mammoth-bone dwellings. Evidence found at the site suggests the community had mechanisms for channeling into specific projects the labor time that was not needed for subsistence. It is possible the community also had mechanisms for resolving disputes. The development of such mechanisms was undoubtedly a crucial phase of human prehistory and hence the work at Mezhirich is yielding insights into a formative period of human society.

Mezhirich, along with several other mammoth-bone communities and many Pleistocene sites without mammoth bones, is in the Ukrainian Republic. A few mammoth-bone sites are in the Byelorussian Republic or the Russian Republic. All three republics lie on the central Russian plain, which stretches from the Carpathian foothills in the west to the Ural Mountains in the east and occupies the southern half of the European U.S.S.R. This vast area is drained by three major river systems, the Dnestr, the Don and the Dnepr, flowing south to the Black Sea and the Sea of Asov.

Most of the Paleolithic sites in this region are near a river, and the sites clustered around each major river tend to have a certain cultural unity. The settlements that include mammoth-bone dwellings are mainly found along the Dnepr and its tributaries.

The Dnepr sites show both cultural similarities and similarities in their original geographic situation. All of them are buried in geologic deposits on a river terrace or on the edge of a plateau adjacent to a river valley. The deposits in which the cultural remains are buried are of two types: loess and colluvium. Loess is a fine dust that was deposited by the wind during the cold, dry periods of the glacial epoch. Colluvium is any material that has slid down the side of a promontory near a river toward the bank of the river itself. Colluvium tends to be coarser than loess.

Loess is a good material for preserving the remnants of a human settlement because it is deposited quickly, it is not acidic and it is impermeable to many substances that can destroy organic remains. The settlements along the Dnepr are often buried in 10 or more meters of loess and therefore have been well preserved. The loess was laid down during the coldest part of the great Ice Age: the period known as the Valdai in the U.S.S.R. The Valdai glaciation lasted from about 100,000 to about 10,000 B.P. During the Valdai maximum, in about 20,000 B.P., the Scandinavian ice sheet covered all northern Russia and extended to near the 55th parallel.

Human communities living on the Russian plain during the Valdai could have experienced considerable climatic fluctuation. There is some evidence that during the late Valdai (after 18,000 B.P.) the climate warmed and cooled in cycles of about 1,000 years' duration. Cold, dry stadial periods alternated with warmer, wetter interstadial periods. In the stadial periods the mean January temperatures may have been as low as 35 to 40 degrees below zero Celsius (−31 to −40 degrees Fahrenheit). The average July temperature might have been about 18 degrees above 0 C. (64 degrees F.).

Except for a shallow summer thaw layer the ground was permanently frozen; the frozen layer began at a depth of about 1.5 meters below the surface and extended downward. The permafrost and the thaw layer were of great significance to the inhabitants in storing food.

Periglacial steppe vegetation consist-

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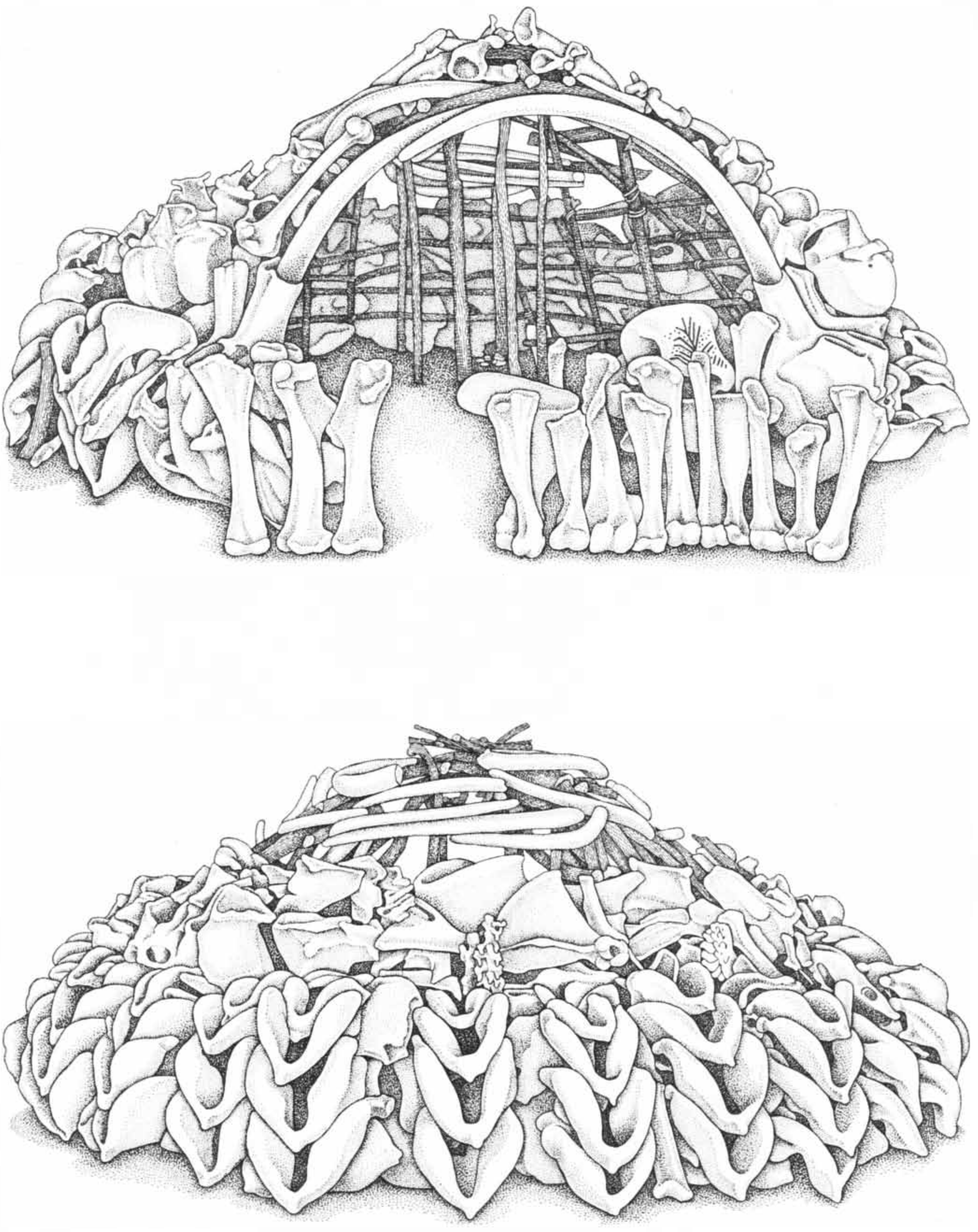

MAMMOTH-BONE DWELLING from a site near the village of Mezhirich in the Ukrainian Republic of the U.S.S.R. was reconstructed under the supervision of Academician Ivan Pidoplichko. The upper panel shows the entrance to the dwelling and the lower panel shows the back. The structure was about five meters across at the base. A Paleolithic hunting-and-gathering band built the dwelling. They placed skulls in a semicircle to form the interior base wall. The outer and upper part of the wall consisted of 95 mandibles arranged "chin down." The roof may have been made of hides supported by a wood frame and held in place by an assortment of bones. The upright bones in front of the entrance come from the legs of the mammoth. A skull decorated with designs in red ocher can be seen just behind them. The dwelling was the first of four mammoth-bone structures to be unearthed at Mezhirich; it has been designated Dwelling No. 1.

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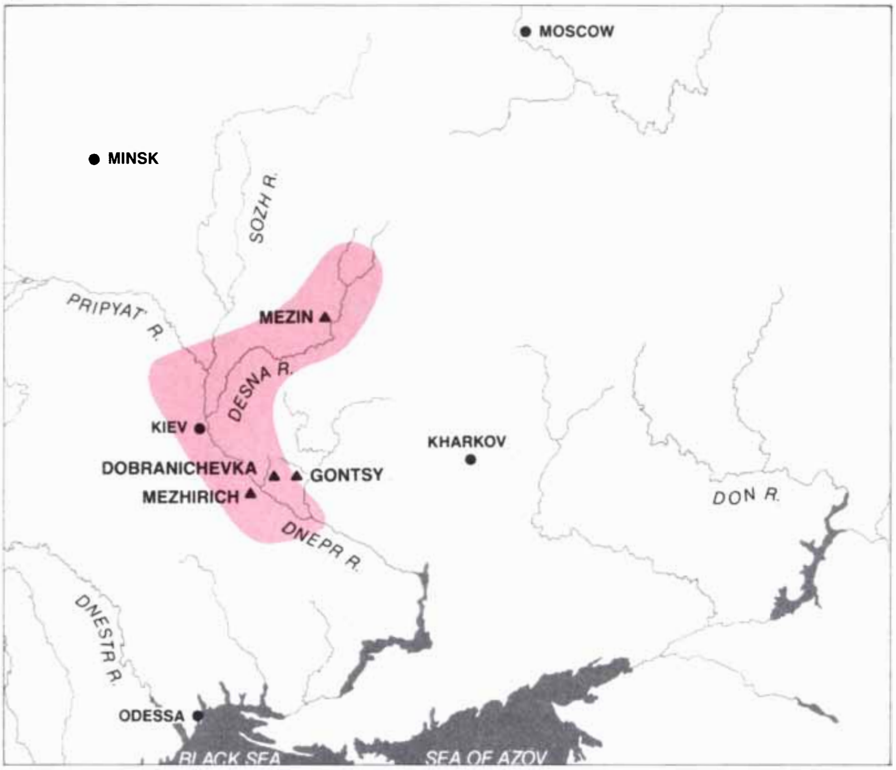
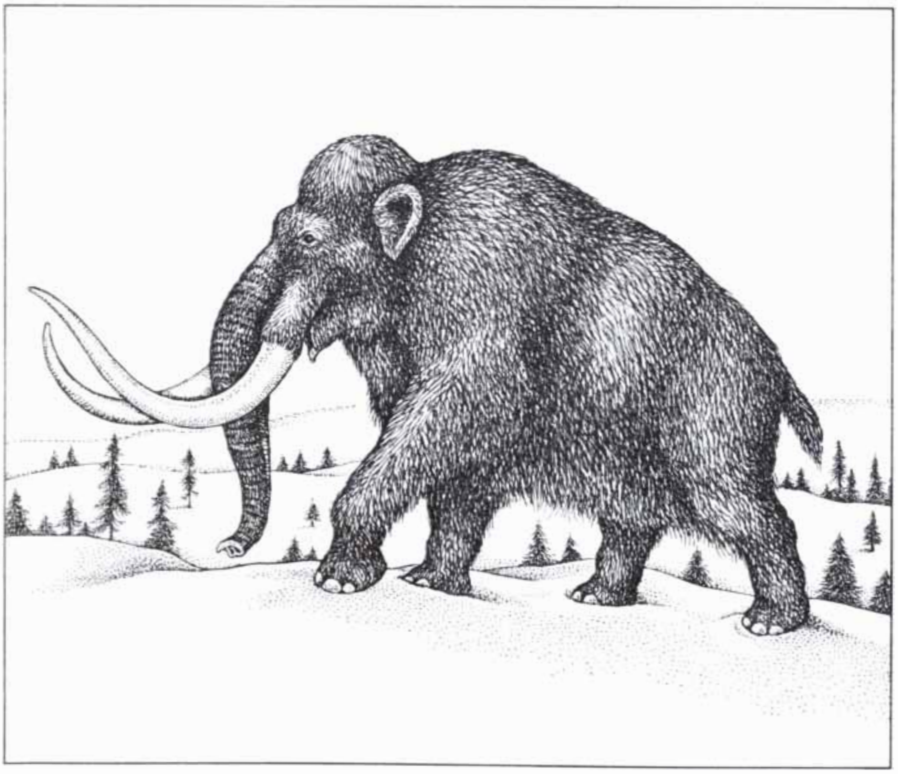


MAMMOTH-BONE SITES of the central Russian plain flank the Dnepr River and its tributaries (*color*). Among the 15 or so sites where mammoth-bone dwellings have been found are Mezhirich, Mezin, Dobranichevka and Gontsy. In 15,000 B.P. (before the present) the region was a periglacial steppe where herds of large herbivores, including the mammoth and the rhinoceros, roamed. The inhabitants of the mammoth-bone dwellings, who hunted the big herbivores, were part of a trading network that may have extended as far south as the Black Sea.



MAMMOTH (*Mammuthus primigenius*) provided the Paleolithic hunting bands with food, clothing and shelter. The adult mammoth reached the size of an elephant and had a coat of course reddish brown hair. The Paleolithic bands hunted mammoths and also collected their bones. The mammoth became extinct on the central Russian plain about 10,000 years ago.

ing mostly of shrubs and grasses covered the plain. Tree growth was sparse and limited primarily to the river valleys. The fine-grained loess was deposited during the stadial periods.

During the warmer interstadial periods the area became a meadow-steppe. Arboreal vegetation was more abundant and coniferous trees were mixed with hardier deciduous species such as oak. Although virtually no soil was laid down during the cold stadial periods, there was some weak soil deposition in the interstadial times. In addition, during the interstadial times erosion cut into terraces and plateaus near the river and created a system of deep ravines. Between the ravines were promontories that offered hunters several advantages: they were good points for observing game, they afforded protection from predators and they were close to water. It was on the promontories that the Paleolithic bands built their camps.

Today the promontories are as much as 30 meters above the floodplain they overlook, but at the time of occupation they were lower, ranging from one meter to 15 meters above the plain. Paleogeographic work done by Maksim Veklich of the Institute of Geology in Kiev, Andrei Velichko of the Institute of Geography in Moscow and Leonid Voznyachuk of the Institute of Geology in Minsk shows that the remains of the hunting-and-gathering settlements are found chiefly in layers of loess deposited after 18,000 B.P.

Radiocarbon dating of raw and burned bone from the sites has confirmed that the settlements were occupied toward the end of the Paleolithic period. For example, radiocarbon dates of samples from Mezhirich range from 18,000 to 14,000 B.P., with most of the dates falling between 15,000 and 14,000.

Systematic excavations carried out in the past three decades have revealed the pattern of spatial organization at the late Paleolithic settlements. The sites are quite large, with some covering as much as 10,000 square meters. The cultural layer, in which the human artifacts are found, is thin, ranging in depth from five to 20 centimeters. Each settlement has between three and six dwellings built of mammoth bones. The dwellings vary from four to seven meters across, enclosing interior floor areas of from eight to 24 square meters.

There is no single pattern of alignment of the mammoth-bone structures. At some sites, including the one near the town of Mezin, the dwellings form a row. At others, including the settlement at Dobranichevka, they are in a rough circle. At still other sites the dwellings have a rectangular arrangement.

Inside many of the mammoth-bone dwellings are the remains of hearths where the inhabitants burned bone as

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fuel. There are also work areas where they fashioned bone and stone into tools and other artifacts. The ground between the dwellings is taken up by storage pits, outside hearths and work areas. Like their internal counterparts, the outside hearths contain burned mammoth bone.

Mezhirich, where our major work was done, includes at least five mammoth-bone structures. Between 1966 and 1977 four of the dwellings were excavated; the fifth currently remains covered. As at the other sites, each dwelling has a foundation wall assembled from large bones of the mammoth. The bones were not just packed into the structure at random. Instead their geometry was exploited as an element of the design.

Skulls were placed at regular intervals in an arc or a full circle to form the foundation of the interior base wall. There were several methods for inserting the skulls in the wall. At Mezhirich and Dobranichevka the skulls were put in with the rostrum (the portion of the skull holding the ends of the tusks) down. At Mezin, on the other hand, the skulls were put in with the occipital region (the back of the head) down. In both placements the flat frontal part of the skull faced the dwelling's interior. The interior wall was sometimes completed with pelvises and scapulas.

The foundation wall was extended upward and outward with bones arranged in an intriguing architectural-anatomical pattern. At Mezhirich the pattern is different for each dwelling that has been excavated. In Dwelling No. 1, which is circular, the upper part of the wall apparently consisted entirely of mandibles. The 95 mandibles are stacked above the skulls in a herringbone pattern with the chins down.

In Dwelling No. 2 the upper part of the wall is made primarily of long bones, such as femurs and tibias. These bones were aligned vertically. Dwelling No. 3 includes an amalgam of various bones; its structure lacks the clarity of the other three excavated dwellings, which suggests it may not have been finished when the site was abandoned.

Dwelling No. 4, which is still being excavated, has the most intriguing design of all. Like the other mammoth-bone structures, No. 4 has a base wall that is roughly circular. Unlike the foundation walls of the other dwelling units, however, the wall of No. 4 is not made from one type of bone: the specific construction material varies from one segment of the wall to the next. The stretch of wall that faces southwest is made of mandibles arranged in a herringbone pattern, mimicking the wall of Dwelling No. 1. Another segment is made up of long bones, as in Dwelling No. 2.

The aesthetic playfulness of Dwelling No. 4 at Mezhirich is not limited to replicating the designs of the other dwellings. The patterns shown in the

DWELLING NO. 4 at Mezhirich mimics the designs of the other mammoth-bone dwellings and introduces variations on those designs. In the other dwellings the builders assembled the base wall from one type of bone. In No. 4, however, each segment of the base wall consists of a different type of bone. Mandibles make up the segment at the lower right. Next to that segment is a piece of a vertebral column. Long bones, skulls and scapulas formed the material for other segments of the wall (*not visible*). The mandible section plays a variation on the design of Dwelling No. 1. In No. 1 all the mandibles are chin down, but in No. 4 two columns of mandibles with the chins down are stacked next to one column in which the chins point up.

other structures are also varied slightly. Whereas in Dwelling No. 1 all the mandibles are stacked with the chins down, in No. 4 the repetitive arrangement is given a twist. The matrix of rows and columns made up of mandibles includes two columns with the chins down next to a single column with the chins up.

The design also incorporates elements of repetition and symmetry. In one segment of the wall a skull is flanked by identical sequences of two scapulas and a pelvis that form mirror-symmetrical reflections of each other. The wall is filled out by pieces of the vertebral column that also show a rhythmic design.

The patterned arrangement of the mammoth-bone remains at Mezhirich makes it fairly clear what the base wall of the dwelling looked like. It is harder to be certain about the design of the roof. The upper part of the structure must have been supported by posts. Unfortunately few postholes have been found, and so we cannot be sure how the supports were arranged.

What has been found is a group of bones with manmade holes that could have served as supports for the vertical members. On the basis of such bones and other information, Pidoplichko concluded that the buildings were domed. Pidoplichko, who was the discoverer of Mezhirich and an authority on mammoth-bone dwellings, argued that the domes were covered with mammoth hides held in place by additional bones and tusks.

Although all the dwellings have significant structural features in common, they vary greatly in how elaborate the design is and in how much bone went into them. Dwelling No. 1 at Mezhirich includes about 21,000 kilograms of bone, No. 2 about 19,000 and No. 4 about 15,000. In contrast, several of the structures from Dobranichevka and Mezin include only 1,000 kilograms of bone apiece.

