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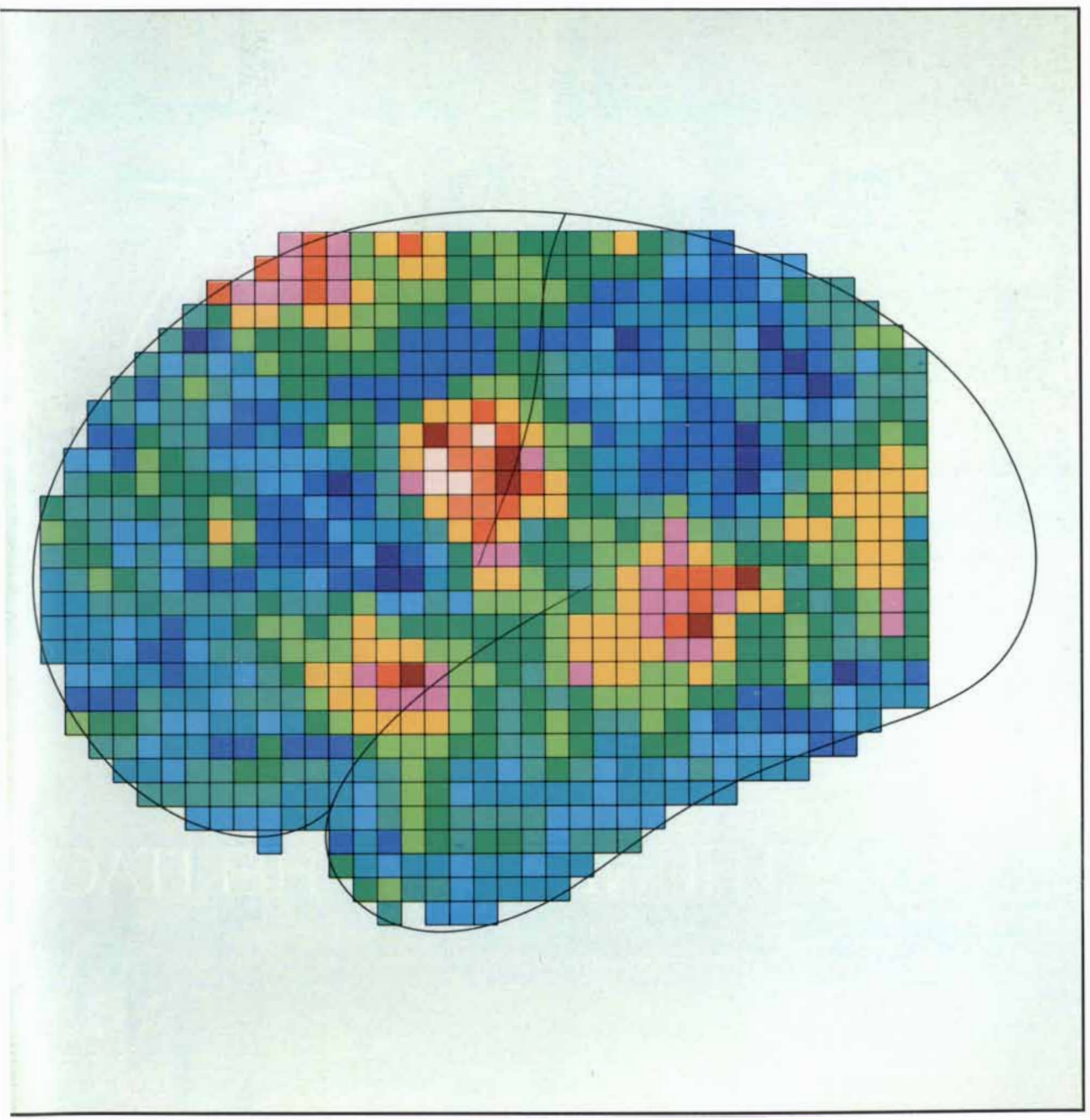

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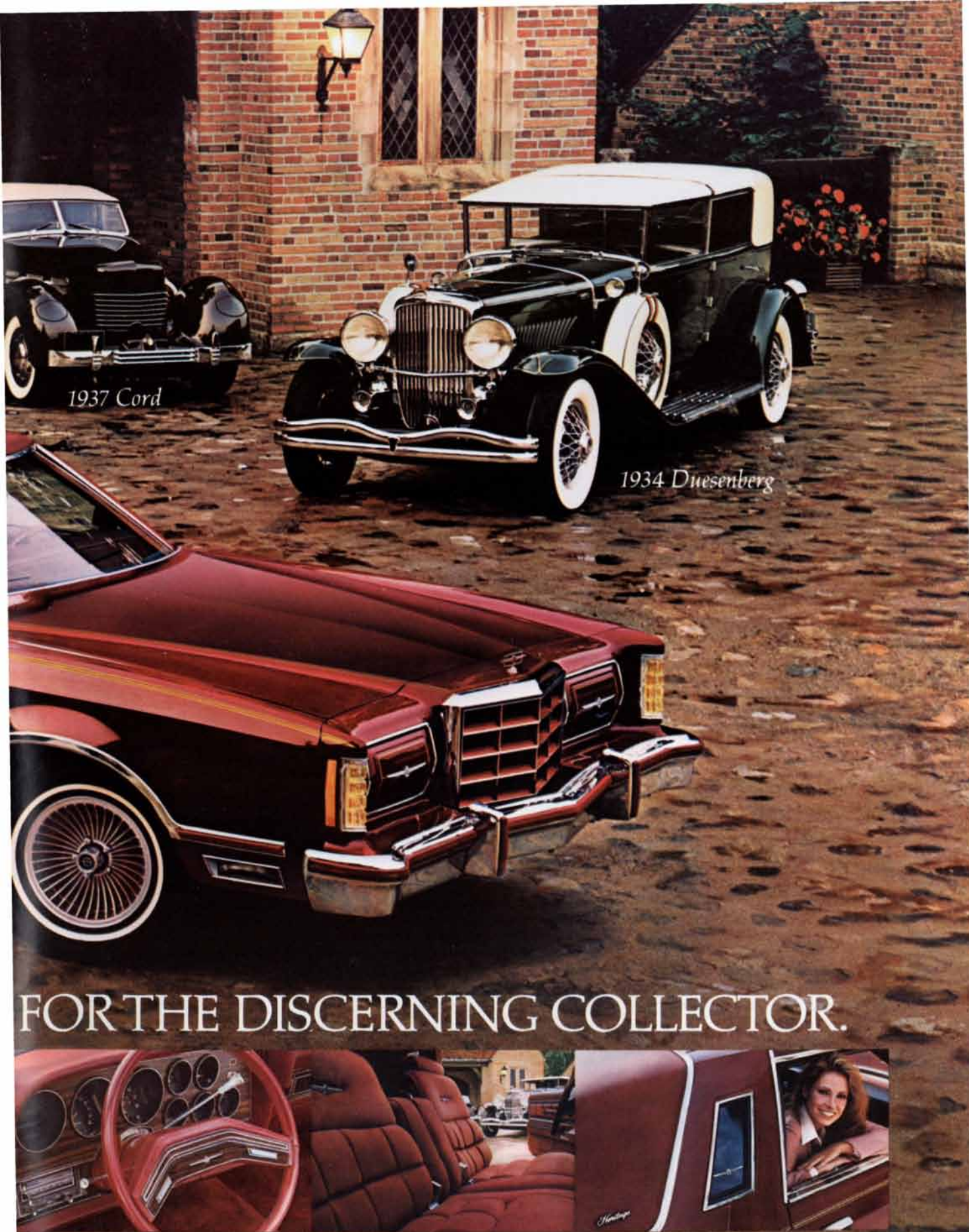