As a result the investment of labor in the dwellings at Mezhirich must have been much greater than the investment at some of the other sites. We estimate that it would have taken 10 men at least 5.6 days to erect Dwelling No. 1, 5.2

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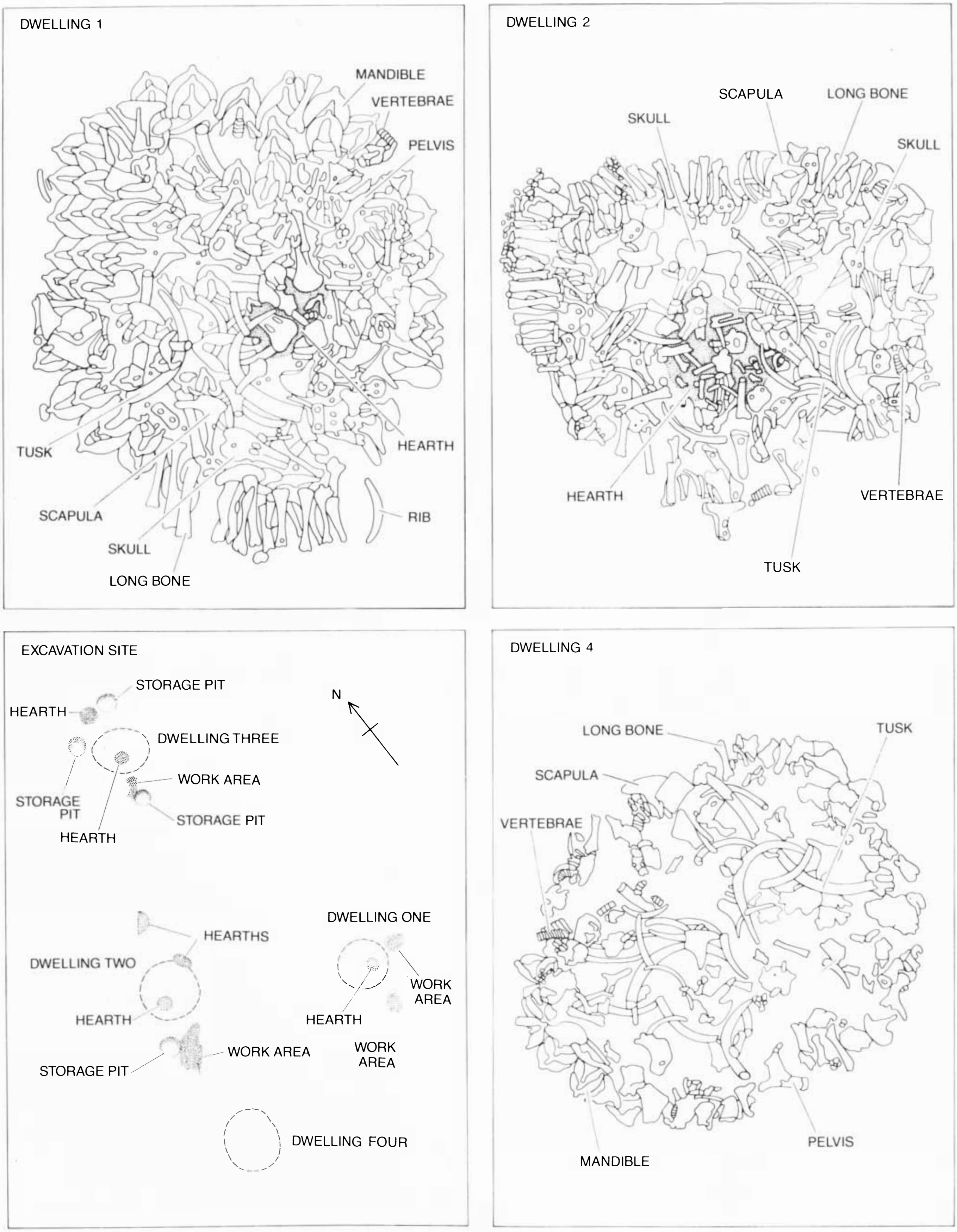

MEZHIRICH SITE PLAN (*lower left*) **shows the location of the four mammoth-bone dwellings that have been excavated. Some evidence suggests that a fifth dwelling remains covered. In the space between the buildings were work areas where tools were made, hearths where bone was burned as fuel and pits for preserving bone and meat. The upper panels and the panel at the lower right show the excavations of dwellings No. 1, No. 2 and No. 4, which have the most developed architectural plans. Dwelling No. 2 was built mainly out of long bones.**

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days to erect No. 2 and 4.3 days to erect No. 4. The smaller dwellings at Mezin and Dobranichevka probably took only a little more than about half a day each to put up. Moreover, these estimates do not take into account the greater intricacy of the architecture at Mezhirich, which undoubtedly increased the disparity in labor time even more.

The complexity of design evident in the buildings at Mezhirich as well as the large amount of labor needed to construct the dwellings suggests that something out of the ordinary was going on at the settlement. It is possible that at Mezhirich building was a ritualized practice. What such rituals might have been is not yet known.

Besides Mezhirich, only one other known site has such detail: the site called Yudinovo, which is currently under excavation. If sites excavated in the past included intricate designs, the designs were not recognized, perhaps because of crude digging techniques.

The channeling of surplus labor suggested by the dwellings at Mezhirich has significant implications for a prehistoric community, and we shall return to these implications. Before doing so it is necessary to consider what is known about the Paleolithic hunters' economy and to describe the artifacts other than the dwellings that were found at the site.

The builders of the mammoth-bone dwellings were not nomads. Settlements such as Mezhirich were occupied over a period of many years. There are also some sites in the region without mammoth-bone dwellings that were built during the same period. It is probable that the hunting bands alternated between the two types of settlement on a seasonal basis. The sites with mammoth-bone structures were probably utilized during the nine-month cold season. The other sites served as temporary warm-weather camps and workshops for making stone tools.

As the Paleolithic hunters moved between their winter and summer homes their economic activities centered on the harvesting of large mammals. The periglacial steppe habitat, which has no contemporary equivalent, supported big herds of gregarious herbivores. In addition to the woolly mammoths there were rhinoceroses, reindeer, horses, bison, musk oxen and also smaller animals such as hares.

The large mammals, which provided the local hunters with the bulk of their caloric intake, were supplemented with fish and birds. The Paleolithic sites include the bones of salmon, perch, pike, ducks, geese, swans and arctic ptarmigans. The wolf and the arctic fox were also taken, but the way the carcasses were treated indicates that these species were hunted for their pelts rather than for their flesh.

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"The first target was NGC 1502, an open cluster forming two diverting chains of stars, one chain containing an easy 7th magnitude pair, which served as a guidepost. Two degrees of declination away is the 12th magnitude planetary NGC 1501, which appeared as a disc seen best at powers from 60 to 130x. I found it again the following weekend despite humid atmosphere and the presence of a 3-day old moon in the west.

"In Gemini I observed NGC 2158. *Burnham's* gives 12th magnitude for this open cluster, but its brilliance in the Questar would indicate that it is probably brighter than 12th.

"The most difficult object I have observed so far is NGC 2438, the planetary nebula within M46. Although *Burnham's* lists it as magnitude 11, I found it more difficult than 1501 which is supposedly one magnitude fainter. I was glad to have seen it, as the *Cambridge* Deep Sky Atlas lists it as an object for at least a 6-inch scope."

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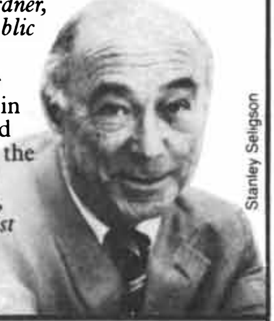

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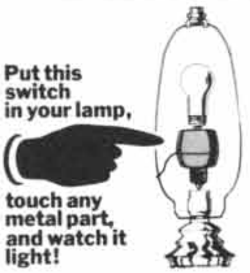

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Although the Paleolithic inhabitants of the steppe were clearly hunters, it is possible that collecting played a significant role in their economy. Bones from a large number of individual mammoths have been found at some sites: 93 at Gontsy, 116 at Mezin and 149 at Mezhirich. The bones from the different carcasses vary greatly in their degree of preservation. Indeed, the variation is so great that it suggests some of the bones were picked up from skeletons of long-dead animals. If many bones were collected rather than hunted, mammoths might have been less significant as a source of food than the number of bones by itself would suggest.

Flesh obtained by hunting and also perhaps bones obtained by collecting were put in pits near the dwellings. The pits were as deep as 1.5 meters, which was deep enough to penetrate the thaw layer of the permafrost and provide extended protection of the meat.

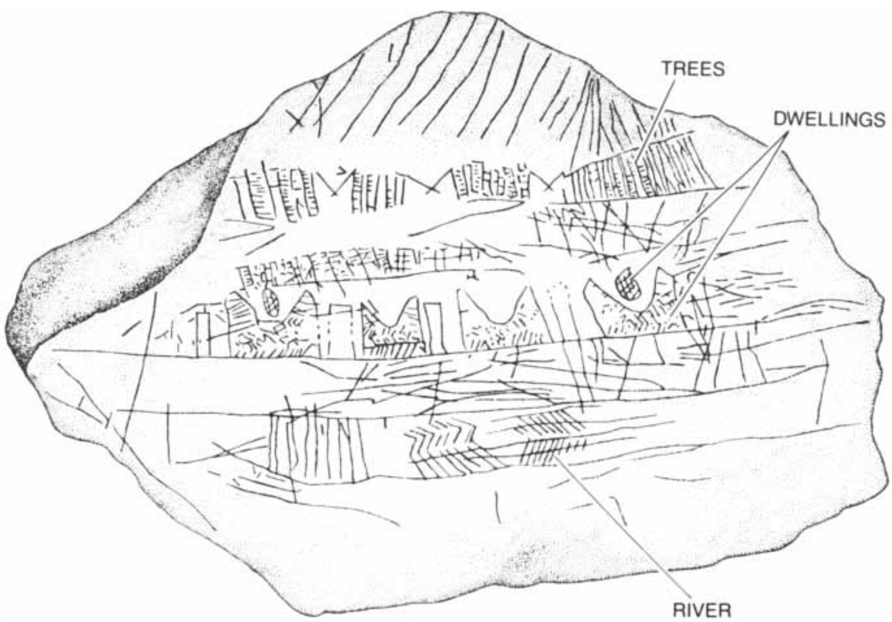
In the processing of meat and the building of the mammoth-bone dwellings stone tools played a crucial role. Among the types of stone tool found at Mezhirich and other Upper Paleolithic sites on the Russian plain are end scrapers for processing hides, burins for shaping hard material such as antlers or ivory, push planes for shaping bone into spearheads and stone points for the initial cutting of meat.

One of the reasons stone tools had such a central position in Upper Paleolithic culture is that they were employed to make artifacts from other materials. Among these materials were bone and ivory, which formed the material for utilitarian objects such as hammers, hoes, piercers, awls, burnishers and needles (with eyes!).

Members of the community also made nonutilitarian objects from bone and ivory. Among the art objects from Mezhirich and Mezin are many mammoth bones covered with designs in red ocher. The residents made decorative objects to wear as well as for their dwellings. From Mezin and Mezhirich come necklaces of seashells, amber and bone beads and perforated wolf and arctic-fox teeth that were used as pendants. The art of the community had advanced beyond decoration to representation: the objects found at Mezin and Mezhirich include stylized figurines.

It is notable that the material for some of the art objects originated quite far from the settlements where they were found. The fossil shells from Mezin were found in marine deposits between 600 and 800 kilometers from the site. The amber used to make beads found at Mezhirich comes from deposits near Kiev, about 150 kilometers distant. The presence of materials from far away suggests that an extensive exchange network existed among the hunter-and-gatherer groups. The network extended from Mezhirich south to the Black Sea and a considerable distance to the west.

The findings discussed so far offer a picture of groups moving seasonally between established camps, hunting large mammals for food and clothing and collecting bones for tools and shelter.



MAMMOTH-IVORY CARVING found at Mezhirich may be the earliest map known. One of the authors (Kornietz) interprets the carving as a map of the Paleolithic community at Mezhirich, including trees, mammoth-bone dwellings and a river. The river could be either the Ros' or the Rosava, the two rivers that join at the site of the contemporary village of Mezhirich. (The name Mezhirich means "between two rivers" in Ukrainian.) Paleogeographers have not been able to determine which of the rivers was closer to the settlement in Paleolithic times.

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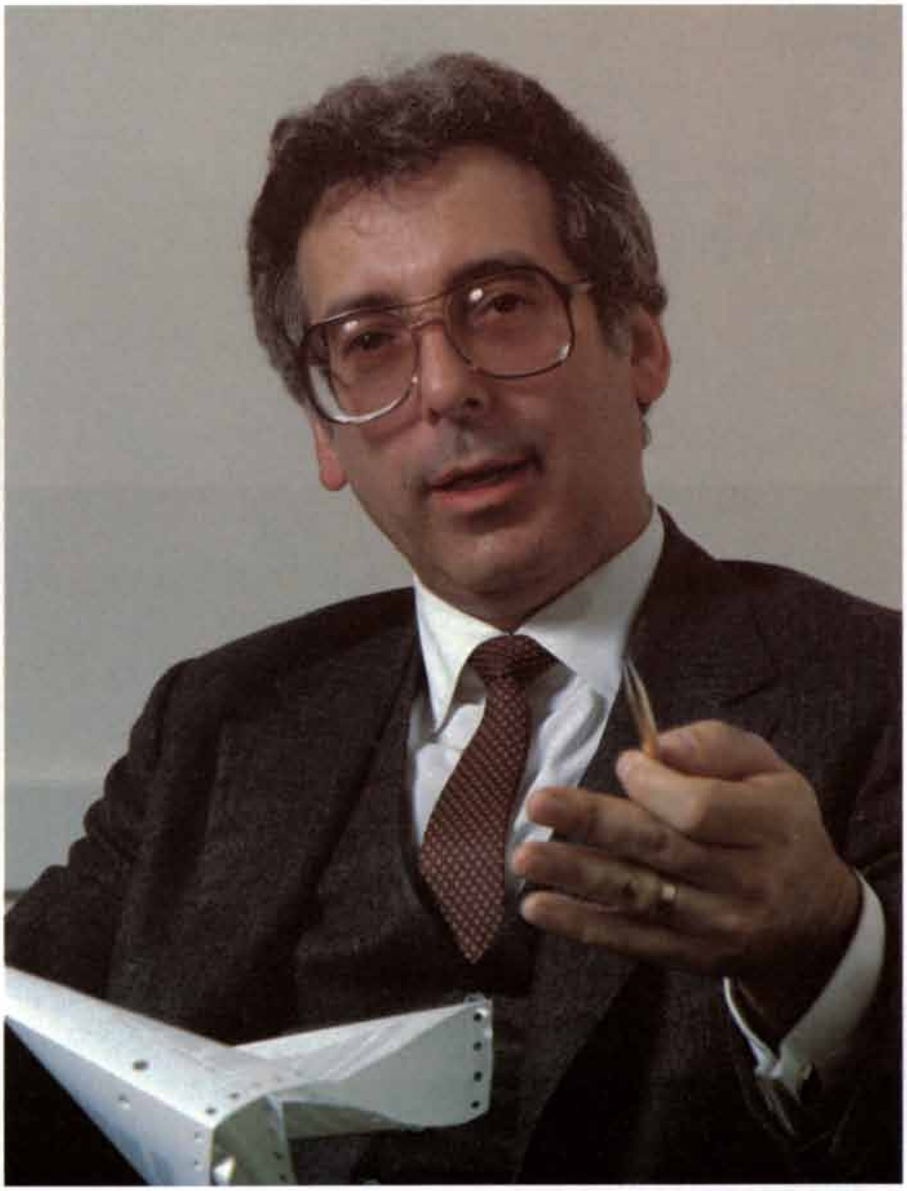

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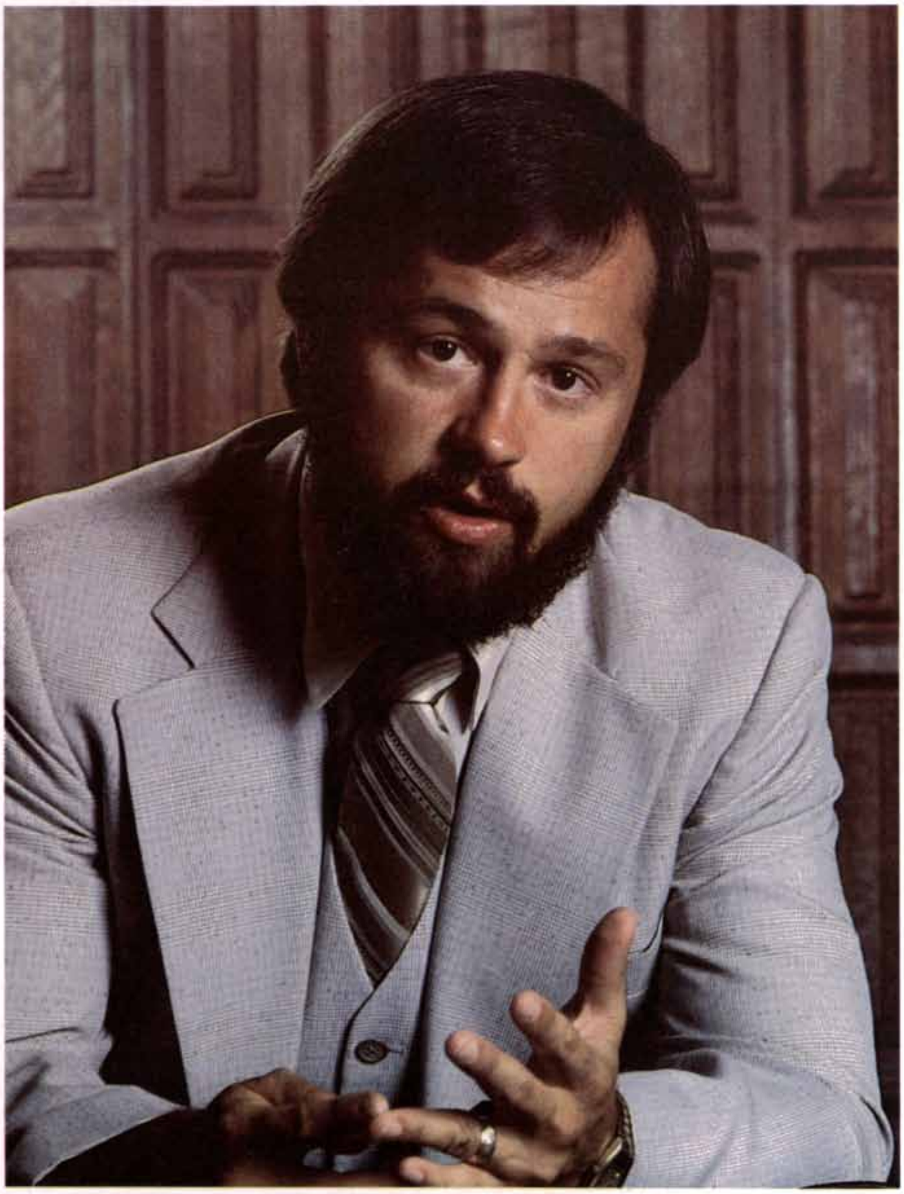

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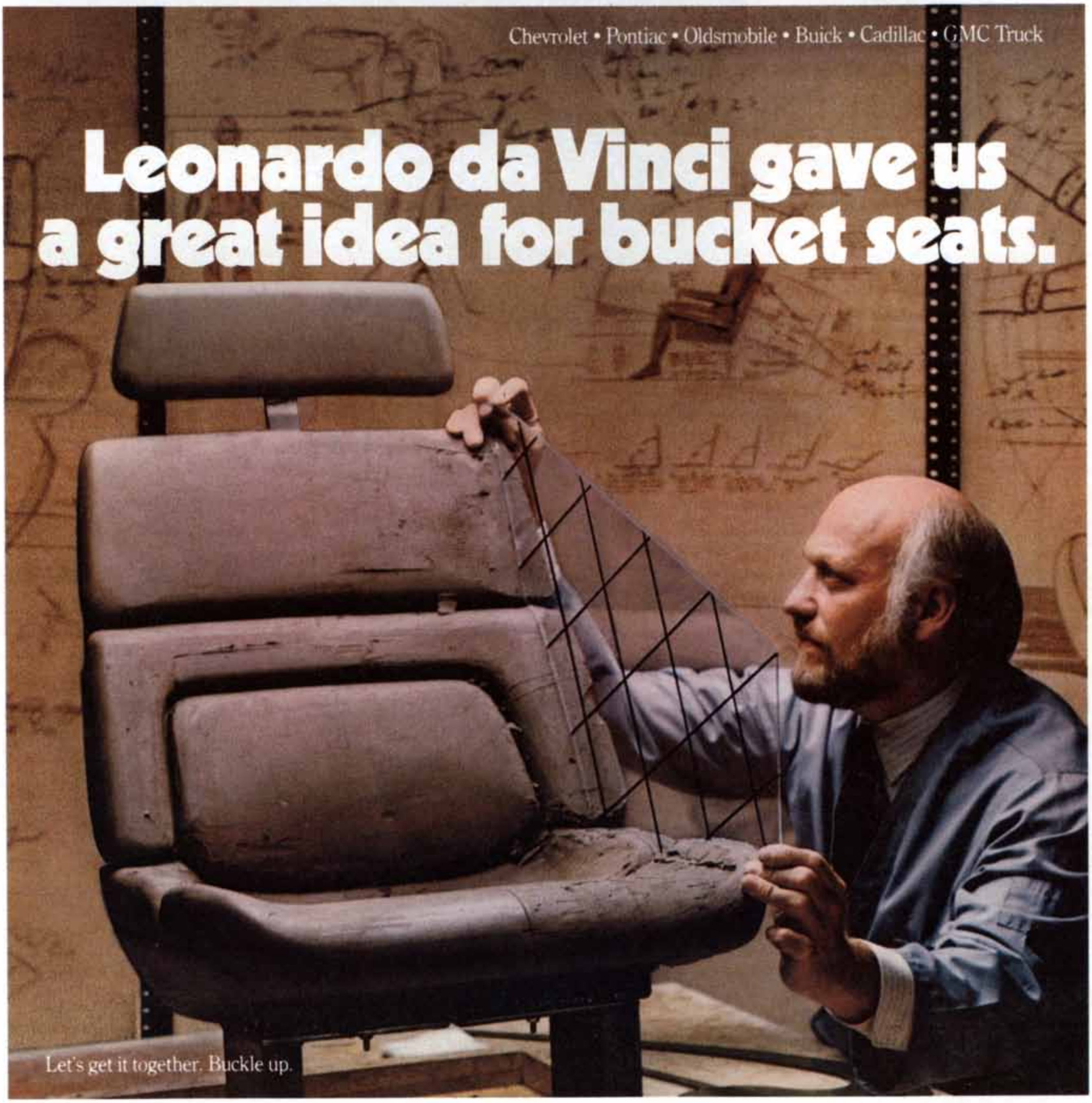

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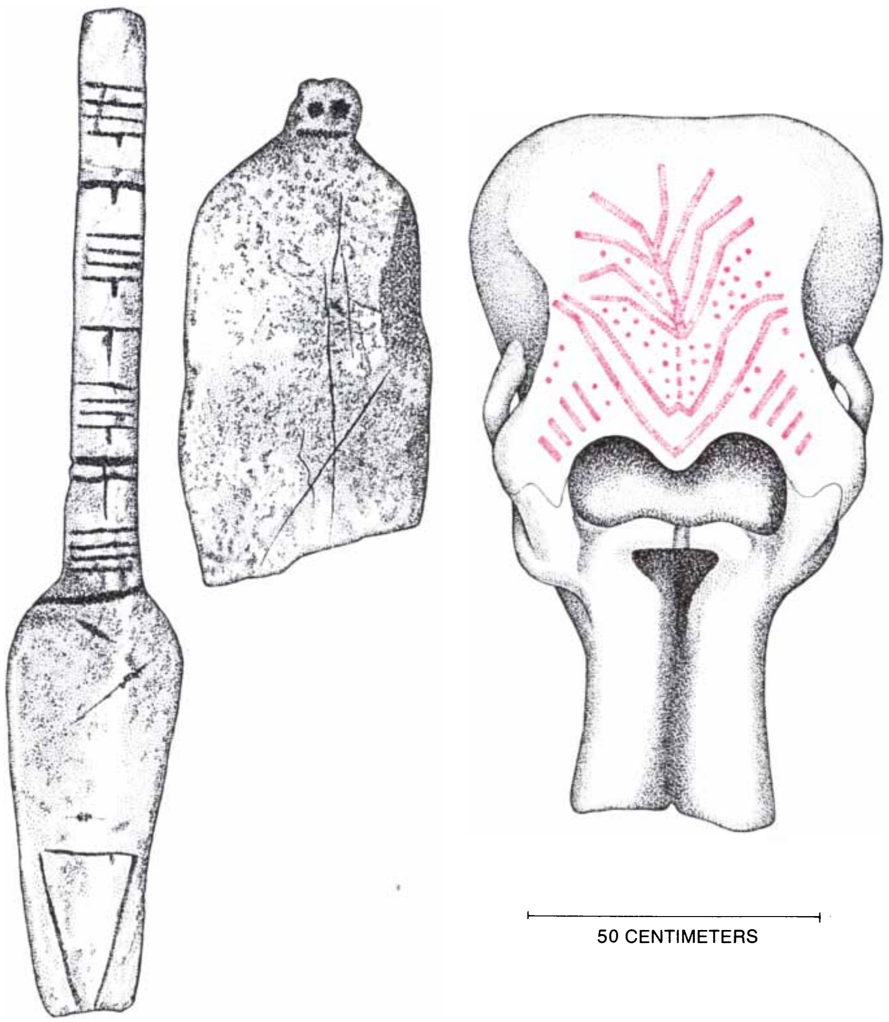
Measurement of the floor space at Mezhirich suggests that the community there included at least 50 members.

What type of social system did these 50 people have? Although it is not easy to reconstruct the belief system or social structure of a vanished people, some inferences can be made from the physical record. The fact that the groups occupied permanent camps implies they had a mechanism for settling disputes. In truly nomadic groups conflicts can be resolved by fission: the disputants simply head in different directions. In a community that has invested heavily in storing food and constructing dwellings, however, there must be institutions for keeping the peace.

What these institutions were is not known, but it is possible they could have been connected to emerging distinctions in social status. In some sites there is an unequal distribution of storage pits, suggesting that some households were able to obtain more of the surplus than others. An emerging status hierarchy could also have been the means of directing the labor needed to construct the mammoth-bone dwellings.

It is generally accepted that the division of human society into groups with unequal status did not occur before the Upper Paleolithic period, when the mammoth-bone dwellings were built. Hence the excavations at Mezhirich and the other sites on the Russian plain may form a window onto a crucial phase of social history: the period when status inequalities came into being. Such a conclusion remains speculative and much work will be needed to confirm it.

The work that has been done at Mezhirich and the other sites, however, tells us a good deal about the builders of the mammoth-bone dwellings. They were affluent foragers in a relatively rich environment. This environment, the Russian plain, was an important part of the Paleolithic world. It was a region where complex hunter-and-gatherer adaptations were common and where a new level of social development may have been achieved.



ART OBJECTS found at Mezhirich suggest a relatively affluent community and one with a fairly high level of cultural development. The object at the left is a stylized female figurine. The object in the middle probably represents a human figure. Both are shown actual size. The mammoth skull at the right bears red-ocher designs. The skull was found in Dwelling No. 1 and can be seen in the illustration on page 165 behind the row of bones fronting the entrance.

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Gothic Structural Experimentation

Gothic builders used the cathedrals themselves as models, modifying designs as structural problems emerged. An analysis of buttressing patterns shows that information spread rapidly among building sites

by Robert Mark and William W. Clark

The cathedral of Notre-Dame de Paris, the construction of which began between 1150 and 1155, was planned to be the tallest space in Gothic architecture. Its vaulted ceilings rise some 33 meters above the floor, more than eight meters higher than those of any of its early Gothic predecessors; the relative increase in height over previous buildings, more than one-third, was the greatest of the entire era. Nevertheless the structural configuration of the Paris choir (the eastern part of the cathedral where services are sung), which was built first, was essentially similar to that of earlier, smaller churches. The outward thrust of the interior vaults against the high window wall (the clerestory) was resisted only by stone quadrant arches hidden under the sloping roof of the adjacent gallery.

In designing the somewhat wider nave, however, with its lighter and more open structure, the Paris builders evidently decided that the concealed quadrant arches were insufficient to support the high clerestory. The increased width meant that the outward thrust of the vaults was greater than the thrust in the choir. More important, in building the choir the craftsmen must have become aware of a new problem for which experience with lower churches could not have prepared them: wind speeds are significantly greater at higher elevations. Wind pressure, it is now known, is proportional to the square of wind speed, and so it has a much stronger impact on tall buildings. Concern for wind loading, we believe, led the builders of the Paris nave to introduce the flying buttress just before 1180. Although similar in structure to the concealed quadrant arch, the flying buttress was exposed and supported the wall at a higher level.

In less than two decades the flying buttress became the stylistic hallmark of Gothic building. The origins and the dissemination of such technological developments in the Middle Ages have long interested historians. Our own structural analyses of a number of medieval buildings have revealed that their designers learned from experience, using the actual buildings in the way today's engineer relies on instrumented prototypes to ascertain the structural behavior of a design. The observation of cracking in weak, newly set mortar, for example, often led to structural modifications that were undoubtedly an important source of design innovation.

Moreover, the experience gained at one building site was transmitted to other construction projects: the earlier building acted as an approximate model to confirm the stability of a new design. Our analysis of Notre Dame and its architectural influence demonstrates a ready communication between medieval building sites and the rapid transmission of technological innovations, in particular the flying buttress. The master masons of later cathedrals, such as those at Chartres and Bourges, seem even to have been aware of flaws in the original buttressing scheme at Paris and to have modified their own designs accordingly.

The Gothic period coincided with late-medieval advances in the manufacture of cloth and an expansion of trade that produced great wealth and led to the growth of cities. The new wealth spurred a prodigious building activity that changed the face of western Europe. In northern France the success of the Gothic style can be seen in practically every village and town.

Unfortunately there are few textual records from before the 13th century to document the work of the Gothic builders and to trace communication among them. Most of the surviving written evidence consists of little more than appreciative remarks by nonspecialists, usually the patrons of a building. The classic example is the Abbot Suger's tantalizing but frustratingly incomplete descriptions of the new construction he commissioned in about 1130 for the abbey church of Saint-Denis, near Paris, the first example of the Gothic style. Another unique document is the year-by-year chronicle by the monk Gervase of the rebuilding of Canterbury Cathedral from 1174 to 1184. Neither of these texts, however, mentions any technological development or indicates that ideas were communicated from one building site to another. Nor have architectural drawings from the 12th century survived, if indeed they ever existed; the earliest evidence of the use of drawings to record and transmit architectural ideas dates from about 1225, almost at the time when Gothic construction activity began to decline.

In the absence of documents the building technology of the Gothic era is best described by studying the buildings themselves. One approach is archaeological. By noting even the most subtle changes in structure and ornament from one part of a cathedral to another it is possible to determine the order in which the different sections were built and usually to identify major episodes of construction. In some cases the construction sequence can be plotted almost year by year, as the Australian architect John James has done for the cathedral of Chartres. Through the systematic archaeological study of a series of buildings we are on the verge of being able to follow the work of individual craftsmen as they moved from site to site, carrying with them information on new construction developments. The artistic signatures of these artisans are discernible in their handling of structural and decorative details.

A second approach to studying Gothic churches relies on modern tools of structural analysis to understand how the buildings actually function. One such technique, which we have employed extensively, is called photoelastic modeling [see "The Structural Analysis of Gothic Cathedrals," by Robert Mark; SCIENTIFIC AMERICAN, November, 1972]. A transparent plastic model of a cathedral cross section is heated to about 150 degrees Celsius, at which

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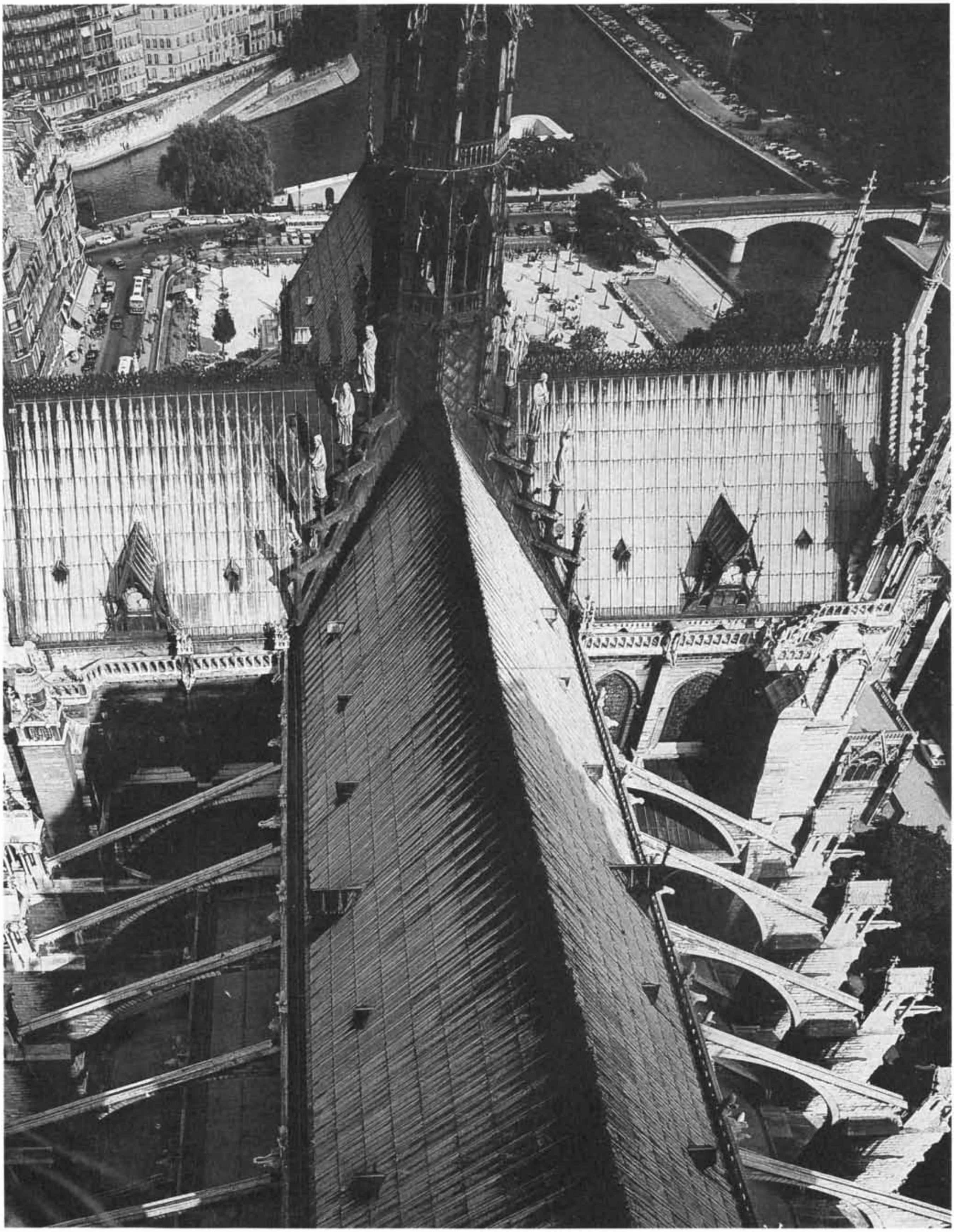

CATHEDRAL OF NOTRE-DAME DE PARIS was the tallest of the Gothic works of the 12th century. The first flying buttresses supported its vast nave. The cathedral was rebuilt extensively in the 13th and 19th centuries; the present buttresses, seen in this view from one of the west towers, are very different from the 12th-century originals. An arch embedded in the buttress wall perpendicular to the south transept (*at right in the photograph*) suggests the disposition of the original flying buttresses (*see top illustration on page 179*).

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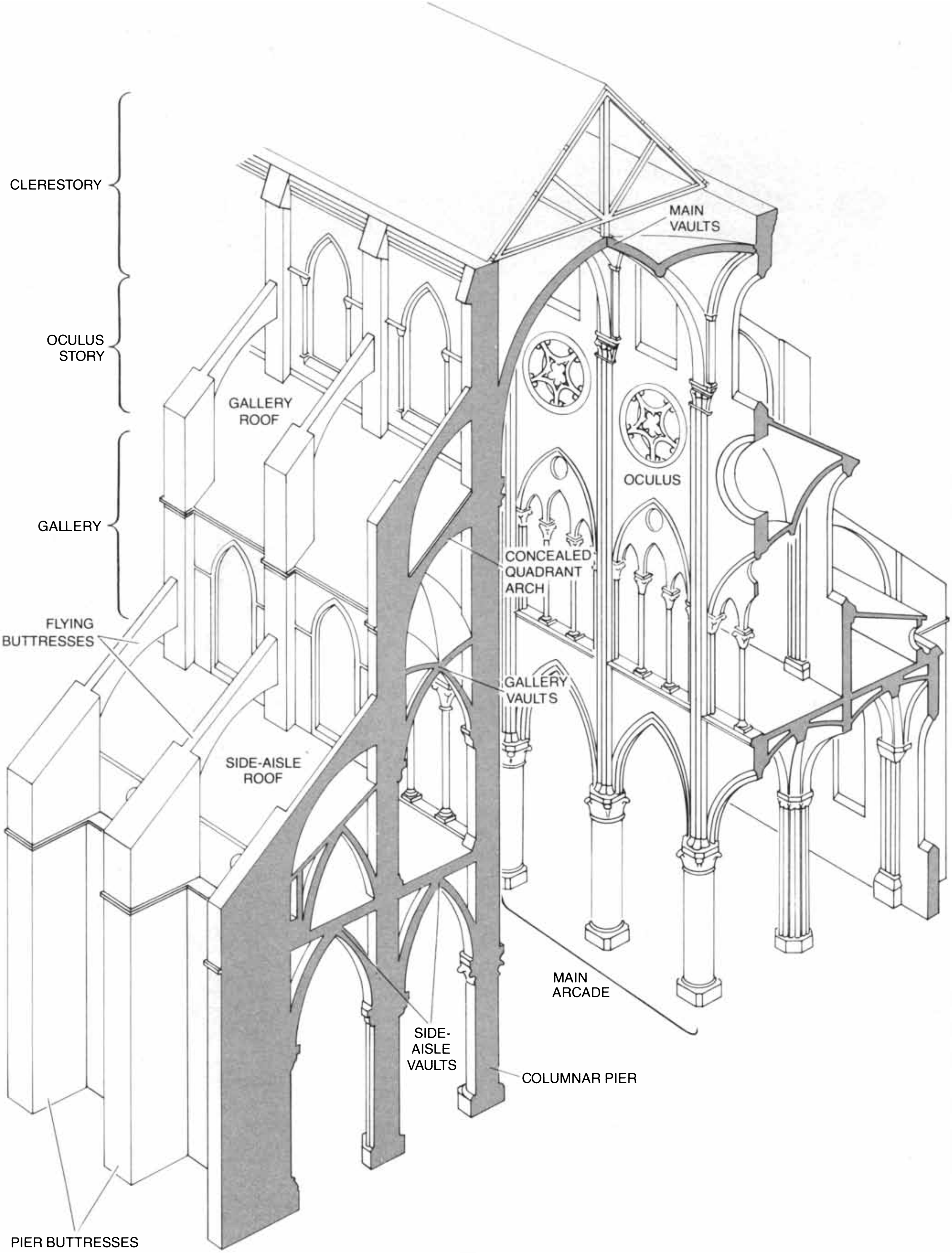

CUTAWAY VIEW OF NOTRE DAME shows the main interior elevation of the original nave (before the 13th-century rebuilding campaign) as reconstructed by the authors on the basis of archaeological and structural analyses. The upper flying buttresses transferred outward thrusts resulting from wind loading to the gallery-level fliers, which in turn transferred those thrusts to the pier buttresses. To the left of the main aisle the cross-section cut (*gray*) is through the buttresses and the piers; to the right it is through the middle of a bay.

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temperature the plastic becomes rubbery and is easily deformed by the application of weights that simulate the forces of dead weight and wind on the building. The deformations are locked in when the model is cooled and produce an interference pattern when it is viewed through crossed polarizing filters. The interference pattern can be interpreted as a contour map of stress and can thus reveal possible design flaws in the building.

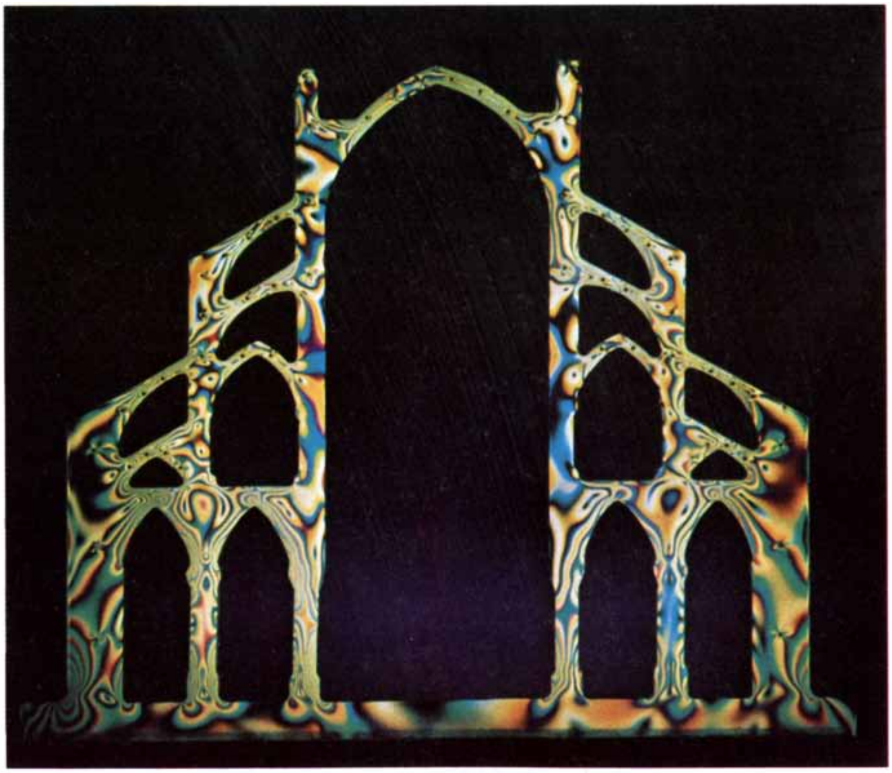
The study of Notre-Dame de Paris by these two approaches has led us to a new reconstruction of the original nave and of the first flying buttresses. The entire buttressing system was extensively rebuilt beginning in the 1220's, and massive restorations were also carried out in the mid-19th century. Archaeological evidence suggests that the original buttressing scheme was much simpler than has previously been thought. It included two separate tiers of flying buttresses: an upper tier above the gallery roof to brace the high clerestory wall and a lower tier to strengthen the outer gallery wall and to help resist the outward thrust transferred by the upper fliers.