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Not running, not jogging, but *walking* is your most *efficient* form of exercise and the *only* one you can *safely* follow *all* the years of your life!

Today, after some 2000 years, modern medical researchers are demonstrating (somewhat to their surprise) that Hippocrates, "the father of medicine" was right . . . walking is man's best *"medicine"!*

Take one example. At a three-day conference on *Exercise in Aging—Its Role in Prevention of Physical Decline* (held October 27-29, 1977, at the National Institute of Health, Bethesda, Maryland) researchers from across the United States, Canada and Western Europe presented papers on this (until now) largely neglected area of research. As their papers were presented, these important points of agreement emerged:

(1) Walking is the most *efficient* form of exercise . . . and the only one you can safely follow all the years of your life.

(2) Exercise can enable your body to maintain a *vital reserve* which has a protective effect during stress.

(3) Exercised *bones* do not demineralize. As a result they are far less likely to break or lose their range of motion.

(4) Exercised *lungs* still exhibit the emphysema-like changes of age, but are far less diminished in their capacity compared to the lungs of sedentary people.

(5) Exercised *cardiovascular systems* show a similar maximum preservation of function.

(6) The benefits of exercise in preventing or correcting obesity are striking.

(7) Late-onset diabetes is almost entirely reversible by exercise if you are overweight.

(8) Daily exercise permits greater food intake and better blood circulation, thus improving each body cell's nourishment while preventing obesity.

(9) The physically impaired, particularly the arthritic, can perhaps benefit the most from exercise . . .

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Raymond J. Shamberger, Ph.D.: On your risk of stomach cancer from untreated beef . . . and how the natural antioxidants, vitamins C and E and selenium, help protect you!

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Sir Hans Krebs, M.D., F.R.C.S.: On the use and misuse of medication. The world-famous Nobel Laureate in Physiology and Medicine warns that too many patients are being made ill due to their own or their physicians carelessness because the new high-potency drugs have side-effects that are almost unavoidable if not carefully monitored.

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Linus Pauling, Ph.D.: On Vitamin C and Cancer. Recent studies show that vitamin C has a large life-extending effect for patients with advanced cancer and suggest a similar large effect for earlier stages of the disease.

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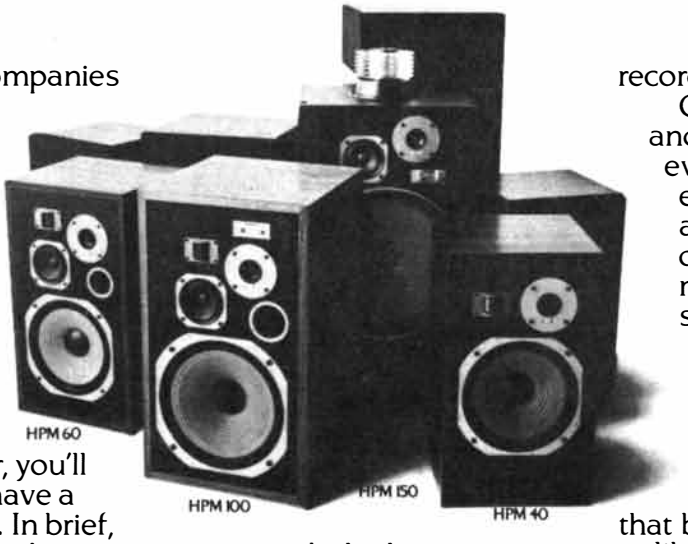
At Pioneer, we think the best way to describe how good HPM speakers are is to tell you what went into them.



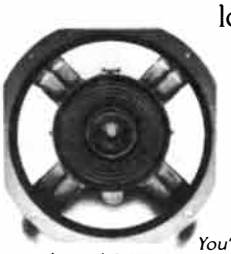
Instead of a conventional tweeter, you'll find HPM speakers have a unique *super*tweeter. In brief, it works on a thin piece of High Polymer Molecular (HPM) film that converts electrical impulses into sound waves without a magnet, voice coil, cone or dome.

The HPM Supertweeter: speaker technology rises to new highs.

As a result, it can reproduce highs with an accuracy and definition that no conventional tweeter could possibly match.