The major evidence of this arrangement is a quadrant arch still preserved in the inner face of a wall buttress supporting the south transept [*see top illustration at right*]. Although it is embedded in the wall and has never been open in the manner of a true flying buttress, its curve almost certainly reflects that of the open flier arches that supported the clerestory of the adjacent nave. This means the original upper fliers must have abutted the main wall at a point about halfway up the original window opening. The lower, or gallery, rank of flying buttresses survived more or less intact until the 19th-century restorations, and so their configuration can be determined from drawings and early photographs made before that building campaign. Further architectural details are suggested by the contemporaneous church of Saint-Martin at Champeaux, which belonged to the bishop of Paris and whose flying buttresses are thought to reflect the original buttressing scheme of the Paris cathedral.

Beginning in the 1220's this scheme was changed dramatically: the upper flying buttresses were replaced by giant fliers that spanned both side aisles. (The original upper fliers had spanned only the inner side aisle, from the clerestory to the gallery wall.) What prompted this change in design?

Earlier investigators have argued that the change was part of an effort to allow more light into the cathedral. The Paris builders seem to have been unprepared for the decrease (compared with earlier buildings) in the amount of light reaching the floor of the church, an effect resulting from its significantly higher

TWELFTH-CENTURY WALL BUTTRESS above the gallery on the south transept at the cathedral has embedded in its inner face an arch that probably repeats the arc of the original upper fliers, which supported the adjacent nave clerestory. This archaeological evidence suggests that the first flying buttresses abutted the clerestory at a point about halfway up the original windows, well below the roof. In the 13th century the upper fliers were replaced by huge flying buttresses spanning both side aisles, and the clerestory windows were enlarged.



PHOTOELASTIC MODEL of the original nave of Notre Dame reveals the distribution of stresses induced by simulated wind loading and shows there probably were structural reasons for rebuilding the flying buttresses. The transparent plastic model is viewed with the aid of polarizing filters. The resulting interference pattern is a contour map of stress intensity in which each color corresponds to a different level of stress. Critical regions occur where the colored lines are closely spaced. Significant tension was found where the flying buttresses abut the clerestory and the gallery. Mortar cracking in these regions probably necessitated frequent repairs until the construction of the new buttresses in the 13th century eliminated the problem.

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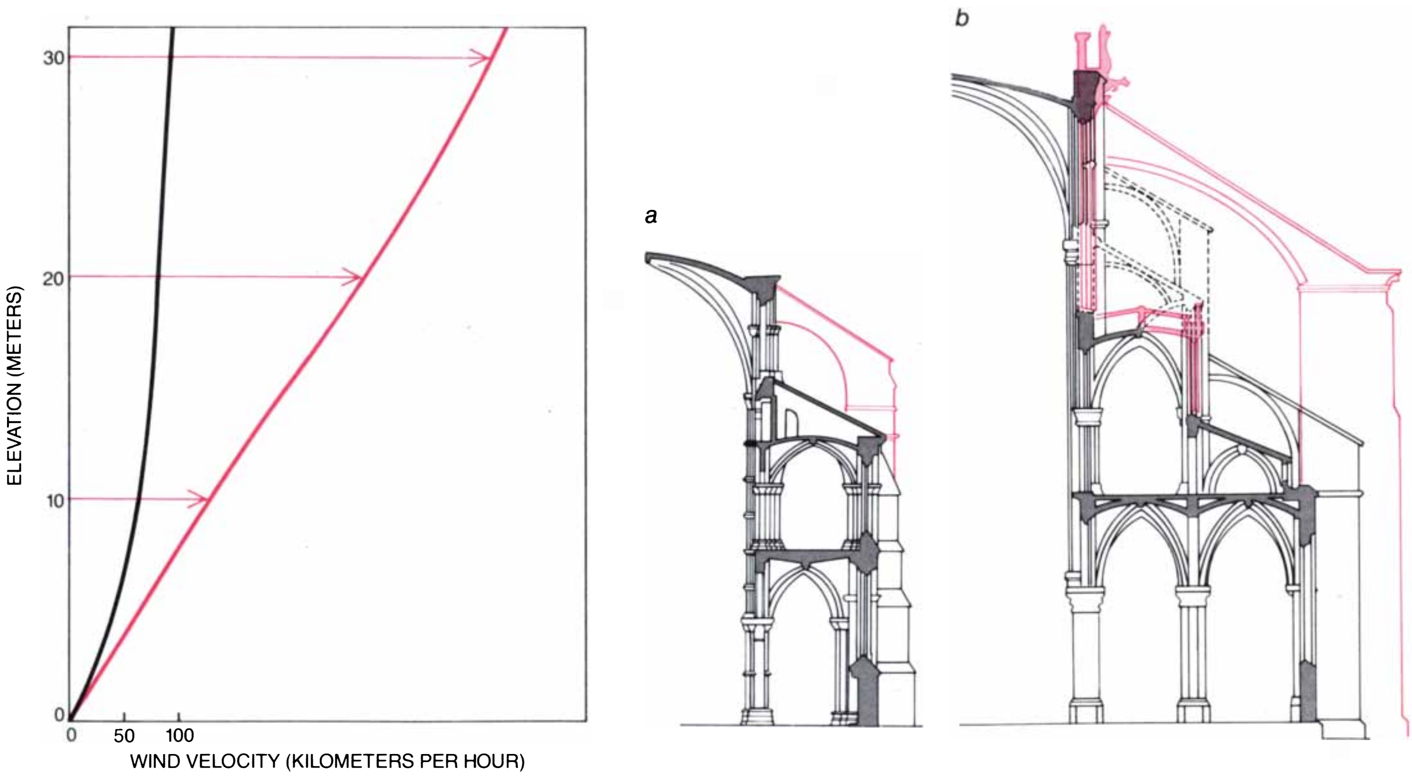
walls. The problem must have become apparent in the choir, however, because in the subsequent construction of the nave the builders raised the height of the gallery vaults and enlarged the gallery windows.

According to one argument, these changes were insufficient to dispel the darkness in the church, and this led directly to the decision in the early 13th century to enlarge the clerestory windows to their present size. To lower the base of the windows it was necessary to lower the roof and outer wall of the gallery; as a result the builders had to modify the flying buttresses, because they were structurally part of the gallery wall. In other words, according to this argument, the changes in structure were only a by-product of the need to change the window design.

Our structural analysis indicates, however, that the rebuilding of the first flying buttresses may actually have been a response to structural problems inherent in the original design. Initially undertaken to confirm the technical validity of the new archaeological reconstruction, photoelastic modeling revealed unanticipated critical levels of tensile stress in two regions of the windward buttressing: where the upper fliers abutted the clerestory and where the lower fliers joined the gallery wall. During particularly severe storms, which present-day meteorological records suggest would have struck Paris from time to time in the 40-to-50-year lifetime of the original buttresses, the wind-produced tension in these regions would have been from three to five times greater than the tensile strength of medieval mortar. Because of the highly localized nature of the tension, it is doubtful that major problems with the fabric would have arisen. The cracking would have been readily apparent, however, and repairs, including the pointing of the affected joints, would have had to be made promptly after every great storm to prevent general deterioration.

Such regular maintenance, however, would have been difficult because the regions in question were relatively inaccessible. This suggests it was more than a coincidence that the 13th-century rebuilding effort eliminated these regions of localized tension. The point of abutment of the new giant fliers with the clerestory was considerably higher, and they also significantly reduced the thrust in the gallery-level fliers.

In making the crucial structural changes, the builders probably seized the opportunity to try to raise the light level in the church by enlarging the clerestory windows. Whereas the structural problems of the original design were effectively solved, the benefits derived from the larger windows were at best slight; as anyone who has visited Notre-Dame de Paris will remember, it remains a dark building.



DEVELOPMENT OF GOTHIC BUTTRESSING reflects the recognition of structural problems associated with the original flying buttresses at Notre Dame. The evolution is depicted here by a sequence of building cross sections and a wind-velocity graph drawn to a common scale. Additions to the original design of each building are shown in color; elements that were eliminated are indicated by broken lines. Maximum wind velocity (*black curve*) increases with elevation, and wind pressure, which is proportional to the square of velocity (*colored curve*), increases dramatically. Because of its great height Notre Dame (*b*) was exposed to more severe wind stresses than previous Gothic churches were. The need to brace the nave wall against winds while allowing light into the church prompted the first

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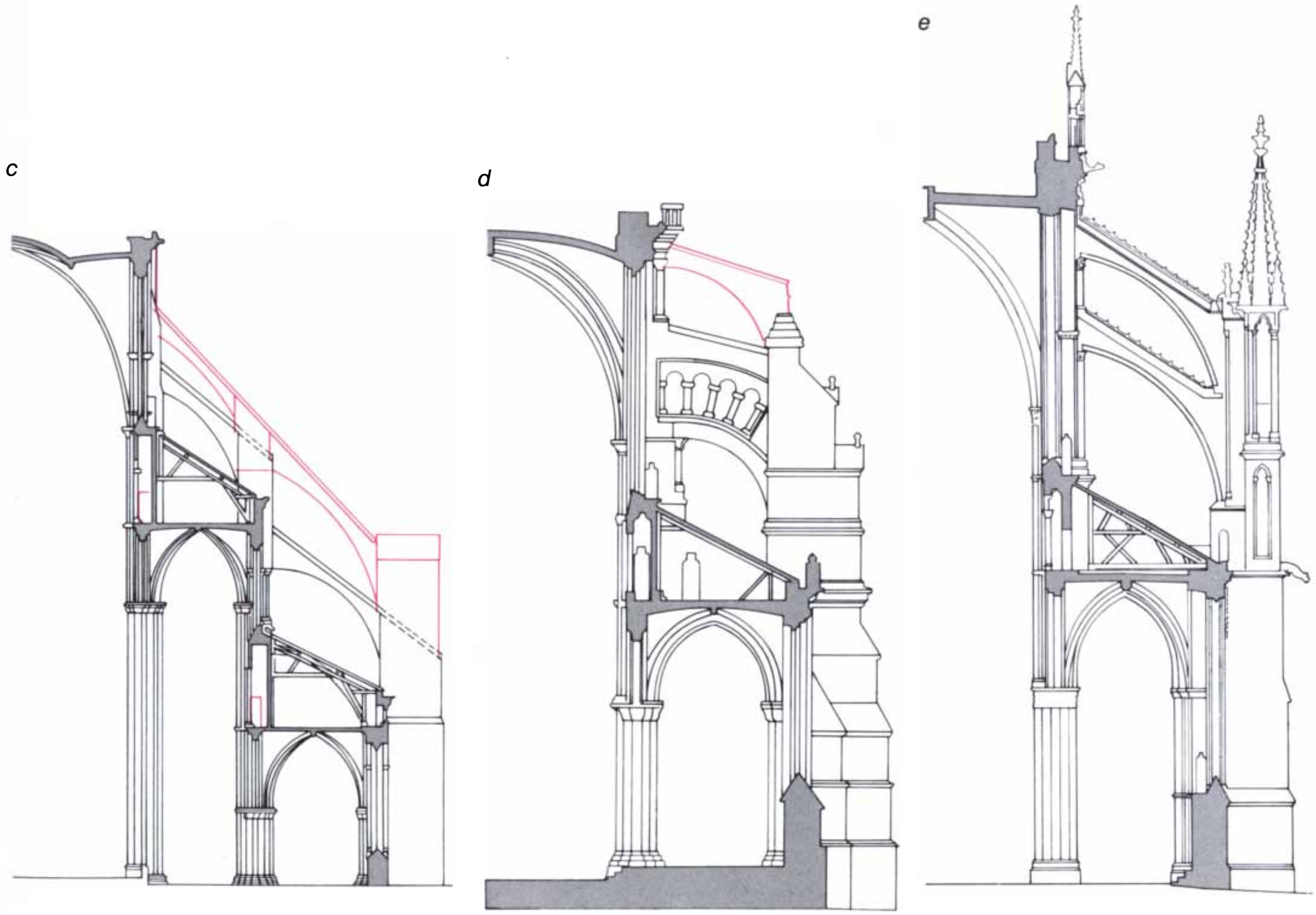
Even before Notre Dame was rebuilt the lessons learned there had been applied at other building sites. The choir of the cathedral of Bourges, constructed between 1195 and 1214, is a simple, light yet sound structure. Its elevation is unique: instead of achieving great height—36 meters from floor to keystone—by enlarging the clerestory, the builders dramatically elevated the inner side aisles. The resulting cross section is more triangular than the cross sections of classic High Gothic buildings such as Chartres and Reims, and the wide, stable base makes the walls less susceptible to lateral deformation. Furthermore, the buttressing system is unusually efficient. Because the fliers were steep, they transmitted the horizontal thrusts from vaulting and wind loading to the foundations more directly, and as a result the entire system of supports could be made lighter. Modeling has indicated that, in spite of its extreme lightness, maximum stresses in the Bourges choir are only one-half to two-thirds as great as those found in other large Gothic churches. In critical regions where tensile stresses tend to develop, such as at the ends of the flying buttresses, the Bourges choir outperforms any other large Gothic building we have analyzed.

How, at this early stage in the development of Gothic buttressing, did the Bourges master arrive at such an effective design? Bourges is often linked to Notre-Dame de Paris, because it has five aisles throughout and a similar ground plan. The late Robert Branner, author of the only modern monograph on Bourges, *La Cathédral de Bourges et sa place dans l'architecture Gothique* (Éditions Tardy, 1962), thought the unknown master had been trained not at Paris but to the northeast, in the Aisne River valley. A comparison of the cathedral's cross section with that of our reconstruction of the original Paris nave, however, reveals a striking similarity in spatial proportions. This similarity suggests that the design of Bourges may have been derived from Paris (and also provides additional corroboration of our Paris reconstruction).

The evidence that the original inspiration for the Bourges buttressing came directly from Paris is actually even stronger. From his archaeological analysis Branner concluded that the original design at Bourges called for only a single flight of fliers to support the choir clerestory, rather than the present double flight. Our own investigations suggest the same is true of the aisle buttressing system. The upper flight of aisle fliers visible today was probably not part of the original plan, and the great pier buttresses to which the fliers transferred outward thrusts were correspondingly shorter. When this scheme is compared with our reconstruction of the Paris nave, the buttressing patterns are seen to resemble each other closely.

At some point during construction the



use of the flying buttress in about 1180. The buttressing was rebuilt beginning in the 1220's in response to structural problems; the new scheme also enabled the builders to lower the gallery roof and enlarge the clerestory windows. Fliers were subsequently added to the cathedral of Laon (*a*), built at about the same time as Notre Dame, even though it was much smaller and probably did not need them. The original designs of the Bourges choir (*c*), completed in 1214, and of the Chartres nave (*d*), completed in 1221, were modified after cracking was observed at Paris. At both buildings upper fliers were added to reinforce the high walls against wind loading. In the Reims nave (*e*) the upper fliers were placed to resist wind loading on the clerestory and roof; the lower ones countered the outward thrust of the vaults.

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BUCKLE UP FOR SAFETY.

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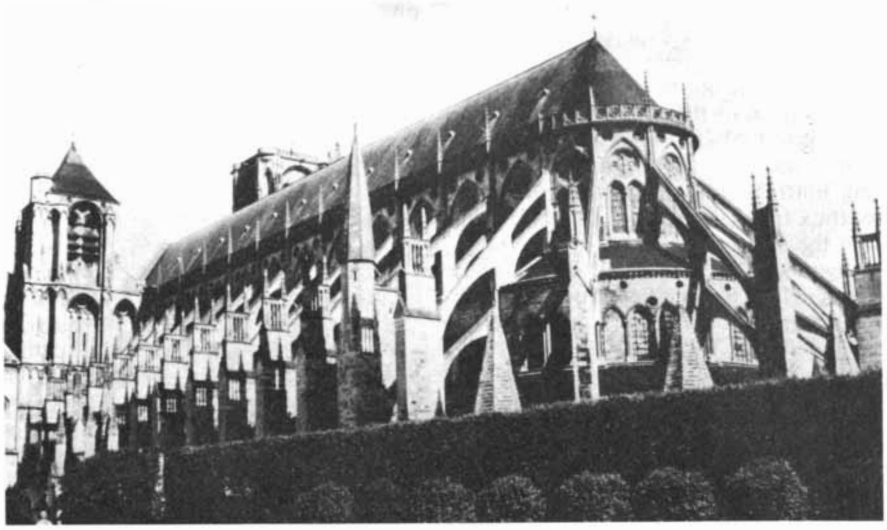
design at Bourges was changed to the one that is still visible. The exact date of this decision is not known, but it probably was made sometime between 1208 and 1214. By then most of the nave at Paris had been standing for perhaps two decades, and it is likely that mortar cracking due to inadequate wind bracing had already been observed. The decision at Paris to construct new flying buttresses abutting the clerestory at a higher level was probably being discussed by the second decade of the 13th century. The bifurcation of the main flying buttresses at Bourges and the raising of the point of abutment of the upper flier with the clerestory, as well as the addition of the second flight of aisle buttresses, can all be seen as precautionary measures taken by a master mason who had heard about the problems at Paris. As it turns out, the movement upward of the abutment of the clerestory fliers was particularly prudent. Photoelastic modeling has shown that the abutment region is the only one in the cathedral where critical tensile stresses tend to develop and that lower abutment would have worsened this problem.

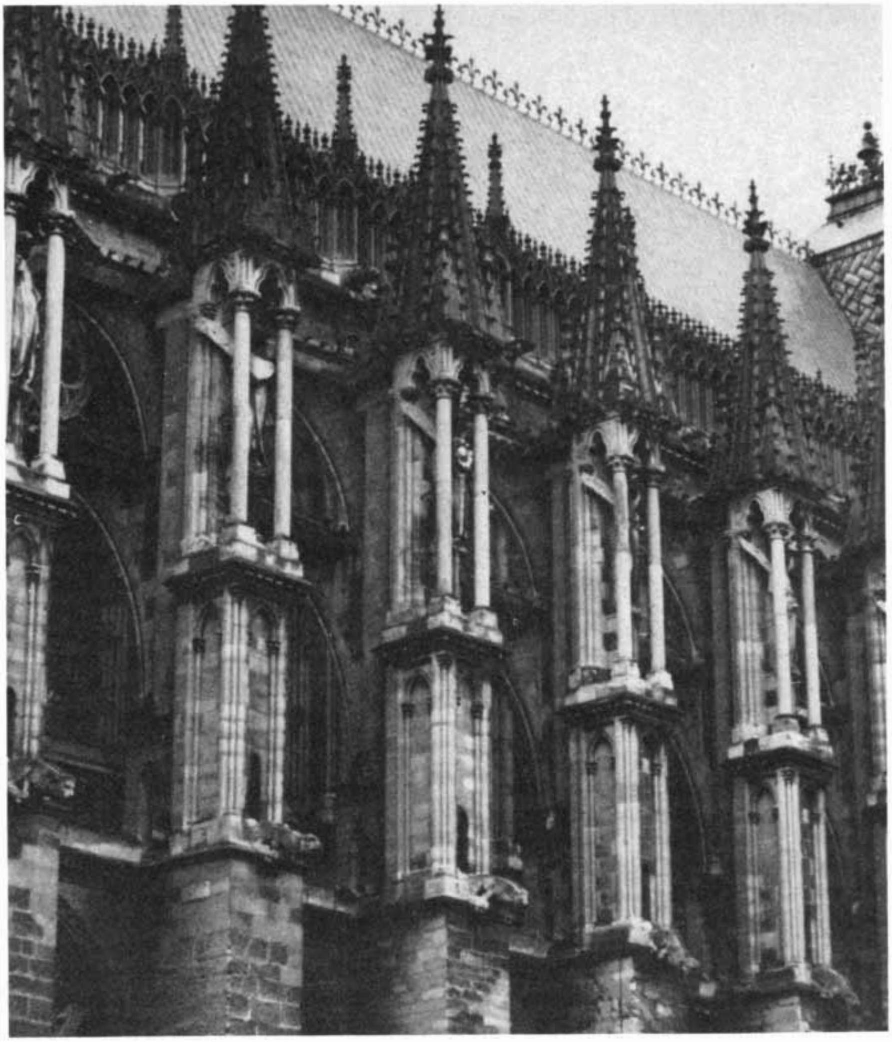
The steep, efficient flying buttresses at Bourges thus appear to be the result of increased awareness, based on the experience at Paris, of the effects of wind on tall buildings. In spite of their economy and their evident technical success, they were not adopted at other High Gothic churches. Perhaps the Bourges buttresses were seen in their time as too light and too daring, or perhaps they were considered a kind of "technical fix" inappropriate for "high" architecture. For whatever reason, the main line of Gothic buttress development passed instead through the cathedral of Chartres.