We've also created special mid-range driver cones that are light enough to give you sharp response, yet rigid enough not to distort. So you're assured of hearing a lot more music, and a lot less distortion.

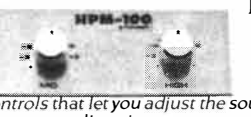
And while most woofers are still made with the same antiquated materials used in 1945, ours are made with a special carbon fiber blend that's allowed us to decrease the weight of the cone, yet increase the strength needed for clarity. This, plus an oversized magnet and a long-throw voice coil let you hear even the deepest notes exactly the way the musicians recorded them.



You'll never hear a sound out of these die cast aluminum frames.

Of course, we could go on and on about the fact that every HPM speaker element has a cast aluminum frame, instead of the flimsy stamped out metal kind. Or about our special compressed wood cabinets that have better acoustic properties than ordinary wood cabinets.

It's features like this that begin to explain why unlike speakers that sound great on only part of the music, HPM speakers sound great on all of it.



Level controls that let you adjust the sound to your listening area.

And this virtue isn't something you'll find in only our most expensive HPM speaker. It's found in *every* HPM speaker.

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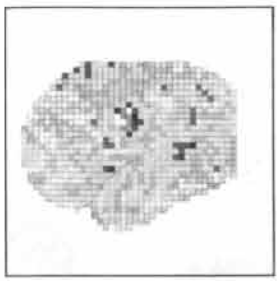

THE COVER

The design on the cover reproduces a computer-generated image representing the pattern of activity in the left side of the cerebral cortex of a normal human subject during the performance of a specific type of behavior (in this case reading aloud). Since the volume of blood flow in a particular area of the cortex is proportional to the activity of the nerve cells in that area, the functions of the cortex can be localized by injecting the radioactive isotope xenon 133 into a brain artery and measuring the regional flow of blood in the cortex during sensory, motor or mental tasks with an array of scintillation detectors (see "Brain Function and Blood Flow," by Niels A. Lassen, David H. Ingvar and Erik Skinhøj, page 62). Each pixel in the image represents a square centimeter of cortex. The colors stand for the level of blood flow; in this reproduction of the image white and red indicate intense activation and dark blue indicates strong inhibition. The image reveals that reading aloud requires the collaboration of seven discrete cortical areas, each specialized for a function such as hearing, seeing or the synthesis of speech. (The primary visual cortex in the back of the brain is not visible because it is not reached by the radioactive isotope.)

THE ILLUSTRATIONS

Cover illustration by Gabor Kiss

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38	*East African Mammals: An Atlas of Evolution in Africa.* © 1978, Academic Press
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63	Niels A. Lassen
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68	Medimatic A/S (*top*), Carol Donner (*bottom*)
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141	Servicio Aerophotografico Nacional
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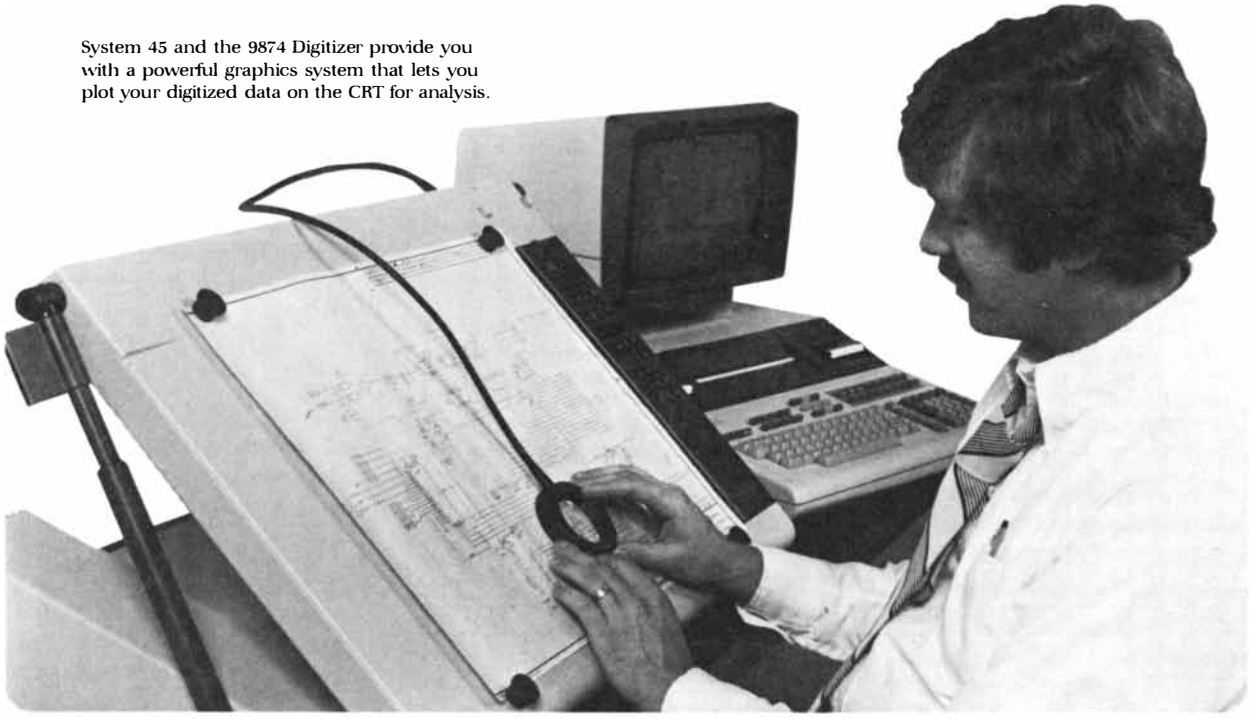
161	Alan D. Iselin (*top*), Lewis Wolpert (*bottom*)
162	Alan D. Iselin (*top left and bottom*), Lewis Wolpert (*top right and middle*)
164	Alan D. Iselin
167	Timothy C. Williams and Janet M. Williams
168–169	Lorelle M. Raboni
174–176	Lorelle M. Raboni
180	Jearl Walker
182–186	Michael Goodman

HP measurement and computer advances



System 45 and the 9874 Digitizer provide you with a powerful graphics system that lets you plot your digitized data on the CRT for analysis.

Convenient, sophisticated new digitizer converts analog data from virtually any graphic form.

HP's new, microprocessor-controlled digitizer provides an accurate, speedy, and convenient method of entering analog data into any 9800 Series desktop computer. The 9874 will convert analog information in virtually any graphic form, be it maps, 35 mm slides, x-rays, photos, movies, or what have you, into a series of discrete X-Y coordinates for computer analysis.

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To further enhance your digitizing system, HP manufactures a continuum of computers and peripherals to meet today's needs as well as to provide a growth path to the future. System 45, HP's powerful graphic desktop computer, makes an ideal partner for the 9874. Its enhanced BASIC language has many of the powerful features of FORTRAN and APL to make programming fast and easy.

extend your possibilities.

System 35 sets a new price/performance standard for dedicated high-speed data acquisition and control.

In a compact, fully integrated desktop package, HP's new System 35 incorporates all the high-performance hardware for the task, up to 256K bytes of user read/write memory, an HP BASIC operating system, and versatile, ready-made I/O capabilities.

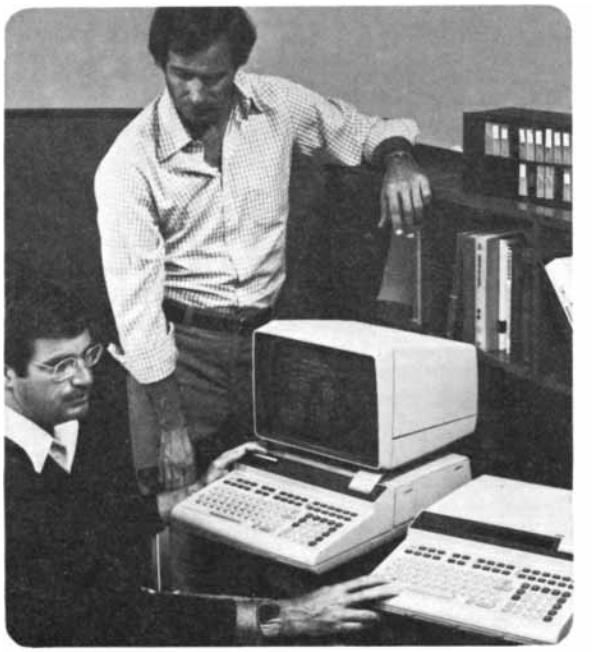
The second in Hewlett-Packard's advanced class of desktop computers, System 35 integrates a high-speed processor, large memory, mass storage, and optional CRT and printer in a compact unit that can easily be moved wherever you need it.

System 35 is especially easy to use. With its built-in HP BASIC operating system, it's ready to begin solving problems as soon as you turn it on. There are no complicated startup procedures, no operating system to load, no compiling to puzzle out.

For data acquisition and control, System 35's I/O ROM and plug-in cards let you interface easily with as many as 14 instruments and peripherals at a time, and achieve this level of performance:

- direct memory access allows communication with high-speed devices at rates up to 400K words per minute
- built-in I/O drivers automatically handle I/O formatting and communications
- buffered I/O and 15 priority levels allow System 35 to control operations and capture real-time data while it performs computations
- autostart, time-out, and automatic error trapping keep System 35 working
- a choice of ready-made plug-in cards for BCD, bit parallel, bit serial, and HP-IB (IEEE 488-1975) devices plus a real time clock interface that can be used as a system pacer or time reference for data logging.

System 35 runs on an HP BASIC operating system contained in a 112K-byte ROM. HP BASIC is entirely compatible with ANSI standard BASIC but is enhanced with powerful FORTRAN-like capabilities such as subprograms with ON-KEY interrupts, array operations,



At left is System 35A, with an 80-character by 24-line CRT display. At right, System 35B has a single-line LED display with a capacity of 32 alphanumeric characters.

multicharacter identifiers, unified mass storage, and graphics commands.

Through a set of optional assembly language ROMs, experienced programmers can gain complete access to System 35's central processor. For many specialized computations and I/O operations, subprograms can be written in assembly language and called in BASIC programs, resulting in as much as a 100-fold increase in execution speed.

Prices for the HP System 35 start at $9,900* with CRT, and at $8,700* with single-line LED display. Either way, the standard system has 64K bytes of user read/write memory.

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LETTERS

Sirs:

Glynn Isaac's demonstration of the archaeological evidence suggesting that long-term social bonds, the consistent use of a home base and food sharing were characteristic of early hominids adds an important new dimension to the understanding of our evolutionary heritage ["The Food-sharing Behavior of Protohuman Hominids," by Glynn Isaac; SCIENTIFIC AMERICAN, April]. I should like to suggest, however, that food sharing did not originate with the Hominidae but represents an elaboration of behaviors characteristic of some members of the living Hominoidea, particularly the chimpanzee.

Food exchange among adult male chimpanzees at the site of predations is described as "tolerated scrounging." This term implies some degree of contest competition and involuntary exchange of food. The question of whether this behavior can appropriately be considered "sharing" is complicated by the absence of an accepted definition of the term. It is clear that food is exchanged among individuals, regardless of the nature of the interaction.

Dr. Isaac does not mention food sharing between chimpanzee females and their offspring, although this behavior occurs more commonly than exchange of meat among adults. At Gombe National Park in Tanzania provisioned bananas were distributed with the greatest frequency by females to their own offspring, according to a report by W. C. McGrew. Jane Goodall has described an extensive repertory of solicitation gestures employed by chimpanzee infants. The responses of the mothers to the solicitations vary, but most often the mothers react tolerantly. My own research indicates that the outcome of such solicitations depends primarily on whether the infant can procure or process the food item independently. Foods that immature individuals cannot obtain and/or prepare for consumption are most frequently shared.