Begun almost simultaneously with Bourges, Chartres was built very rapidly; it was virtually completed by 1221. The principal design innovation at Chartres was the great enlargement of the clerestory windows. They drop well below the level at which the main vaults spring from the vertical piers. This achievement has generally been interpreted as deriving from a realization of the full potential of the flying buttress, but from a technical point of view the buttressing of the Chartres nave is relatively ponderous and even clumsy: it includes the equivalent of three separate flying buttresses, as well as an unnecessary spur wall under the side-aisle roof, perpendicular to the main wall.

The uppermost fliers are particularly remarkable. They spring awkwardly from the top of the pier buttress and cut through a projecting cornice at the top of the nave wall. No one doubts that they were not part of the original design, but when and why were they added? It was long thought they were a response



BUTTRESSING OF BOURGES CATHEDRAL is striking in its economy, particularly in the choir (*foreground*). Because the fliers are so steep, they convey the forces of wind and vaulting more directly and can therefore be far lighter than other High Gothic buttresses.



PINNACLES atop the pier buttresses at Reims are slotted and hollowed out, whereas their purely decorative counterparts along the west facade of the cathedral are solid. The combined weight of each buttress pinnacle and of the statue in the niche below is almost equal to the weight of the stone removed from the buttress to create the niche. This suggests the builder was concerned that the weight of solid pinnacles might have decreased the stability of the buttresses.

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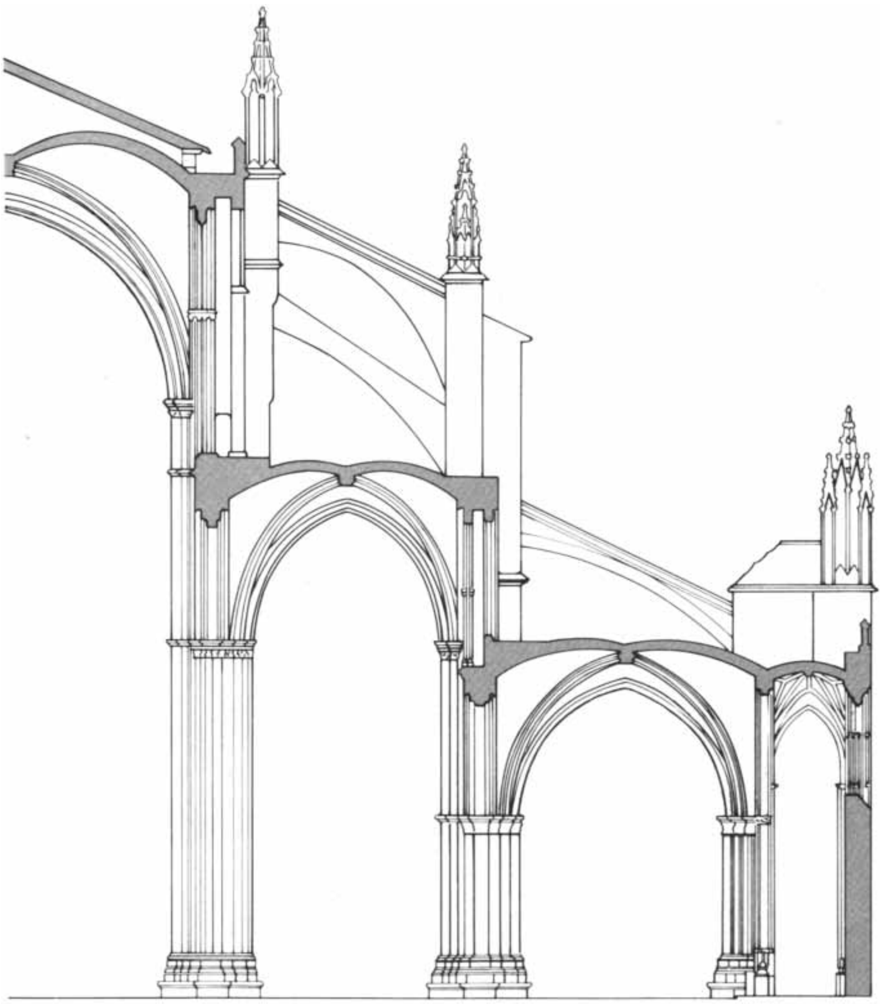
to the *Expertise* of 1316, a report by a group of Parisian experts recommending that the keepers of the cathedral "attend to the buttresses." Modern reinterpretation of the document indicates, however, that its vague injunction referred only to the need to repair existing buttresses. Furthermore, modeling of the Chartres nave both with and without the relatively light upper fliers has shown them to be not fully effective in reducing local tension caused by high winds. It is thus unlikely that they were intended as a corrective to an obvious design fault seen by the Paris experts.

Instead the upper fliers at Chartres were probably added at the end of the original building campaign. New archaeological evidence assembled by John James puts the date of their construction at about 1221. One reasonable interpretation is that the Chartres builder, like his counterpart at Bourges, added new fliers as a precaution against the possible effects of high winds on his structure. The likely source of such caution, both on the part of the builder and on the part of his clients who had to pay for the additional construction, was of course the experience at Paris earlier in the 13th century.

Although the upper fliers were not entirely effective at Chartres, they seem to have pointed the way to the judicious placement of flying buttresses in later High Gothic cathedrals. In these buildings a lower tier of fliers is positioned to resist the outward thrust of the nave vaults, and an upper tier braces the high clerestory wall and the tall timber roof against wind loading. The classic example of this design is the vast cathedral of Reims, begun in about 1210. The Reims buttressing is more refined than that of Chartres: the unnecessary spur wall below the side-aisle roof was eliminated, as was the third flier arch. Yet Reims is relatively conservative compared with the taller structures begun later in the century, such as the huge cathedrals of Amiens (1220), Beauvais (1225) and Cologne (1248).

The cautious approach at Reims, as at Chartres, may well be attributable to the influence of Notre-Dame de Paris. At Reims it extended even to minor details, for example to the design of the pinnacles that top the pier buttresses and lend a strong, unified visual impact to the cathedral exterior. Ordinarily a pinnacle placed near the outside edge of a buttress adds to the bending effect created by the outward thrust of the fliers and thereby diminishes the stability of the pier buttress. Because the pinnacle is relatively light compared with the great weight of the buttress, this effect is small, and at most churches it was ignored. At Reims, on the contrary, the builder appears to have taken some pains to lessen the effect of pinnacle loading. The central spire of each pinnacle is slotted and hollowed so that the weight of the pinnacle, combined with that of the statue in the niche below it, is estimated to be 52 tons—or only about two tons less than the estimated weight of the stone removed from the buttress to form the niche. The pinnacle therefore does not affect the overall stability of the buttress.

Such a sophisticated balancing of mass might seem to be beyond the ability of a prescientific builder. Yet in regions of the cathedral where the pinnacles have only a decorative rather than a structural role, such as along the west facade, they are solid and heavier than their counterparts on the pier buttresses. This supports our view that the hollowing out of the pier-buttress pinnacles was the premeditated act of a builder concerned about the stability of the buttressing. The structural conservatism was quite deliberate, and it probably was a response to the problems encountered at Paris.



TOLEDO CATHEDRAL section shows substantial upper flying buttresses that appear unnecessary for its structure. They were probably deployed in reaction to the observation, before building began at Toledo in about 1227, of wind-induced tensile cracking at Notre Dame.

Caution born of the experience gained at Notre Dame appears to have been a pervasive influence in Gothic architecture of the early 13th century, even affecting many smaller churches. One example is the cathedral at Laon, the construction of which was well advanced by the time the flying buttress was invented. There is no reason to believe fliers were necessary at Laon, which has an interior height of only 24 meters, but they were nonetheless incorporated, almost immediately after they appeared at Paris, into an otherwise unaltered structural scheme. An even clearer example of overbuilding is the Parisian abbey church of Saint-Germain-des-Prés. Flying buttresses were added to the already completed choir, even though its vaults are barely 14 meters high, significantly less than half the size of those of Notre Dame.

The influence of Notre Dame was not confined to France. In Spain, for example, a number of major Gothic churches were under construction in the third decade of the 13th century, just as reno-

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vations were being undertaken at Paris to address the problem of wind-produced tensile stress. The buttressing of the cathedral of Toledo resembles our reconstructions of the original buttressing of both Paris and Bourges. Compared with the French cathedrals, however, Toledo is relatively broad for its height (about 31 meters), and the roof is low-pitched, so that the maximum force of winds against the clerestory is relatively small. Nevertheless, the clerestory is buttressed by two tiers of fliers. The upper tier, which in the classic French churches resists wind loading on the roof, seems to have only a visual role at the cathedral of Toledo. It too was probably a response to the experience at Paris.

The modification of an entire series of Gothic cathedrals following the observation of structural flaws in an earlier building has a parallel in the present, one that also involves new experience gained from light construction on a large scale. When the 854-meter main span of the Tacoma Narrows suspension bridge opened in July, 1940, it was the third-longest in the world. Moreover, its weight per meter of roadway was by far the lightest of any long span. The Tacoma Narrows Bridge epitomized the early 20th-century trend toward lighter, almost ribbonlike roadway decks and slender towers. The depth of its plate-girder deck stiffening was only 1/350th of the span.

Four months after the bridge opened, a fairly steady 40-mile-per-hour morning wind produced severe twisting oscillations in the span; it collapsed catastrophically by midday. The only direct casualty was a dog abandoned in an automobile, but an indirect casualty was the "thin aesthetic" in American suspension bridges. Many of the suspension spans built during the period between the two world wars, including the Bronx-Whitestone Bridge in New York and the Golden Gate Bridge in San Francisco, were quickly stiffened, usually through the addition of heavy trusses to the roadway decks. The generation of bridges built after the disaster also incorporated such trusses.

Thus even in the scientific age architects and engineers must gain experience from completed structures, particularly from those that are much larger than earlier prototypes. And if the experience is to have a maximum benefit, it must be rapidly communicated to other building sites. From our studies of prescientific, Gothic structures we have concluded that similar, if a bit slower, communication occurred as early as the 12th century. With the establishment of such a network of communication the empirical approach to structural design proved surprisingly effective.

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BAVARIA:
The European High-Technology Showcase

This survey of Bavarian technology was written by Joel Stratte-McClure following visits to government ministries, universities, financial institutions, private research organizations and industrial companies throughout Bavaria.

BMW

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The Bavarian past is still very much alive in the midst of the high-technology present. A BMW aerodynamic test vehicle, the magnetically levitated (maglev) train system and the headquarters of the Bayerische Vereinsbank present different faces of Bavaria.

Bavaria, with its capital Munich, is the dynamic pacesetter for much state-of-the-art technological development in the Federal Republic of Germany. This area, West Germany's southernmost federal state, is as renowned for its brain power as for its beer (820 of Germany's 1,200 breweries, or one-third of the world's total, are in Bavaria, and beer consumption is almost twice the national average).

A barrage of posters at the Munich-Riem airport greets the visitor to the geographical heart of Europe, advertising neither perfume nor liquor but some of the numerous research-intensive electronics companies in the area. The advertisements underscore an important point about Bavaria: one out of four jobs and 25 percent of the revenue from the West German electronics industry is generated in the area, which sells 44 percent of its electronics products abroad.

A visit to the Deutsches Museum on the banks of the Isar River, displaying exhibits dedicated. to the history of technology, will establish that Bavarian innovation did not begin yesterday. The first German railway was built in Bavaria, and Rudolf Diesel worked with the Krupp Company and Maschinenfabrik Augsburg-Nürnberg (M.A.N.) to develop the "sparkless" internal combustion engine. The German and European patent office across the street from the museum is a reminder that Bavarian innovation probably will not end in the near future.

Contemporary developments are numerous. The world's first magnetically levitated (maglev) train system has been developed by a team including engineers from Messerschmitt-Bölkow-Blohm (MBB) and Krauss-Maffei. The system, which has yet to be installed on a commercial basis but is being marketed by a joint enterprise called Transrapid International, reduces operating costs by means of friction-free suspension, guidance and propulsion.

Munich is also the base for collaboration between European data-processing firms. Siemens, the United Kingdom's ICL and Bull of France have formed a research laboratory for knowledge engineering. And a four-year technical university outside Munich that trains students for the beer industry still thrives.

"Bavaria is synonymous with innovation because the industry here is dominated by small- and medium-size companies, which quickly adapt to new technologies and business opportunities," explains Klaus Hauptfleisch of the Bayerische Landesbank's Department of Economic Research. "Small- and medium-size firms have been particularly important in such new industries as biotechnology and robotics. In addition, a number of regional advantages set Bavaria apart from the rest of West Germany: industrial growth is twice as fast, unemployment is lower and clean industries attract well-educated, skilled labor from northern Germany and other countries."

The cultural, educational, technological, financial and industrial tradition and infrastructure in Bavaria have prompted numerous domestic and foreign firms—in industrial sectors ranging from aerospace, agribusiness, automotive, data processing, glass and optical instruments, machine tools, telecommunications, textiles and traffic systems—to settle in Munich, Nuremberg, Augsburg, Hof, Ingolstadt, Erlangen, Schweinfurt and other parts of Bavaria. Consequently exports have grown about tenfold in the past two decades, with Italy and France remaining the most important customers. There has also been a rise in exports to the Far East, which now accounts for about 13 percent of the total. Typically, exports reflect the industrial infrastructure. Motor vehicles (which make up 27 percent of total exports), machinery (ball, roller and needle bearings are manufactured for machines worldwide by FAG Kugelfischer Georg Schäfer), electrotechnical products and chemical products lead the list, but musical instruments, glass products and ceramics and leather goods are also sold abroad.

The Clocks Tick Differently

According to an old proverb, in Bavaria even the clocks tick differently. This

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may not be true, but some statistical surprises do await the visitor to the area. As the largest of the 11 West German federal states, it is the country's most important food producer. It is physically larger than Switzerland, Denmark, Belgium or the Netherlands, and it is more populous than Belgium, Austria or Sweden. Although 30 percent of the work force was engaged in agriculture 30 years ago (two-thirds of Europe's hops are produced in the Hallertau region), only nine percent of Bavarians work in agriculture today, whereas 44 percent are engaged in manufacturing industries and 47 percent in transportation, communications and services. Over half of the region's industrial jobs are in advanced-technology areas such as electrotechnology, electronics and computers, chemistry, high-technology machine tools, precision instruments, optics and aerospace.

Behind the figures are some industrial surprises. A relatively small company called Eurosil sells its low-power integrated circuits to Japanese firms, which use them in digital watches. Motorola in Bavaria exports some of its microsystem products to Arizona for resale in the United States. A small microcomputer company (Periphere Computer Systeme), on its way to becoming a data processing equipment maker for the broad market, has transferred its technology to a U.S. company. And beer producer Löwenbräu has licensees in a dozen foreign countries and opened a new plant this year in Istanbul.

Big Bavarian companies, traditional industries with a high-technology outlook, are household names from New York to Tokyo: the electronics firm Siemens, automobile manufacturer BMW (Bayerische Motoren Werke AG), commercial transport producer M.A.N., automobile company Audi and aerospace manufacturer MBB.

BAVARIA BY NUMBERS

Area:	27,240 square miles (28.4% of the Federal Republic of Germany)	
Population:	11 million (17.8% of the population of the Federal Republic of Germany)	
Main Cities:		Population
Munich		1.3 million
Nuremberg		490,000
Augsburg		248,000
Hegensburg		132,604
Work Force by Industry:		%
Agriculture and forestry		9.2
Manufacturing		44.2
Commerce, transportation and communications		16.4
Service industries		30.2
Manufacturing:		
No. of firms with over 20 employees		9,832
No. of craft businesses		125,000
Foreign Trade (1983):		
Exports		DM 60,600,000
Imports		DM 53,400,000

From Wagner to Electronics

The tradition of the Bavarian past surrounds the innovation of the present. Bavaria remains a colorful land of baroque churches, Renaissance town halls, dizzying castles and Richard Wagner's operas (all attractions that helped to increase American tourism by 37 percent in 1983), and even today 125,000 firms are devoted to craft production.

The past and the present are close together in an automated bottling plant at Löwenbräu producing 80,000 bottles of beer an hour (a purity law in force since 1516 specifies that all Bavarian beer must be made from barley, water, hops and yeast only). It is the same building in which a simulator was housed during the 1920's to study the movements of beer shipments on the high seas. The brewers tried to determine how to keep beer from deteriorating on long voyages. Bavaria might have the longest ski trails in Germany, but it is also a center of nuclear fusion research and was the first German state to establish a ministry for the environment.

A service industry flourishes in Bavaria. Roughly a quarter of all German banking institutions have a home office in Bavaria (there is a bank for every 1,200 Bavarians but only one for every 1,400 people in the rest of the country). The world's largest reinsurer (Münchener Rückversicherung, which has palatial offices near Munich's English Gardens) and Europe's largest accident and damage insurers, largest legal fee insurer and second-largest health insurer operate out of the area. (West Germans spend more per capita on insurance than any other members of the European Economic Community.)

Although most of the insurance companies and financial institutions have large financial stakes in a diverse number of industries, they are also striving to improve operations in their own sector. Business at the Bayerische Hypoteken-und-Wechsel-Bank (known simply as the Hypo Bank) has tripled since 1972, but the number of employees has remained constant.

The local electronics industry includes small but innovative companies such as Preh in Bad Neustadt, which employs 1,800 people and manufactures precision electronic components and computer keyboards and graphic pads, and Rohde & Schwarz in Munich, which has 4,000 employees and manufactures measuring equipment. But it is Siemens, which came to Bavaria from Berlin following World War II and now employs about 100,000 people in 25 factories in the region, that sets the pace for Bavarian electronics.

Siemens is one of the six largest electrical and electronics companies in the world. Divisions include power engineering and automation, electrical installations, communications, data systems, components and medical engineering. In 1984 Siemens increased spending on capital projects by 20 percent and boosted R&D expenditure to 3.8 billion deutsch marks (DM)* from DM3.5 billion the previous year.

Today Siemens is a renowned leader in telecommunications network development (integrated services digital networks), the digitalization of communications, automation and robotics and new energy systems. In addition, the company allocates an increasing amount of funds for research and development on medical techniques and engineering, including magnetic resonance tomography for imaging internal organs and tissue.

"We want to become more creative and offensive in our research and development activities and translate those results more quickly into products," says Siemens' chairman, Karlheinz Kaske. As a step in that direction Siemens regularly holds seminars to bring the whole pipeline of marketing, production and research personnel together to formulate specific plans for product development.

Kraftwerk Union (KWU), a Siemens subsidiary, is a firm believer in nuclear power, which currently generates a quarter of all electrical power in Bavaria. In fact, the use of nuclear power in Bavaria is expected to increase from nine percent in 1980 to about 35 percent in 1985, and KWU foresees business in Turkey, Egypt, Japan and China. In Brazil and Argentina, it has already made technology transfer agreements. Although KWU does not have any factories in Bavaria, the company's engineering staff and laboratories are in Erlangen.

"The first West German nuclear power plant was built in Bavaria, and worldwide KWU now has 20 plants in operation, 12 under construction and four under contract," explains Wolfgang Braun, vice president of KWU's nuclear divisions. "Although our nuclear business now represents 80 percent of our total business, we also build conventional power plants."

Less than five percent of KWU's research and development is government financed—"which keeps us independent," says Braun—and the company maintains a number of cooperative agreements with firms in the United States and other countries. KWU spends DM200 million annually on research and development, allocating one-third for the improvement of present technology and plant safety, one-third for inspection and repair of service equipment and one-third for new products. Some recent developments are systems to monitor acoustic leakage, remote-controlled un-

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Showcase BAVARIA

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Automobiles and Aerospace

Bavarian automobiles are especially acclaimed for their technological prowess. Typically, a BMW annual report was replete with pictures and testimonials of Japanese clients happy with their Bavarian acquisition.