The similarity in the form of human and chimpanzee manual solicitation gestures is suggestive of a common phylogenetic origin. Dr. Isaac has suggested in another publication that the transport of food may have originated as a means of feeding dependent offspring, a behavior closely related in function to the primary context of food sharing in chimpanzees. It is also noteworthy that there is little difference in the solicitation gestures of adult chimpanzees and immature chimpanzees.

These data suggest that food sharing along with a number of other behaviors once believed to be diagnostic of the human condition (for example tool use) may also be considered an elaboration and extension of a basic hominoid behavior pattern.

JOAN B. SILK

Department of Anthropology
University of California
Davis

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Sirs:

Thomas A. Croft's fascinating article "Nighttime Images of the Earth from Space" [SCIENTIFIC AMERICAN, July] includes a satellite picture of a giant gas flare in the West Siberian oil fields, made in January, 1975. The author comments that this flare is one of the biggest he detected in his examination of the pictures recorded in the U.S. Air Force's Defense Meteorological Satellite Program. The flare in question is associated with the giant Samotlor oil field near Nizhnevartovsk, which at the time the image was made was producing 1.6 million barrels a day, or about a sixth of all Russian oil. Since then, in an effort to make productive use of the waste gas, the Russians have completed three gas plants on the site, separating the natural-gas liquids for petrochemical uses and piping the residual gas to a power station at Surgut, in the cluster of bright lights to the west. In a further effort to find a market for the gas, a 700-mile gas pipeline was completed in 1977 from Samotlor southeast to the city of Kemerovo, which appears on the satel-

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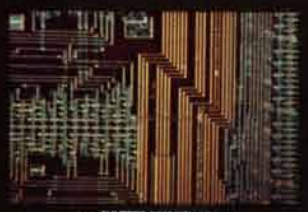
Seville . . . the first American car to combine international size and timeless styling with Cadillac comfort and convenience. The first luxury car anywhere to offer the choice of either the standard 5.7 litre EFI engine or the available 5.7 litre diesel V8. (Seville is equipped with GM-built engines produced by various divisions. See your Cadillac dealer for details.) Seville is also first to offer Trip Computer . . . for vital trip information. More Americans have chosen to own Seville than any luxury import model. Now, for 1979 . . . the significance of Seville. The craftsmanship of Cadillac. The luxury car of the decade. At your Cadillac dealer.

hexa·photo·cybernetic

Technology this advanced deserves its own word.



The incredible new Canon A-1. It's on the cutting edge of technology, with state-of-the-art electronics and computerized operation.

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lite image as the city light near the precise midpoint of the right-hand edge. There the gas will also be burned in power stations and be used as a raw material in ammonia production. (The details of this pipeline project were reported in *Soviet Geography,* February, 1978, page 149.)

THEODORE SHABAD

Editor
Soviet Geography
New York

Sirs:

Dr. Croft's article "Nighttime Images of the Earth from Space" accents dramatically the wasteful flaring of natural gas in many regions of the world. He points up the problem of liquefying natural gas: the huge costs of plants and cryogenic freighters, and the need for plants to be large if the process is to be economic.

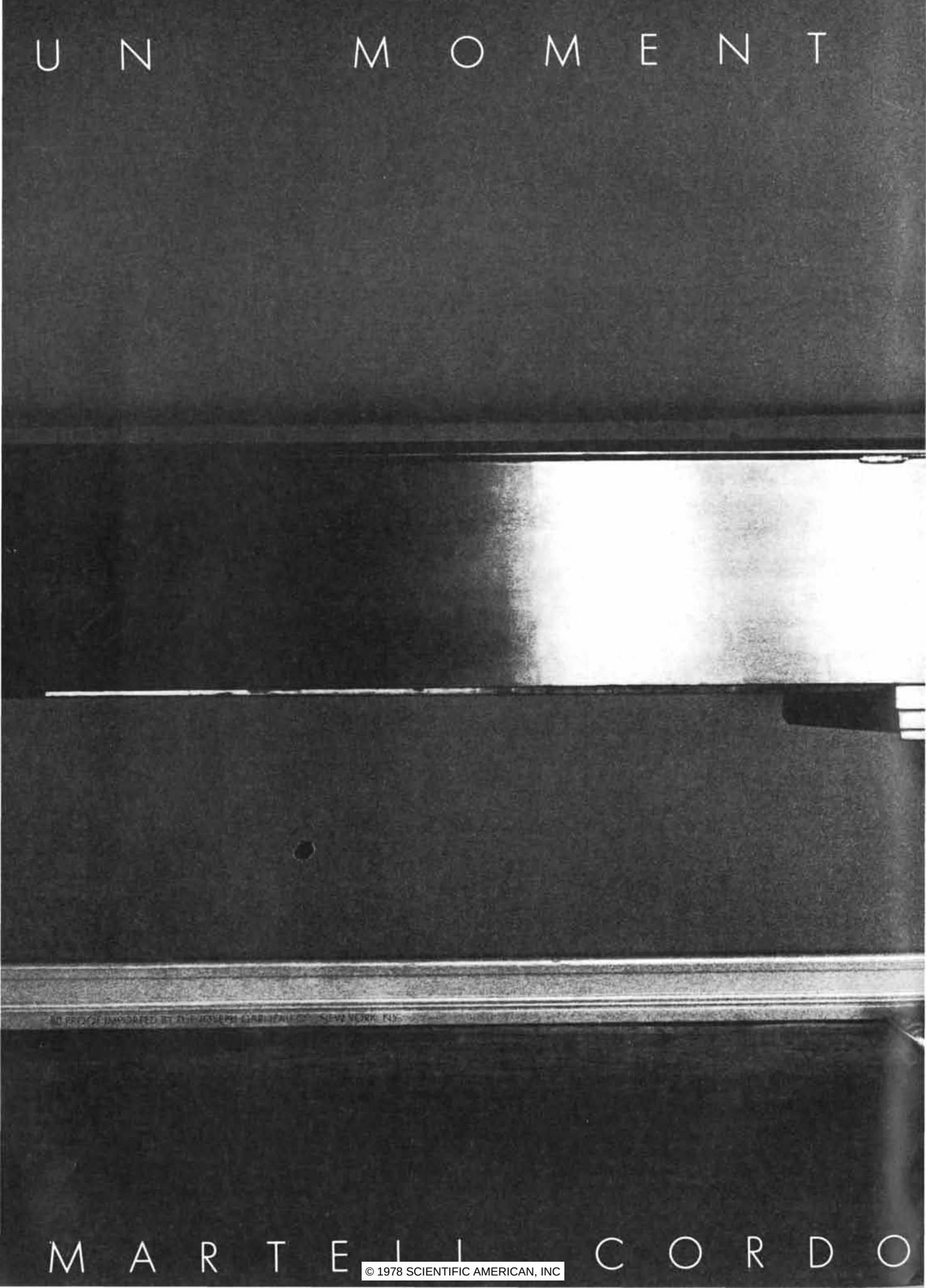
Not mentioned is another practical solution, now being implemented by the U.S.S.R.: the conversion of natural gas into methanol. Two plants are under construction (to be completed in 1981), each capable of converting roughly 125 million cubic feet of natural gas into 2,500 metric tons per day. By geographic coincidence one of the two plants is being built at Tomsk, only about 500 miles up the Ob River from Surgut in northern Siberia, where a "giant gas flare" was disclosed by one of the satellite images. (The other plant is at Gubakha, just east of the Kama Reservoir in the foothills of the Ural Mountains.)

While the two Russian plants will be larger than any methanol plants in existence today, the British company handling the design and engineering, Davy International Ltd., has also built plants with an output as small as 150 metric tons per day in Korea and Taiwan. Thus the economics of small plants appear to be acceptable.

A point of interest is the projected uses of the Russian plants' output. To put the matter into scale, U.S. production of methanol is about 9,000 metric tons per day, and world production is on the order of 25,000 to 30,000 metric tons per day. Substantially all methanol now produced is utilized as a feedstock for organic chemical production. Can an additional 5,000 metric tons (along with the output of other plants, planned or under construction) be absorbed in such use? It seems doubtful, and the answer may lie in the beginning use of methanol as a fuel, transportable in ordinary tankers and lacking the potential dangers that appear to be inherent in liquefied natural gas.

H. EARL TREMAIN

Flanders, N.J.



50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

OCTOBER, 1928: "It is astonishing to discover in this boasted 'age of reason' how many millions of otherwise sane, level-headed, intelligent people still dwell, after a fashion, in the very midst of the Dark Ages. We refer to the recent craze for astrology, the 'science' of the stars in their control over the destiny of human individuals. One need only visit the corner bookstore to learn that there is at present an enormous sale of books on the subject; they have broken into the ranks of the very best sellers. Astrology was the parent of astronomy, but when astronomy came of age, it parted company with its parent, ashamed of its origin. Do the good souls who believe the stars exert some influence over our lives know what stars are? Let them buy a dollar book on astronomy, the offspring of their beloved occult study of subtle influences, and find out what sort of thing is the universe in which they live."

"The Eastman Kodak Research Laboratories, under the direction of Dr. C. E. K. Mees, has been working for a number of years to develop color movies. The most radical element in a new process is the film. Instead of having the usual smooth surface the side opposite the sensitive coating is embossed with cylindrical lenses so small as to be invisible. These lenses, which are part of the film itself and made of the film substance, would each look, vastly magnified, like the rib of a corrugated iron roof. They run the length of the film and 559 of them occupy an inch. The effect of these invisibly small lenses is to separate the rays of light that enter the camera through a filter divided into three strips: one red, one green and one blue. Each of the three colors of the filter lets into the camera from the scene in front of it only the light rays of its own color. The three differently colored light rays register on the film only as black and white, but each tiny lens embossed on the film so distributes the light rays falling upon it that the different colors register on the sensitive film emulsion as a distinct black-and-white impression for each color at that point. The light of the projector then passes through the film in such a way that it shines through the tiny film lenses and then through the projector lens, and each ray is directed through the proper color on the light filter, to fall on its proper spot on the screen. The combination of the three colors red, green and blue gives every possible natural color."

"Characterized as one of the most romantic achievements of the modern industrial era, the plant of the A. O. Smith Corporation for making automobile frames is virtually one huge automatic machine that receives and inspects strip steel and manufactures a completed enameled frame in less than two hours. Except for minor operations such as pickling, cleaning and oiling the stock and inspecting the assembled frame, the automatic machine takes care of all operations. The unit being manufactured is not touched by human hands, each frame remaining on conveyors 90 per cent of the time. There are 552 operations on each frame, and since the plant has a capacity of 7,000 frames a day, the daily operations performed by the machinery total 4,000,000. The plant is 600 by 212 feet. It is said that the number of men employed to supervise the automatic equipment—about 200—is less than a fifth the number that would be needed for a semi-automatic plant of equal capacity."

SCIENTIFIC AMERICAN

OCTOBER, 1878: "Formerly Galveston, Tex., was accustomed to having an epidemic of yellow fever every three or four years. The last and worst the city ever suffered was in 1867. At that time the level of the city was low, and there was standing water under nearly all the older houses. Seeing that the fever spread most rapidly and was most fatal where the stagnant water stood, it was ordered that the grade of the city should be raised four feet, and that the space under every house that had water under it should be filled with sand. At the same time the system of surface drainage was improved, and strict sanitary regulations were adopted and enforced. If every Southern city had been kept as clean as Galveston, the present terrible epidemic of yellow fever in the South might never have occurred."

"A series of systematic experiments on the transplantation of tissues has recently been carried out by Dr. Zahn. The first observations were made on the transfer of hyaline cartilage from one adult animal to another. These attempts, however, yielded negative results: the cells of the tissues perished. The experiments were much more successful when the fragment was taken from foetal cartilage."