"Currently environmental problems have number one priority in development at BMW. We are discussing the introduction of unleaded gasoline with the government in order to reach extremely low emission standards, as in the United States," explained Hans Hagen, BMW's technical director, at the company's headquarters on the edge of Munich. "The main objective of this development is to improve the economy, in particular the fuel efficiency, of our automobiles without sacrificing typical BMW features such as power and performance."

According to Hagen, fuel consumption in BMW's declined 17 percent from 1978 to 1985 while a variety of innovations increased performance. "In tomorrow's BMW, electronics will not only control the engine but also the drive shaft and automatic transmission," Hagen predicts. "Engine management is one of our most interesting developments, along with electronic transmission and engine controls."

BMW is constructing a new manufacturing facility in Regensburg to handle additional production requirements. The plant should be turning out a hundred cars a day by 1986, twice as many by 1988 and 400 a day in 1991.

Audi, an hour's drive away from Munich in Ingolstadt, is continuing to promote the permanent four-wheel drive. The "Quattro" concept will soon be an option for all models. Decrease in resistance during driving by reduction of weight and improvement of aerodynamics, increase of driving performance and safety, further improvement of quality and increased efforts to improve environmental protection are R&D priorities.

"We believe weight can be reduced by 10 to 20 percent during the next 10 years," says Jörn Klingel, manager of development projects at Audi. "We also hope to extend the life of the car from six to eight years by increasing corrosion resistance. Work on achieving a maintenance-free vehicle represents a valuable percentage of our research and development."

"We have never made a move toward designing lower-performance cars because market demand was never for such cars but simply for lower fuel consumption," adds H. C. Ferdinand Piëch, head of research and development and vice chairman of the management board of Audi. "In the future, we will keep our cars at the same performance level and size, but they will have considerably lower fuel consumption."

M.A.N.'s research and development is concentrated in three areas: transport, including commercial vehicles, road structures, exhaust gas turbochargers and airport equipment; energy, including thermal power plants and components, solar power plants and flywheel energy accumulators, and communications.

"M.A.N. spends DM200 million per year on research and development and has 100 computer-aided design and manufacturing (CAD/CAM) workplaces to assist us in making modifications that will cut fuel consumption another 10 percent in the next decade," explains Kurt Detzer of M.A.N.'s technical and planning department.

In the aerospace sector, Bavarian contributions to the pan-European Airbus and the Tornado multirole combat aircraft project accounted for over half of the sector's sales. MBB predominates in the field, with activities in civil and military aircraft, defense systems, helicopters, transport and electronic systems and space technology.

"MBB is a high-technology-product company that is becoming increasingly influenced by market demand," says Horst Prem, director of technology at MBB. "Formerly we concentrated chiefly on metals, but chemistry is gaining in importance with us because we are using more plastics and incorporating more electronics in many of the components that we manufacture."

MBB is currently concentrating its R&D efforts on three major technical areas: microelectronics, control technology, and composites and materials. The company has increased transfer of technologies to companies working in areas such as fiber composite materials, quality-control and simulation technologies and CAD/CAM processes.

"We want to increase international cooperation because it increases our market," says Peter Kraus of MBB's space division.

Motoren-und-Turbinen-Union (MTU) in Munich has about 10 percent of the Western world's civil aviation engine business and will increase its civil work from 26 percent today to about 50 percent in 1986. The company participates in most international engine programs and is consistently making headway on new materials, improved engine aerodynamics and thermodynamics and digital engine control.

"We will halve the number of parts in a new fighter engine by using advanced aerodesign that will reduce the number of the turbine and compressor stages," says MTU's engineering director, Wolfgang Heilmann. "We spend 20 percent of our revenue on research and development, and collaboration forces us to be competitive with our partners."

Another important Bavarian company, Dornier, is involved in a number of aircraft development programs. Among its projects it manufactures components for the A310 Airbus and the European remote sensing satellite ERS-1.

Backing Industry with Scholarship

Much of Bavaria's scientific bent is the result of an excellent university network dating from the time of certain Bavarian kings who had a special interest in scholarship. Today educational institutions and industry cooperate together in what is known as the dual training system, which often leads to fruitful on-the-job training. In addition, Bavarian university laboratories, as well as research institutes, conduct research and development in aerodynamics, astrophysics, biochemistry, communications, metallurgy and other areas.

The application-oriented technical university in Munich, for example, does research and development in 10 special fields, including software engineering, chemical reactions and mass-transfer processes, physics and physical chemistry and civil and surveying engineering. Expansion of the technical university network has created new state and technical universities covering a wide variety of fields.

Bavarian support of basic research after the war resulted in its becoming an important center in areas as diverse as astrophysics and behavioral studies, biochemistry and patent law. Pure, fundamental research is contributed by the laboratories of the Max Planck Institute throughout Germany. There are 12 separate institutes in Munich, including those for international and comparative social law; laser research, physics and astrophysics; plasma physics; psychiatry; psychopathology, and psychotherapy. The budget for the institutes of DM986 million in 1984, which increases at about 3.5 percent annually, is financed primarily by the state and federal governments. Other institutes conduct research and development in the natural sciences and engineering, aerospace, biology and medicine. Most Bavarian research, however, is self-financed by companies.

Attracting Foreign Capital

The Bavarian infrastructure attracts foreign financing and know-how to the region. About 1.1 billion of the DM5 billion invested in Bavaria since 1962, or about 22 percent of investments, comes from U.S. companies. Motorola recently bought 15 acres of land near the airport to extend its operations (this site will itself be a large advertisement). Robert Heikes, general manager of National

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MBB's integration and parallel transfer of know-how from field to field insures that nothing is left to chance – from concept to the last detail – achieving new levels of sophistication in research, development and manufacture. This has made MBB into a world-renowned problem-solving specialist and – internationally – into the major German program partner.*

Achievements such as the Airbus, Tornado, BO105 and BK117 in aviation, the SPACELAB spacecraft and TV-Sat, the Roland, HOT and Milan defense systems – among others – open limitless vistas in terms of new applications. For example: From helicopter rotors to wind-driven power plants, from satellite power systems to solar energy power plants.

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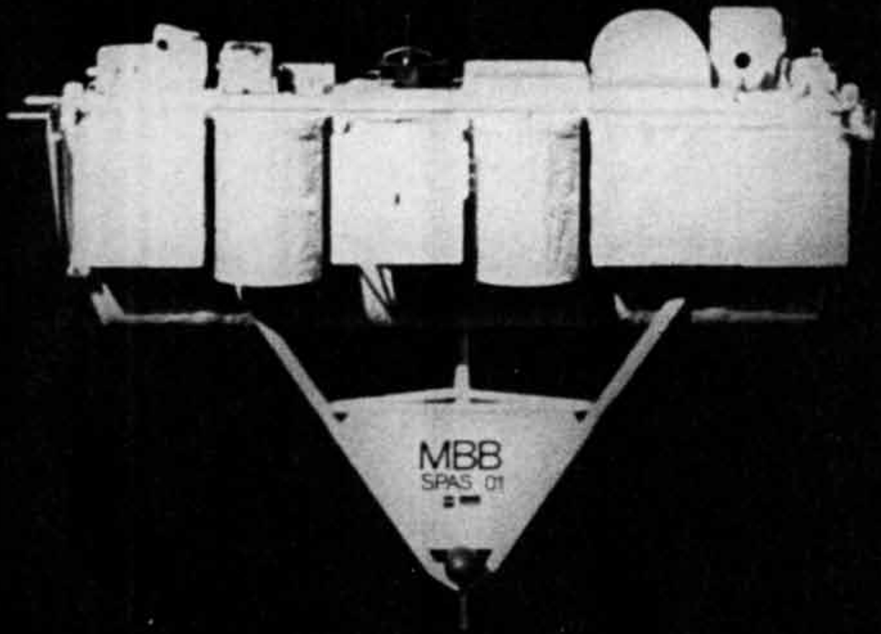

MBB

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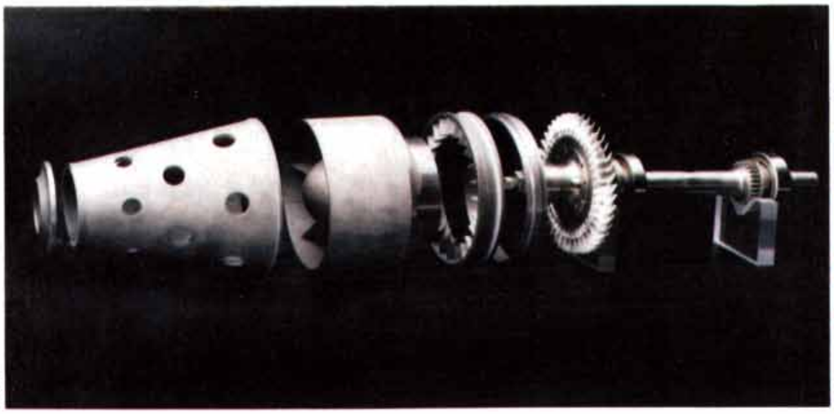


MTU

Löwenbräu

Bavarian companies are producing a number of new materials for use in a wide range of components and equipment. At left are several ceramic components produced by MTU. Löwenbräu, however, does not use any new materials for its beer-brewing techniques.

Semiconductor, says, "It takes about 30 microseconds to fit into the Bavarian mindset and marketplace" and is studying the possibility of a quick turnaround facility for semicustom devices in Munich.

Motorola, National Semiconductor and other electronics and data processing companies (Digital Equipment, Texas Instruments, Intel, Tandem Computers, Fairchild, Hitachi) were attracted to Bavaria for similar reasons, as were a number of companies in the petrochemical and machine tool sectors.

"Bavaria is centrally accessible, attracts good people and has the necessary industrial competition," says Fred Shlapak, general manager of Motorola. "Existing industry provides resources and there is a good local market: 25 percent of our products are sold in West Germany. Problems? Not as much movement and cross-fertilization of employees as in the United States, difficulties in recruiting senior management personnel and a labor system that does not encourage a seven-day work week."

Bavarian industrial land is still abundant: only three percent is currently being used for industrial purposes. State financial assistance is available for investment along the eastern borders.

"We don't manufacture in Bavaria, but we have our European headquarters for marketing and design of microprocessors, microprocessor systems and semicustom devices here, employing 300 people," adds National Semiconductor's Heikes. "We can attract many nationalities and the work ethic is reasonable, but as elsewhere in Europe there's too much vacation."

Although his replacement will be European, Heikes feels it is necessary to have American employees in Bavaria to introduce American techniques and technology. At the same time National Semiconductor sends 10 to 15 Europeans to the United States to provide a two-way transfer of talent.

"American companies need local management and should respect traditions," cautions Horst Gebert, president of Eurosil, in which United Technologies Corporation has a substantial stake. "When one U.S. company fired people here, it did not endear itself to the local population."

Despite so much technological activity it would be erroneous to conclude that Bavaria is another Silicon Valley. For one thing, venture capital is still much less available than in the United States. "Entrepreneurs and venture capital aren't that plentiful and change can be slow," says Heikes.

"We are behind the U.S. in practicing a venture capital philosophy," agrees Wilhelm Arendts, chairman of the board of managing directors of the Hypo Bank. "We need more tax advantages for the entrepreneur, and somehow we must better sponsor innovation if we are to narrow the technology gap between ourselves and the United States and Japan."

But venture capital is beginning to flourish and be invested in Bavaria. Siemens has traditionally encouraged engineers to set up their own firms. The parent company often assists in financing new ventures and has established an investment company, Venture Capital Beteiligungs (VCB) GmbH, to provide financial and technical support for new enterprises. Earlier this year Siemens' first industrial spinoff took place with the creation of Integrated Circuit Testing, which markets electronic test equipment. Financing for the venture comes from the German-American-British capital investment firm Techno Venture Management, in which VCB has a 31.25 percent stake.

"Our venture capital efforts will allow us to get into new high-technology companies and buy technology we aren't developing ourselves," says Bernhard Nottbeck of Siemens' research department. "Not all of our R&D results fit the company's product or equipment spectrum, and we need outside avenues for their commercialization."

Bavarian banks are discussing participation in a risk capital fund set up by the government's ministry of finance, and the Munich-based Bayerische Vereinsbank has created a special unit to service new high-technology businesses.

"German firms were undercapitalized because they had to start over after World War II, which is why banks have traditionally played an important role in Bavaria and the other states," explains Günther Thalmeier of the Bayerische Landesbank.

"The structural problems traditional German industry faces are forcing banks to provide not only financing but also management expertise, market evaluations and other services," adds Hans-Detlef Bösel, senior vice president at the Bayerische Vereinsbank. "But for conservative banks it is often difficult to evaluate software companies, where assets are in the employees' heads. However, since 50 percent of Bavarian industry will be high technology or service oriented in 1990 the banks must make the necessary adaptations."

Although the importance of venture capital companies is unlikely to be as great as in the United States, they will undoubtedly be an integral part in the future of Bavarian technology, and another factor that will enable Bavaria to maintain its reputation as Europe's high-technology showcase.

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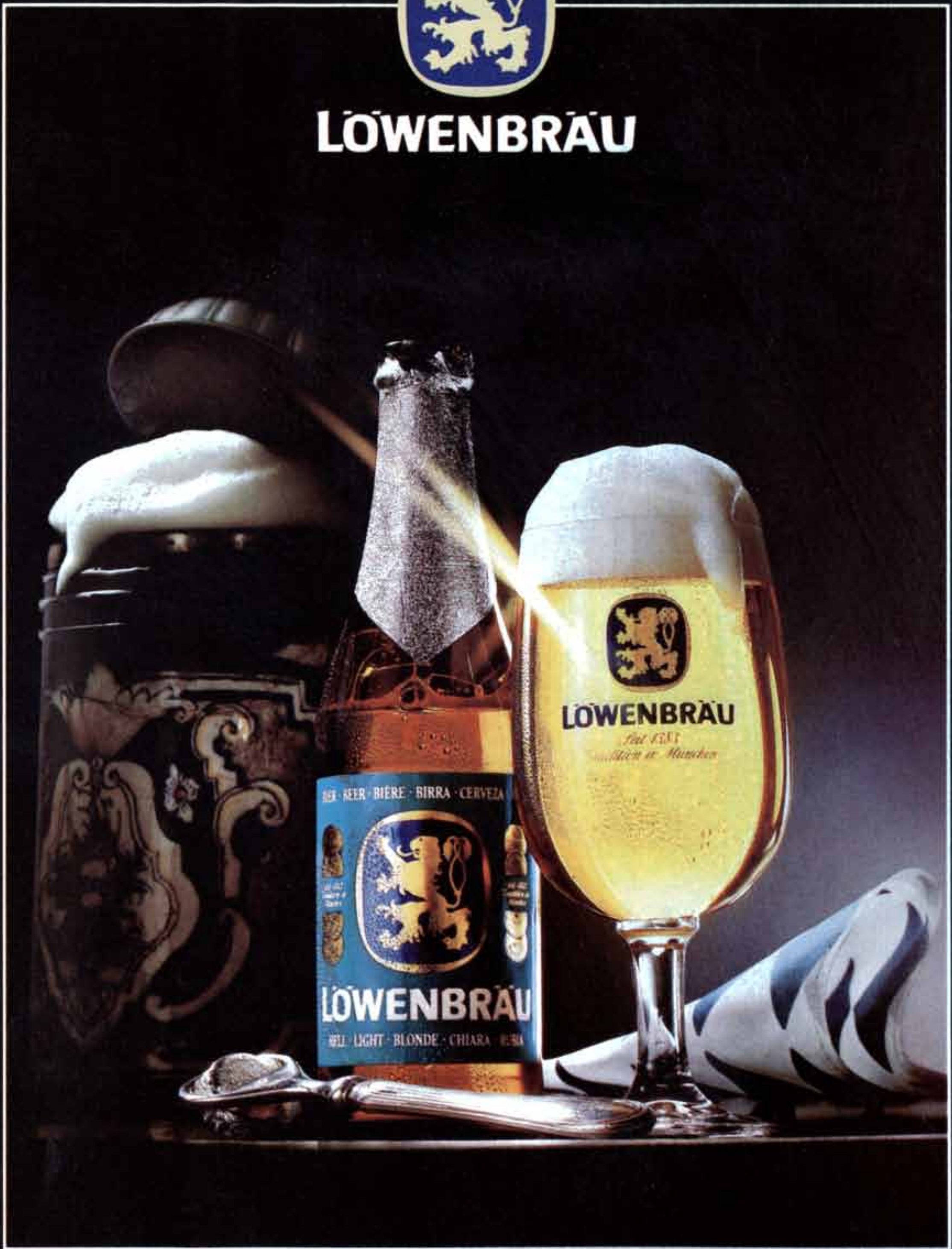
LÖWENBRÄU



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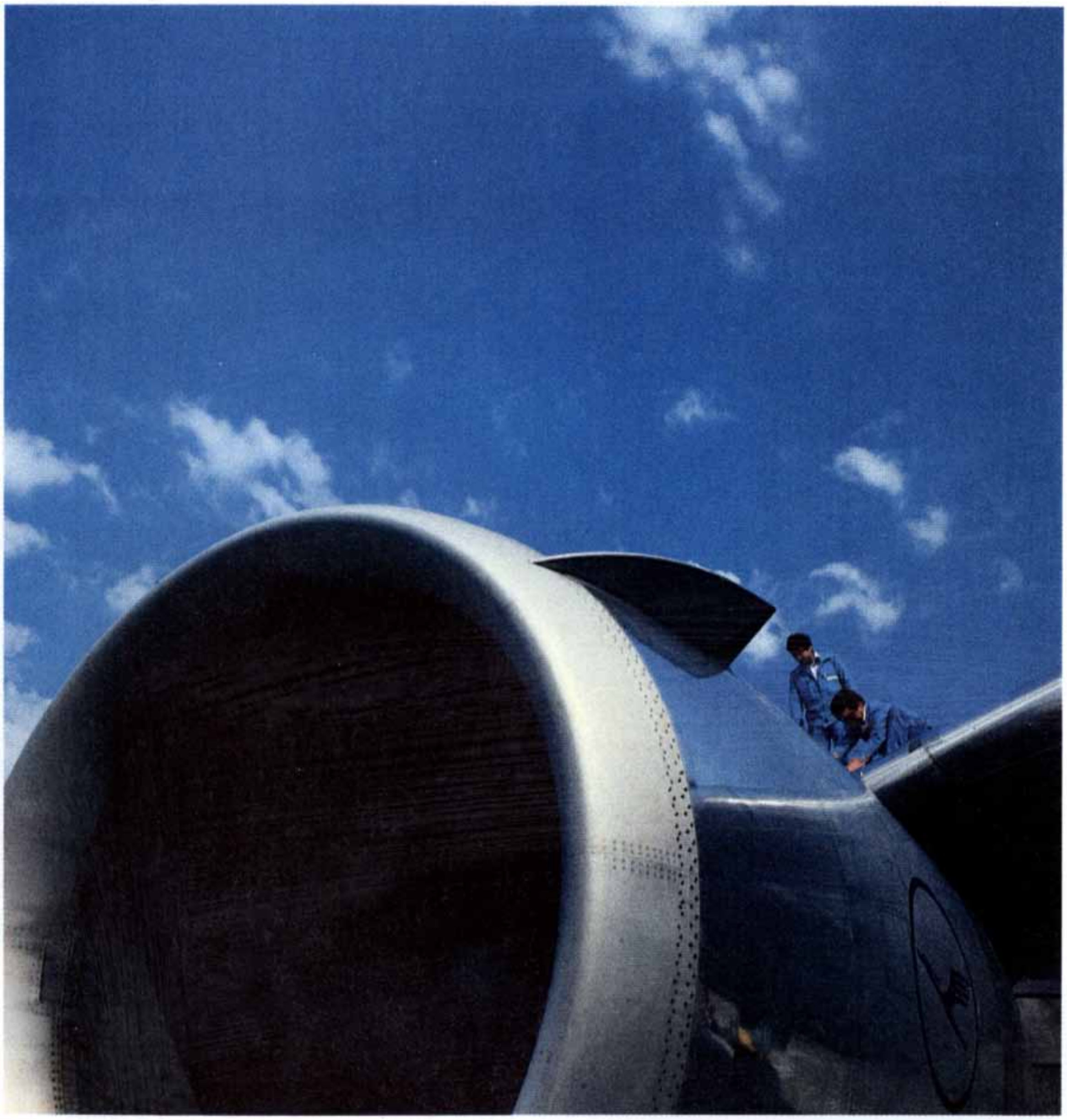

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THE AMATEUR SCIENTIST

A ball bearing aids in the study of light and also serves as a lens

by Jearl Walker

If you were asked to envision the uses that might be made of a ball bearing, you probably would not think of it as a tool for the study of light or as a kind of photographic lens. It can be both of those things, and thereby hangs a tale about the nature of light.