"In the latest form of the spectroscope the prism disappears altogether. Almost every one has noticed the colors on mother-of-pearl, and any one with a microscope can see that these colors are formed by numerous lines invisible to the naked eye. It occurred to Fraunhofer to produce these artificially, drawing lines on glass with a diamond by means of a ruling engine and a micrometer screw. In this way he succeeded in producing a spectrum so pure that as many of the solar lines could be seen in it as in the spectrum from a prism. More recently Mr. Rutherfurd has constructed an engine of wonderful accuracy and has ruled such lines on speculum metal with a precision almost beyond belief. This little plate of metal, which can be hidden in the hand, is optically equal to the most powerful train of prisms yet constructed. For most researches on the sun these 'gratings' appear to be displacing all older forms of the spectroscope."

"A prediction made about 10 years since by an eminent engineer, that the time was not far distant when the business of railroads would be confined to the transportation of passengers, mails and costly freight, and that all produce and other heavy or bulky merchandise would be transported by steam road wagons over the common roads, or over roads graded specially for the purpose, does not appear so visionary as it did then. Indeed, it seems quite possible that before another quarter of a century has passed the prediction will be verified so far, at least, as concerns roads running through the thickly settled parts of the country and to the feeders of the great trunk railroad lines. Even as we write the contractors for carrying the daily mail between Yuma and San Diego are building a steam wagon to transport passengers, baggage and mail across 100 miles of desert that lies in their route, and they count on traveling at the rate of eight or 10 miles an hour on the sandy roads."

"A short time since SCIENTIFIC AMERICAN briefly noted the fact that Mr. Muybridge of San Francisco had perfected an automatic apparatus by which he had succeeded in recording the action of horses in motion. In taking these photographs Mr. Muybridge employed a series of cameras operated by electricity. The exposure for each negative was about the two-thousandth part of a second. In his analysis of the stride of the trotting horse Mr. Muybridge notes that the horse is entirely in the air for about half the length of the stride, and for a brief interval it has only one foot on the ground. The most careless observer of these photographs will not fail to notice that the conventional picture of a trotting horse in motion does not appear in any of them. Mr. Muybridge's ingenious and successful efforts to catch and fix the fleeting attitudes of moving animals thus not only make a notable addition to our stock of positive knowledge but also must effect a radical change in the art of depicting horses in motion."

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THE AUTHORS

PHILIP MORRISON and PAUL F. WALKER ("A New Strategy for Military Spending") are members of the Boston Study Group, whose new book, *The Price of Our Defense: A New Strategy for Military Spending,* provides the basis for their article. (The other members of the group are Randall Forsberg, Martin Moore-Ede, Phylis Morrison and George Sommaripa.) Morrison is professor of physics at the Massachusetts Institute of Technology. He obtained his Ph.D. under J. Robert Oppenheimer at the University of California at Berkeley in 1940 and then worked on the wartime atomic-bomb project, first in Chicago and later at Los Alamos. After 19 years on the faculty of Cornell University he went to M.I.T. in 1965. That same year Morrison also undertook to write the department "Books" for SCIENTIFIC AMERICAN. Walker is research fellow in the Program for Science and International Affairs at Harvard University. He did his undergraduate work at College of the Holy Cross and then enlisted in the army. After learning Russian at the Defense Language Institute and attending the Army Security School, he served as a Russian intelligence specialist with the Army Security Agency and was stationed at the border between West and East Germany. He also worked briefly as a consultant on defense expenditures and arms transfers for the U.S. Department of Commerce and the U.S. Arms Control and Disarmament Agency. Walker then returned to academic life, receiving his master's degree in international relations from the Johns Hopkins School of Advanced International Studies in 1973 and his Ph.D. in political science from M.I.T. in September of this year.

NIELS A. LASSEN, DAVID H. INGVAR and ERIK SKINHØJ ("Brain Function and Blood Flow") have collaborated on investigations of cerebral blood circulation in man for 20 years. Lassen is chief of the department of clinical physiology at Bispebjerg Hospital in Copenhagen. He obtained his M.D. and Ph.D. degrees from the University of Copenhagen, and in 1957 he studied the circulation of the brain with Seymour S. Kety, who was then at the National Institute of Mental Health in the U.S. Ingvar is professor and chief of the department of clinical neurophysiology at the University of Lund in Sweden. He received his M.D. and Ph.D. degrees at Lund and from 1951 to 1953 was a fellow at the Montreal Neurological Institute under Wilder Penfield and Herbert Jasper. Skinhøj is professor and chief of the department of neurology at the University of Copenhagen. As a student during World War II he took part in the resistance movement and was imprisoned in a German concentration camp. After the war he returned to the University of Copenhagen to obtain his Ph.D. The authors wish to thank their many collaborators, particularly Edda Sveinsdottir of the Institute of Computer Science at the University of Copenhagen.

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DAVID N. SCHRAMM and ROBERT N. CLAYTON ("Did a Supernova Trigger the Formation of the Solar System?") are both on the faculty of the University of Chicago. Schramm is professor and chairman of the department of astronomy and astrophysics. He received his bachelor's degree from the Massachusetts Institute of Technology and his Ph.D. in 1971 from the California Institute of Technology. After two years on the faculty of the University of Texas at Austin he went to Chicago in 1974. Schramm's research interests include the origin of chemical elements in supernova explosions, stellar and galactic evolution, the consequences of gravitational collapse and the link between cosmology and the physics of atomic nuclei and high-energy particles. Clayton is professor and chairman of the department of geophysical sciences and also professor of chemistry. A native of Canada, he did his undergraduate work at Queen's University and obtained his Ph.D. in chemistry from Cal Tech. Clayton then spent two years on the faculty of Pennsylvania State University before joining the Chicago faculty in 1958.