Is light a wave? In the early years of the 19th century the idea met with much opposition. Physicists still hewed strongly to Newton's model of light as particles. In 1818 a wave model for light was proposed by Augustin Jean Fresnel in a competition held by the French Academy. The judging committee included the mathematicians Pierre Simon de Laplace and Siméon Denis Poisson and the physicists Dominique François Arago, Jean Baptiste Biot and Joseph Louis Gay-Lussac.

Fresnel's work was opposed, notably by Poisson, who put forward a thought experiment intended to discredit it. If a bright beam illuminates an opaque object of circular cross section, he said, then according to Fresnel's work a bright spot should appear at the center of the shadow of the object. Since such a result was clearly absurd, the model must be erroneous.

Arago soon arranged the experiment and found the bright spot, thereby vindicating both Fresnel and the wave model of light. The spot had actually been seen in 1773 by other workers but had been forgotten. Today the phenomenon is often and ironically called the Poisson spot. A spot of this kind is surrounded by bright and dark circles, all within the shadow of the sphere or disk creating the pattern.

In an experiment illustrating this principle, devised by Dale Blaszczak of Cleveland State University, I photographed the pattern cast by a ball bearing. We were also able to employ the bearing as a lens so that it formed an image in its shadow. The Poisson pattern and the image from an opaque ball both derive from diffraction, a property due to the wave nature of light.

The propagation of a light wave is sometimes considered in terms of tiny wave generators positioned along a wave front at any given instant. These generators, which are merely mathematical inventions, emit small waves strongly forward (in the direction of travel of the light), less strongly sideways and not at all backward. As these small waves interfere with each other (overlap) they re-create the wave front ahead of its previous position. Thus the wave front is described as moving by means of the continuous generation and interference of the small waves from the generators.

Although the generators and their waves do not exist, they help physicists in picturing many aspects of light. One important example is the diffraction of light by a narrow slit (about the width of a razor blade) in an otherwise opaque screen. When the wave front travels into the slit, most of it is eliminated by the screen, together with most of the generators. The remaining generators still emit waves in the forward direction, but they no longer interfere enough to re-create the previous wave front. Instead of traveling along a straight line through the slit, the light spreads from it.

If the light intercepts a surface such as a sheet of paper, the spreading can be seen. Many places are brightly lighted because the light waves arriving there are in phase and interfere constructively: the wave crests arrive simultaneously, thereby creating a large light wave. Other places are dark because the waves arrive out of phase and interfere destructively: a crest of one wave arrives with the trough of another, so that the waves cancel.

The spread in the pattern of bright and dark places depends on the size of the slit. Suppose the slit is rectangular and the long side is vertical. The configuration creates a pattern well spread horizontally and condensed vertically. Such a pattern is called the diffraction pattern of the aperture.

Sometimes the shape of an aperture and its diffraction pattern are related in a simple way. For example, an aperture resembling the letter *H* has essentially three slits. The short horizontal slit creates a vertical diffraction pattern, and the two vertical slits yield overlapping horizontal patterns.

You might try to guess the shapes of the apertures that created the patterns in the bottom illustration on the opposite page. Each aperture was a letter that I typed on smooth paper as a capital in the Letter Gothic style. I had each one photographed with Kodak direct positive film, which was then processed with the kit designed for that film. The resulting slides were opaque except for the letters, which were transparent.

To photograph the diffraction patterns I mounted a slide in the beam from a helium-neon laser so that the letter was fully illuminated. About 20 meters on the other side of the slide I positioned a 35-millimeter camera in the diffraction pattern. I removed the lens so that the pattern would directly illuminate the film when the shutter was released.

With the room lights off I photographed the pattern with a range of shutter speeds. Can you guess the letters from the diffraction patterns? The letters are approximately in the correct places to spell a name that has long been associated with this magazine, but I have eliminated any repeated letter and cannot guarantee that the patterns are oriented properly.

A second way of explaining diffraction is useful when the aperture is circular. Surrounding its center are Fresnel zones, which direct light to the paper that makes it possible to view the rings of the diffraction pattern.

Look at the center of the pattern. Light arriving there from the central zone is exactly out of phase with light arriving from the second zone because of a difference in the travel distances. Light from the third zone reaches the center of the diffraction pattern exactly out of phase with the contribution from the second zone for the same reason. The zones of higher order are defined in a similar way. Each zone directs light (to the center of the diffraction pattern) that is out of phase with the light from an adjacent zone.

The size of the zones depends on the distances between the aperture, the light source and the paper. Thus these distances determine how many zones lie in the aperture. Suppose the paper is far enough away for the central zone to fill the aperture. Then the center of the diffraction pattern is bright. If the paper is brought closer, a second zone appears in the aperture. Then the center of the diffraction pattern is dark because the light arriving from the central zone and the light arriving from the second zone interfere destructively.

When the paper is brought even clos-

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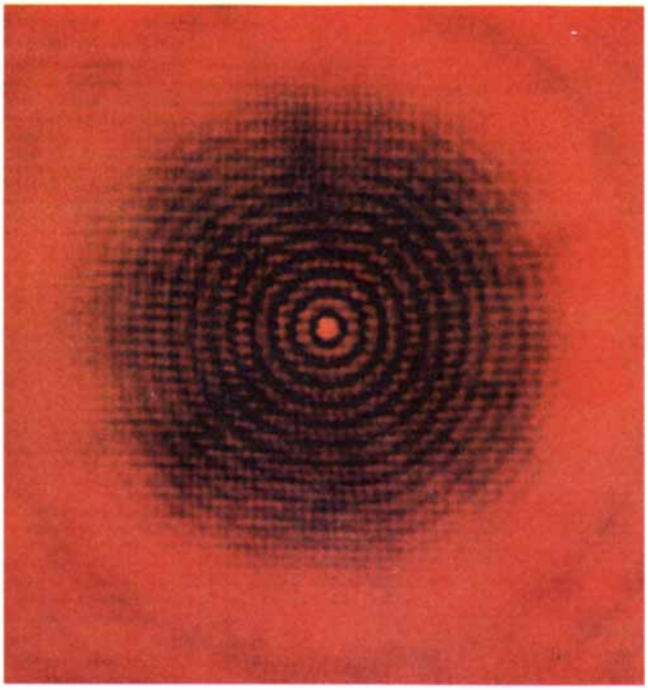
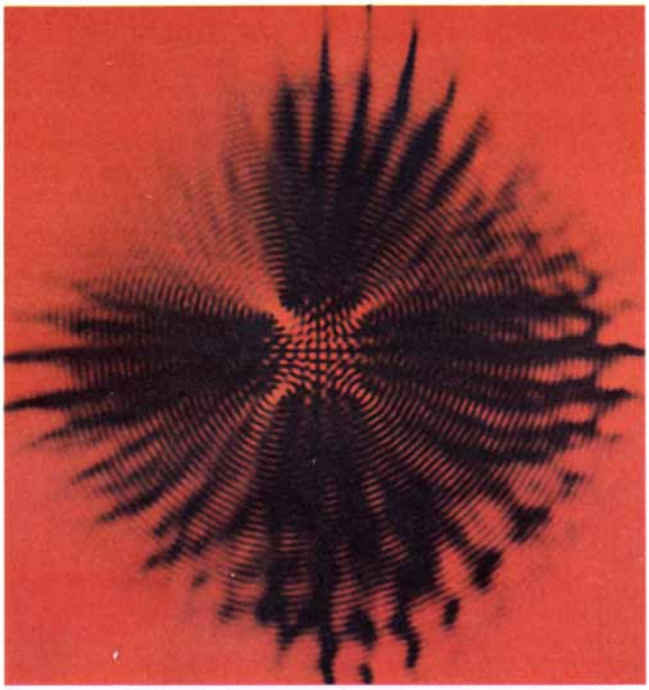
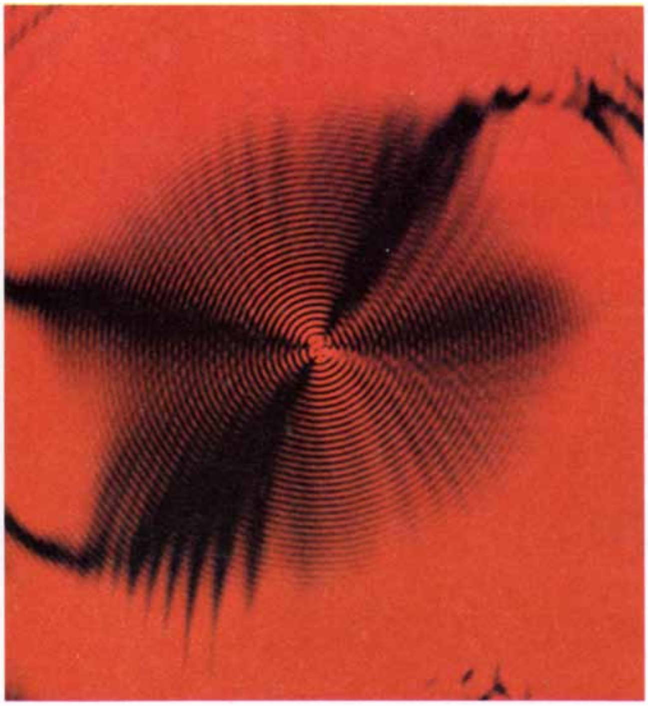


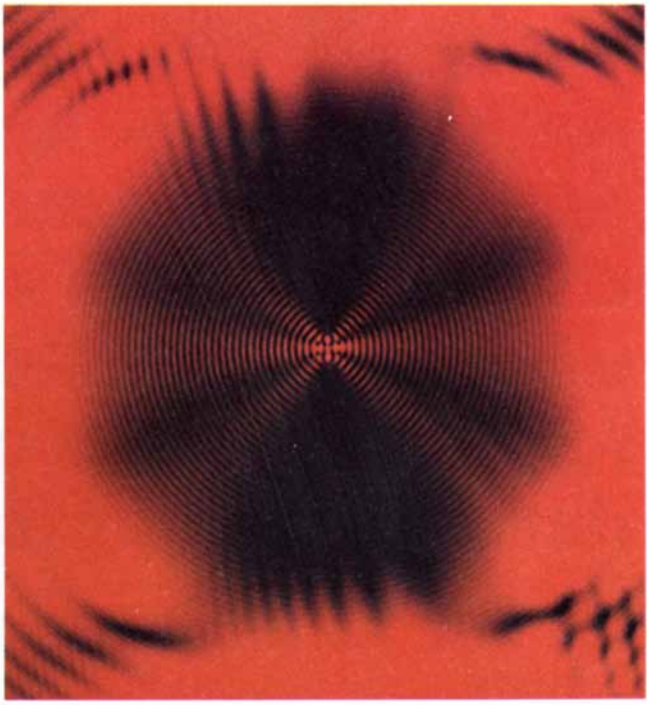
A bearing and its Poisson pattern



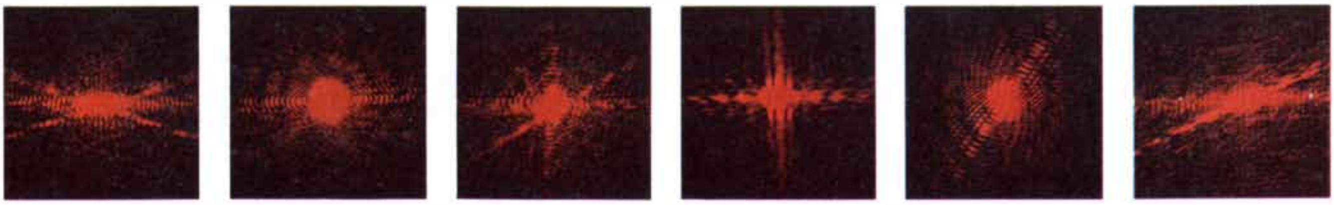
A grid in the shadow of a bearing



A 2 imaged by diffraction



An I imaged by diffraction



Diffraction patterns suggesting a name

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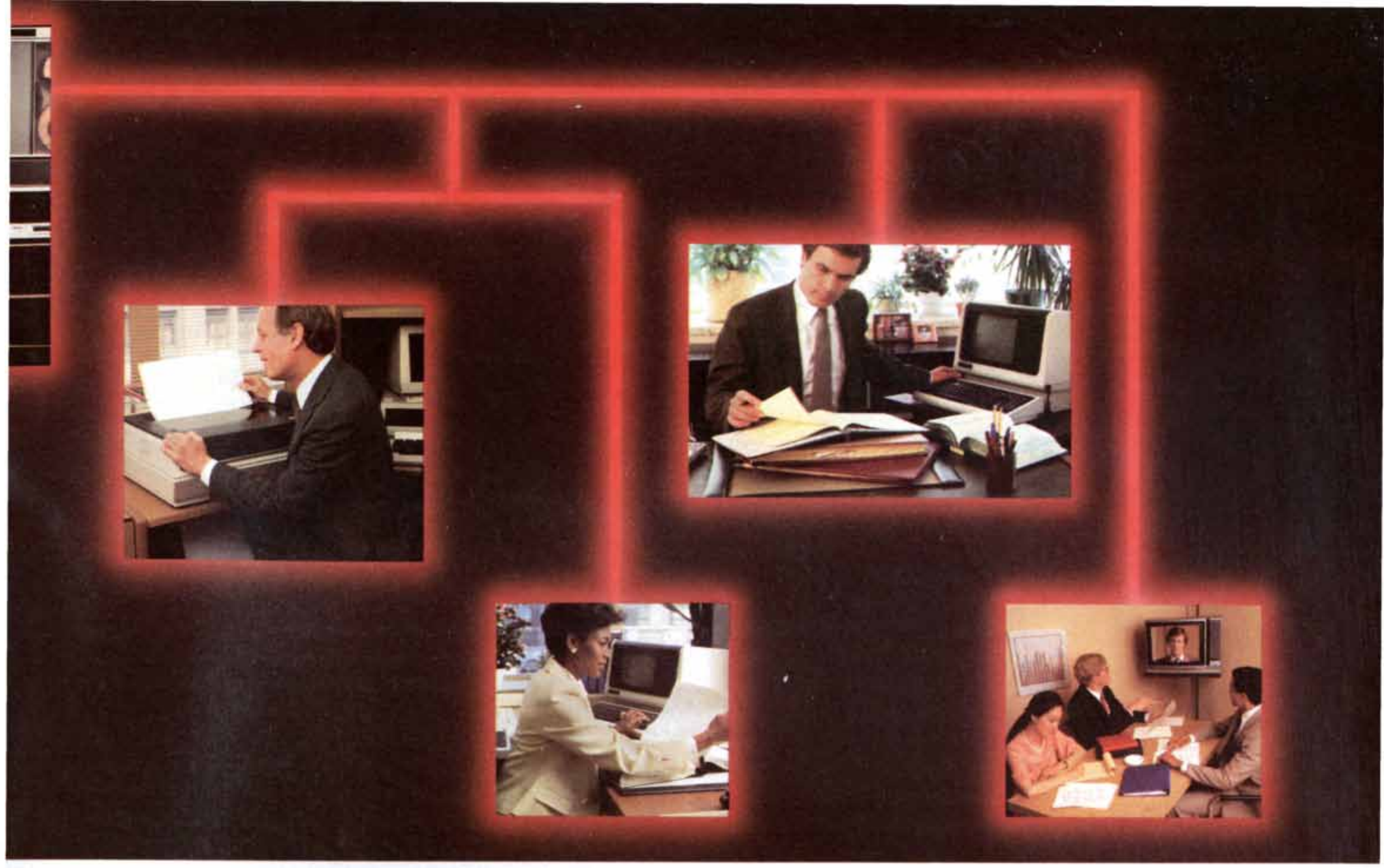

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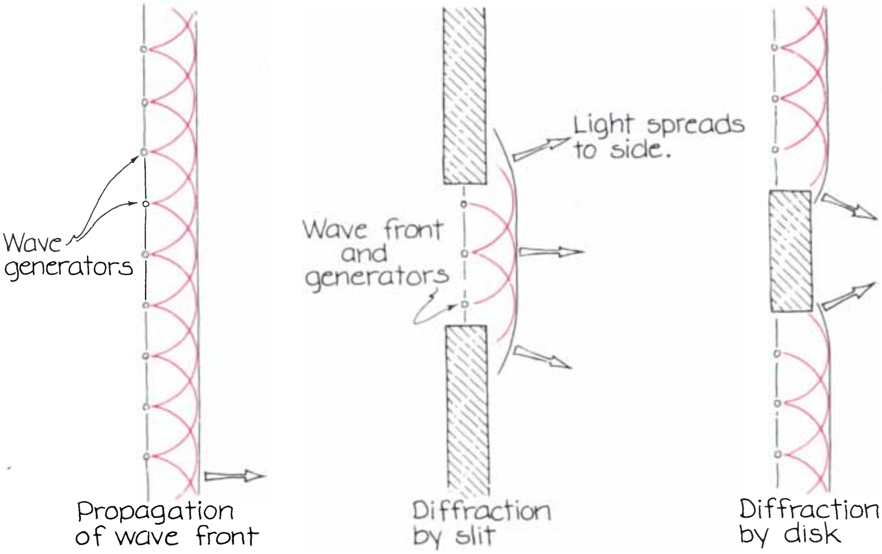
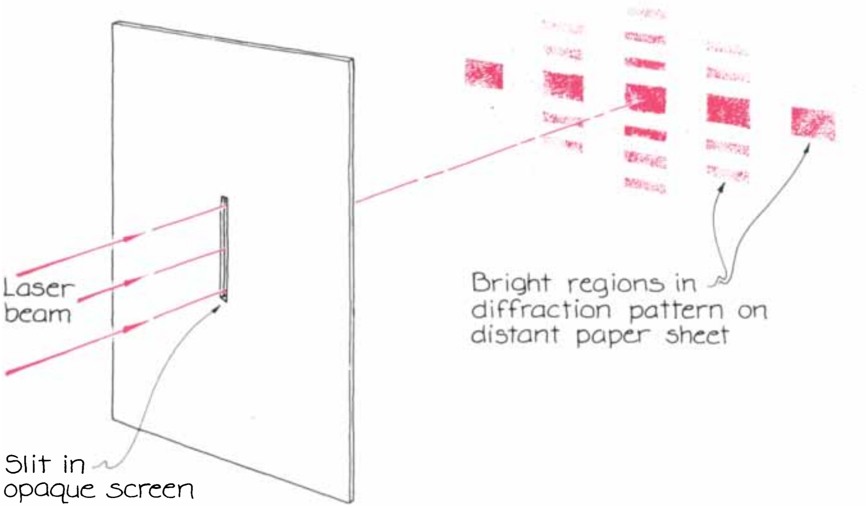
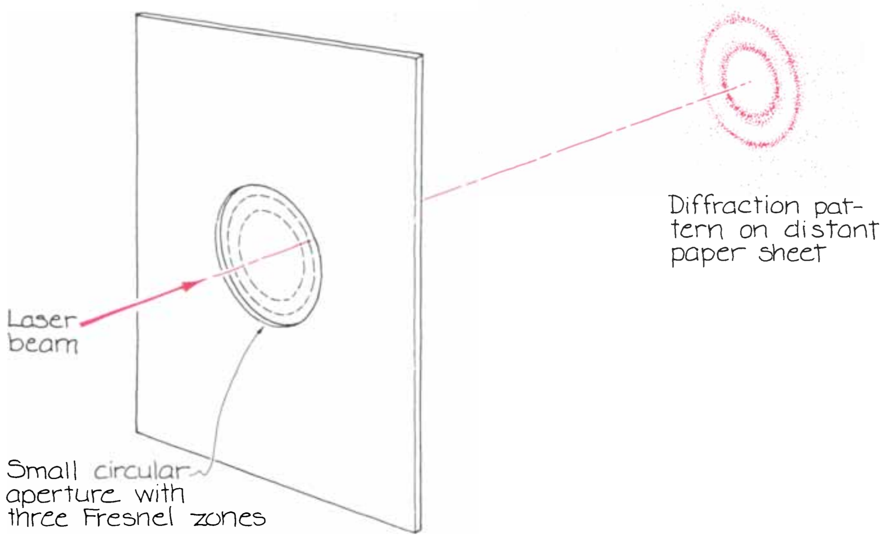


How wave generators propagate light



Diffraction from a slit



Fresnel zones in a circular aperture

er, the third zone appears in the aperture. Although light waves from the central zone and the next zone still cancel, the center of the diffraction pattern is bright because of light from the third zone. As the paper is moved toward the aperture the center of the diffraction pattern alternates between being bright (when the number of zones filling the aperture is odd) and dark (when the number of zones is even).

During the dark stages the light is never fully canceled because of what is called the obliquity factor. Light from a zone proceeds strongly in the direct forward direction but less strongly to the sides. The light from a zone of large radius is therefore slightly weaker at the center of the diffraction pattern than light from an adjacent zone with a smaller radius. The two contributions interfere destructively at the paper sheet but are not completely destructive.

Diffraction patterns can also be created by opaque objects. Blaszczak investigated the phenomenon by examining the Poisson pattern cast by a circular metal disk three-eighths of an inch in diameter. He glued the disk to a thin metal wire (30 gauge) and then suspended the wire between two holders attached to a ring stand. The disk was approximately 10 meters from the laser. A lens expanded the beam. The shadow fell on white paper 30 meters behind the disk. Blaszczak examined the small shadow with a magnifying lens after adjusting the orientation of the disk. When the disk was perpendicular to the beam (thereby presenting a circular cross section to it), the Poisson pattern appeared.

Sometimes Blaszczak placed a lens in front of the laser to spread the light. Sometimes he then recollimated the light into a wider beam without divergence. (To recollimate make the first lens focus the light onto a pinhole. Light passing through the pinhole then travels through a second lens that has its focal point on the pinhole.) The Poisson pattern appeared in each case.

We tried to form an image with the disk by placing a photographic slide of a human face in the recollimated light about midway between the laser and the disk. The shadow region displayed a complex interference pattern, but it bore no resemblance to the face.

We replaced the disk with a one-centimeter ball bearing that was exceptionally round and smooth. It cast a brilliant Poisson pattern. We made the pattern larger by spreading the laser beam and then moving the bearing close to the laser. This arrangement provided more distance between the bearing and the paper that displayed the pattern.

We examined the pattern through a magnifying lens. Then we employed a camera as the magnifier. When the lens was removed and the camera intercept-

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ed the shadow of the bearing, we looked through the viewfinder and saw a magnified Poisson pattern.

I must warn you that such an arrangement is dangerous. If you look through the viewfinder of a camera that is in the path of a laser beam, your eye focuses the light onto your retina. A pattern that is quite bright can ruin the retina, resulting in blindness. Your only sensation may be that the light seems uncomfortably bright, and you may not be aware of the full damage being done.

It is much safer to examine the patterns on paper by means of a magnifying lens because the intensity of the light is reduced by scattering from the paper. (We looked through the viewfinder because on paper the pattern is so small that it is hard to see.) Even the paper arrangement can be dangerous with a high-powered laser. Our laser is rated at 10 milliwatts, which means it has a maximum output of 10 milliwatts. All the patterns we saw could be generated just as easily with a laser of lower power.

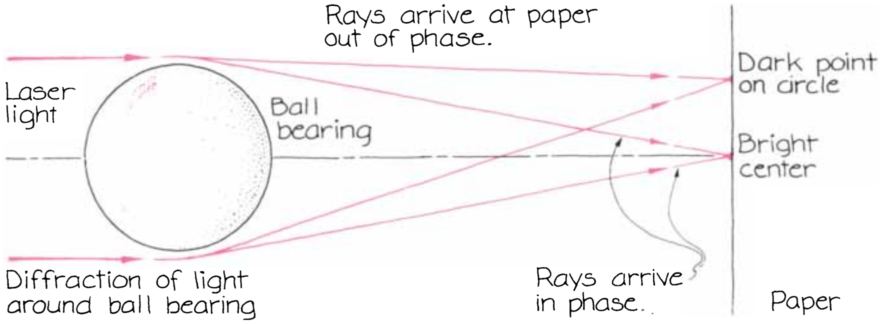
You might try to photograph the Poisson pattern on a paper sheet. Place the camera off to one side in order not to block the light going toward the paper. Since from such an angle the pattern will no longer be circular, rotate the paper so that a line perpendicular from it lies midway between the incident light and the line of view from the camera.

The camera must have a lens to focus the pattern onto the film. My attempts with this arrangement were disappointing because light scattered from the paper often ended up washing out the delicate Poisson pattern.

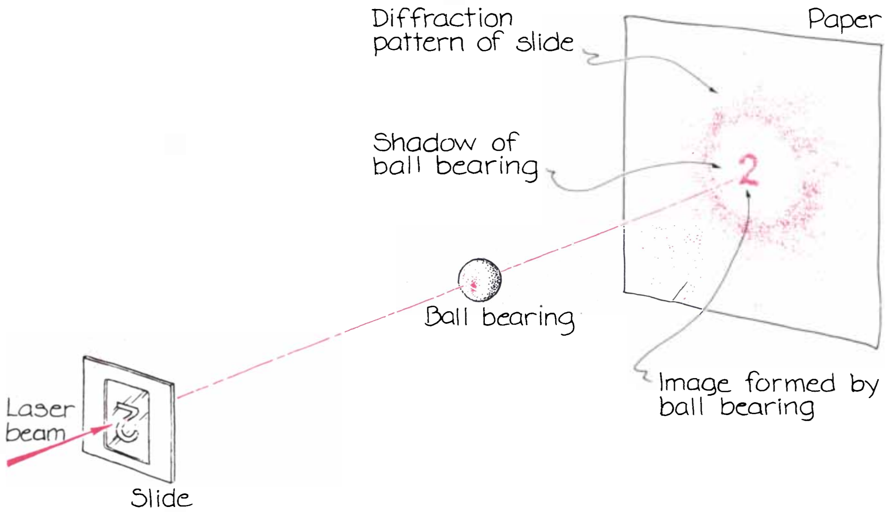
I tried another approach. With the room lights out and the lens off I placed the camera directly in the shadow of the ball bearing and exposed the film at several camera speeds. Using color film of 400 ASA speed, I made my best photographs with the shortest exposure times, usually 1/1,000 or 1/500 second. If you have a dim laser, use film rated at 1,000 ASA. For classroom work I prefer color slides (400 ASA) so that the results can be projected.

The Poisson pattern derives from the diffraction of light around the sides of the bearing. Suppose the bearing is illuminated by light with a straight wave front. When the wave front reaches the bearing, some of its mathematical generators are blocked and eliminated by the bearing. The remaining ones still produce small forward waves, but the interference between waves can no longer re-create the original wave front. Instead some of the light spreads into the shadow region of the bearing.

All the generators on the wave front passing the bearing are in phase. When the light waves reach the paper, their phase and their interference are determined by how far they have traveled. The light reaching the center of the shadow from one side of the bearing travels just as far as the light from the opposite side. This light remains in phase and interferes constructively, producing the Poisson spot.



How a bearing forms a Poisson pattern



Creating the image of a 2 with a ball bearing

Surrounding the spot is a dark circle, created by destructive interference. Consider any point on the circle. The point is dark because the light arriving from one side of the bearing must travel farther than the light from the side directly opposite. The extra distance of travel puts the two waves of light exactly out of phase.

Slightly farther off center is a circle produced by constructive interference. Again light coming from one side of the bearing must travel farther than light coming from the side directly opposite, but this time the extra distance puts the waves back in phase. (One wave lags behind the other by a full wavelength.) Usually quite a few bright and dark circles can be seen surrounding the Poisson spot.

The pattern can also be explained in terms of Fresnel zones. The bearing blocks the light from the central zones. (In our experimental arrangement the first several hundred zones are blocked.) Just outside the bearing lies the first exposed zone. The center of the shadow receives light from this zone and all the other exposed zones lying at greater distances from the bearing. Since adjacent zones are out of phase with each other, they interfere destructively. The obliquity factor, however, diminishes the contributions from the outer zones in such a way that the intensity at the center of the shadow is roughly a fourth what it would be if only the first exposed zone illuminated it.

Consider the zones illuminating a point in the first dark circle in the Poisson pattern. From the view of that point the bearing is not centered on the zones. Thus some of the zones near the bearing are only partially exposed. The net result is that the zones cancel each other and the resulting point in the Poisson pattern is dark.

Next consider a point on the first bright circle in the Poisson pattern. For this point the bearing is even more off center from the zones. Again some of the zones near the bearing are only partially exposed. This time the net result is brightness.

If the bearing presents a noncircular cross section to the laser beam, the Poisson pattern is distorted or missing. One concludes that the wave generators on

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one side of the bearing are not matched by generators placed symmetrically on the opposite side. In terms of the Fresnel zones one argues that the innermost zones are not fully exposed because the bearing lacks circular symmetry. The resulting pattern on the paper can be complicated. If the asymmetry is great enough, the exposed portions of the zones can cancel the light at all points on the paper, leaving the shadow dark.

Since the ball bearing diffracts light into its shadow, it can produce an image somewhat as a convex lens does, except that the image arises from diffraction rather than refraction. Blaszczak and I figured that imaging would be easier with the ball bearing since the disk requires careful orientation to present a circular cross section to the laser beam.

We first obtained a bright Poisson pattern. Then in the beam we placed a slide that was opaque except for a small transparent 2. The figure, which was fully illuminated, created a diffraction pattern across the ball bearing. We gradually shifted the position of the bearing while checking its shadow for an image of the 2.

We searched for days without success. We moved the experiment into two rooms joined by a door so that we could extend the baseline to about 80 meters. The laser was at one end, the paper sheet was at the other end and the bearing was about midway between them. We replaced the crude mounting for the bearing with micrometer mounts so that we could vary the position of the bearing smoothly. One micrometer mount moved the bearing vertically, the other one moved it horizontally.

Part of our problem was the diffraction pattern cast by the wire to which the bearing was glued. Sometimes part of that pattern extended into the region we searched for a 2. We also tried slides of letters and other numbers.

Finally, we experimented with a slide containing a rectangular grid of black lines, each line separated from the next by about two millimeters. Blaszczak figured that the repeated pattern might reduce the severe requirements of positioning the bearing. He was right. When we examined the shadow of the bearing, we found an image of the grid at the center. Outside the shadow was the portion of the grid's original diffraction pattern that bypassed the bearing. The central pattern was formed only because the bearing diffracted some of the light, sending it into the shadow region.

We returned to the slide of the 2 with greater patience. We adjusted the placement of the bearing in the diffraction pattern cast by the 2. We varied the distance between the slide and the bearing and between the bearing and the paper (or the camera). Nearly always the center of the shadow consisted of a complex interference pattern that never resembled a 2. At last we got it with the bearing at approximately the center of the diffraction pattern from the 2.

Was the figure truly an image of the slide or merely a fortunate orientation of dark and bright interference bands? One way to check is to examine the orientation of the image. If the bearing serves as a convex lens, the image will be inverted and reversed left and right from the orientation of the object. The image of the 2 we found was indeed so reoriented.

As seen from the laser the slide had a 2 that was inverted and reversed. What we saw on the paper was a 2 of the proper orientation. We were also successful with imaging an *I*, but we always failed with more complex shapes such as a face. (Some older textbooks on optics mention that investigators imaged faces with coins or metal spheres but give little detail on how.)

To understand how an inverted image can form in the shadow of the bearing imagine a slide with two pinholes positioned in a laser beam. Each pinhole acts as a point source of light for the bearing, creating a Poisson pattern centered on a line running from the pinhole through the center of the bearing. The center spots of these patterns are the images of the pinholes. Their separation matches the separation between the pinholes if the bearing is midway between the slide and the paper. If the bearing is closer to the sheet, the images are closer. If the bearing is closer to the slide, the images are farther apart. Thus the bearing can magnify the separation of the pinholes.

The imaging of the pinholes is far murkier from a bearing than it is from a lens because of the severe distortions in the overlap of the Poisson patterns surrounding each pinhole image. Depending on the alignment of the slide and the bearing, the overlap can result in many different designs, some of which make recognition of the images difficult.

Our easy success in imaging the grid was probably due to the repetition of the pattern. Usually the bright and dark lines near the center of the shadow confuse the imaging of an object. With the grid as the object the lines were forced into a grid formation, thereby aiding the identification of the image.

Similar imaging and distortion should result when other slides are put in the laser beam. For example, an aperture in the shape of an *I* can be considered as a series of pinholes forming the letter. Each pinhole creates a Poisson spot in the shadow of the bearing. If the imaging is successful, the composite of the spots forms an *I*.

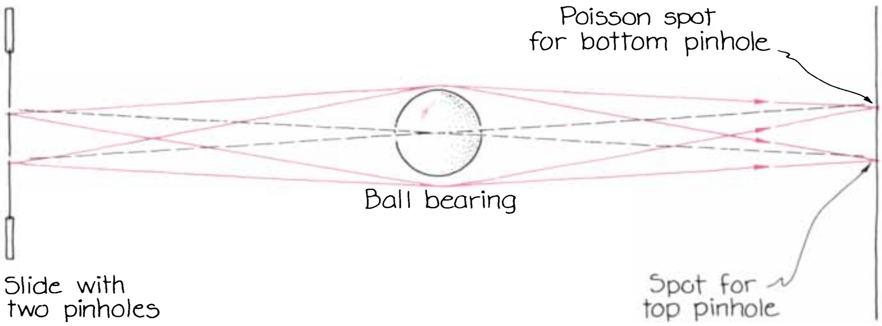
When we tried the experiment, we sometimes found in a string of Poisson spots that each spot was surrounded by a dark ring. Sometimes the overlap of patterns yielded two dark, roughly parallel lines that more closely outlined an *I*. Similar distortion appeared when we put an *M* in the beam. If we adjusted the position of the bearing properly, the images of the vertical sections of the *M* resembled the image of an *I*. The internal lines appeared as small spots.

Often the diffraction pattern cast by the suspension wire seemed to distort the center of the bearing's shadow. To avoid this problem we glued the bearing to a microscope slide, which we attached by tape to the micrometer mounts. Although small scratches in the glass still caused some distortion of the bearing's shadow patterns, the patterns were clearer than before.

We wondered what would happen if part of the light diffracting around the bearing was blocked. We held a card near the bearing. The edge of the card created a strong diffraction pattern of its own in the shadow region.

We then resorted to a different arrangement, putting a slide with a single pinhole in the laser beam and moving the bearing close to it. The pinhole diffracted the light into a pattern of bright and dark circles around a bright center. In our previous work the bearing was far enough away to be bathed with light from the center of the pattern.

We moved the bearing close enough to make the first dark circle in the pinhole's pattern fall on the perimeter of the bearing. Hence all along the perimeter of the bearing's cross section the light



Imaging two pinholes

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Possible images of I

from the pinhole interfered destructively, leaving the perimeter in darkness. The Poisson pattern in the shadow of the bearing disappeared.

Next we moved the bearing close enough to make the first bright circle of the pinhole's diffraction pattern graze the perimeter of the bearing. The Poisson pattern reappeared. We moved the bearing slightly to one side so that it was off-center in the pinhole's diffraction pattern. On one side the center of the pattern brightly illuminated the perimeter of the bearing. On the opposite side part of a dark circle grazed the bearing's surface. This time the shadow of the bearing showed a bright flare through the center. The Poisson pattern was washed out.

Apparently the creation of the Poisson pattern depends on the diffraction of light around opposite sides of the bearing. When the side of the bearing lies in a dark part of the pinhole's diffraction pattern, the light rays passing that side are out of phase. Although they are diffracted into the shadow region, they remain out of phase and so interfere destructively.

When the pinhole's dark ring grazed the full perimeter of the bearing, none of the light reaching the shadow region survived destructive interference. The region was dark. If part of the perimeter was grazed with a dark ring, light passing that side could not interfere constructively with light passing the opposite side. This time the shadow region received light from one side of the bearing but lacked the pattern of concentric circles.

Although imaging by a sphere or a disk has been investigated since 1818, I can find no record of detailed studies. The amateur experimenter therefore has plenty of scope. How far should a ball bearing be from the slide and the point of observation in order to enhance the image? Where should the bearing be in the diffraction pattern cast by the slide? Should the bearing be large or small? Can a sphere much larger than a ball bearing form images in its shadow region? Is there any way to reduce the distortion of the image due to the overlap of Poisson patterns?

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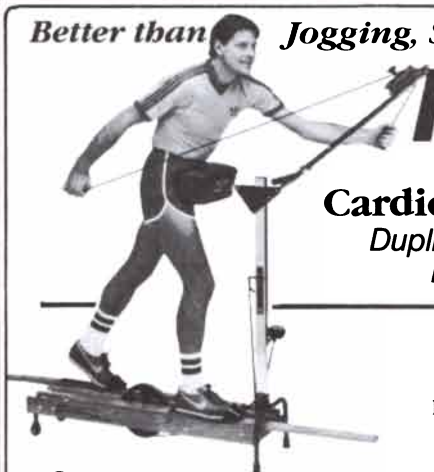

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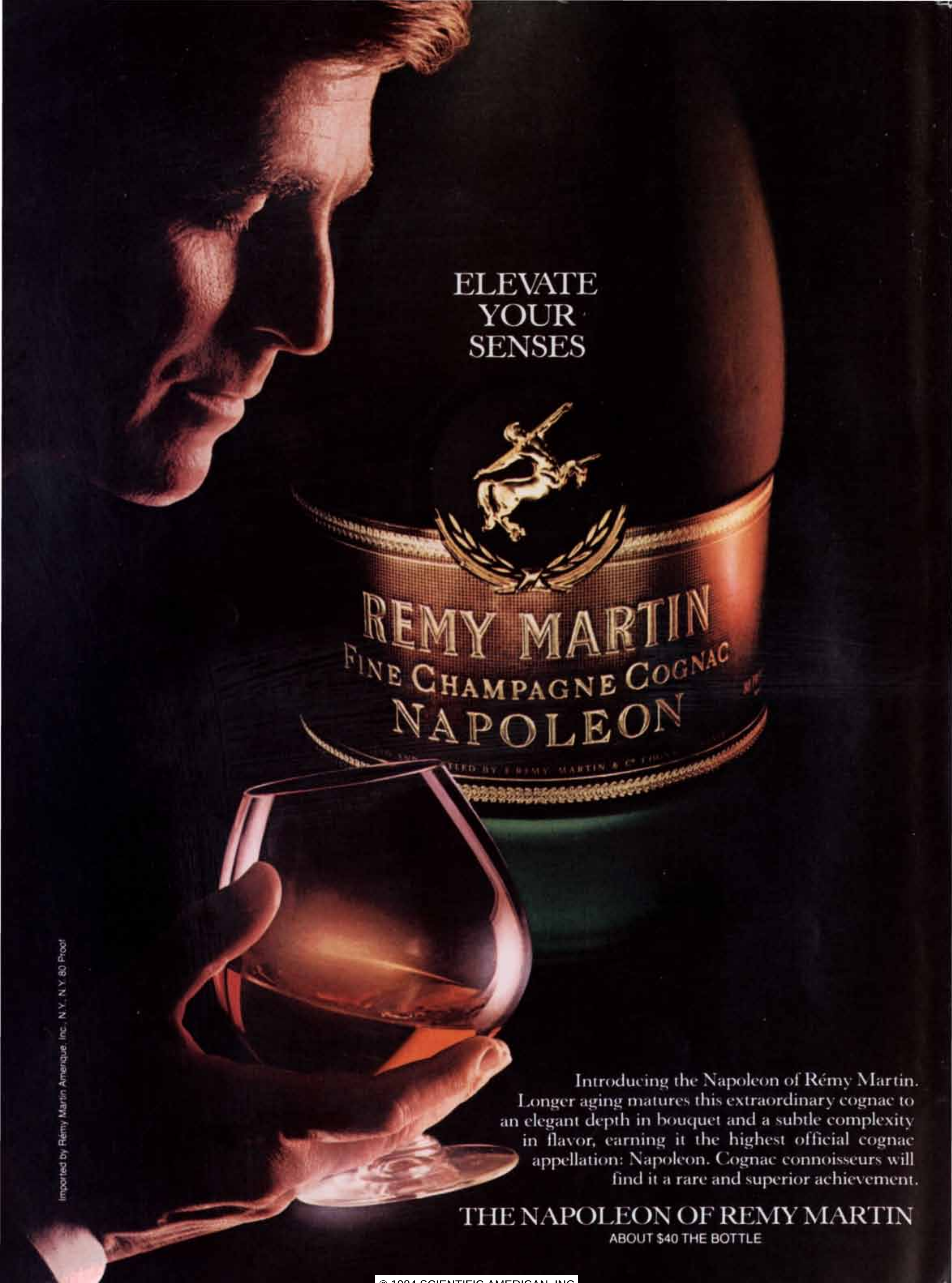

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