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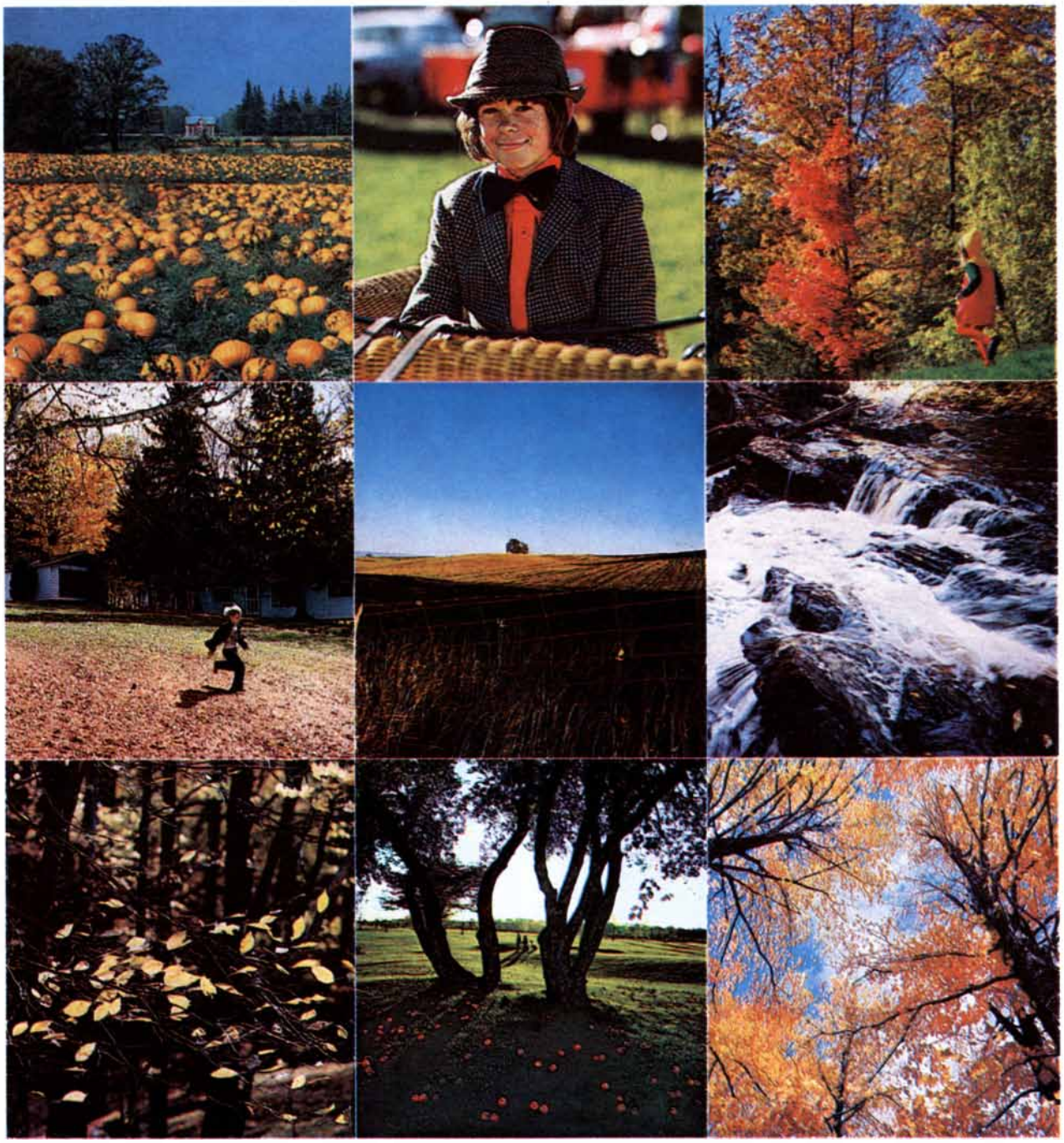
LEWIS WOLPERT ("Pattern Formation in Biological Development") is professor of applied biology at the Middlesex Hospital Medical School in London. Born in South Africa, he studied engineering at the University of the Witwatersrand. He then worked at the National Building Research Institute in Britain for two years and spent a year with the Water Planning Department in Israel. Becoming dissatisfied with engineering, he went on to do his doctoral research on the mechanics of cell cleavage with J. F. Danielli at Kings College in London. He then joined the zoology faculty at Kings College and worked on amoeboid movement and regeneration in hydra. Wolpert moved to the Middlesex Hospital Medical School in 1966.

TIMOTHY C. WILLIAMS and JANET M. WILLIAMS ("An Oceanic Mass Migration of Land Birds") are a husband-and-wife research team. Timothy Williams is associate professor of biology at Swarthmore College. A graduate of Swarthmore, he received his master's degree from Harvard University and his Ph.D. from Rockefeller University in 1968. After seven years spent teaching at the State University of New York at Buffalo and a year of working as a visiting scientist at the Woods Hole Oceanographic Institution, Williams joined the Swarthmore faculty in 1976. Janet Williams is an independent investigator at the Marine Biological Laboratory in Woods Hole. She was graduated from Colby College and obtained her master's degree from New York University in 1967.



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MATHEMATICAL GAMES

Puzzles and number-theory problems arising from the curious fractions of ancient Egypt

by Martin Gardner

Long before the Christian Era, Chinese mathematicians had a surprisingly sophisticated comprehension of fractions. They accepted any whole number as a numerator or denominator and had excellent rules for adding, subtracting, multiplying and dividing fractions. As is common practice today, the Chinese preferred to work with proper fractions, or fractions that have the numerator smaller than the denominator, a feature reflected in their calling the numerator *tzu* (son) and the denominator *mu* (mother).

The ancient Egyptians, however, had a peculiarly hobbled approach to fractions. They understood rational fractions with numerators greater than 1 well enough but apparently could not deal with them as single numbers. With the sole exception of 2/3, for which there was a special hieroglyph, they had symbols only for unit fractions, that is, fractions that are the reciprocals of positive integers, with 1 above the line and any positive integer below.

To manipulate fractions with numerators higher than 1 the Egyptians expressed such fractions as sums of distinct unit fractions. For example, instead of writing 5/6 they wrote $1/2 + 1/3$. They devised rules for carrying out all the necessary arithmetical operations on expressions of this type. In certain cases, particularly those involving addition, there are advantages to working with fractions in the expanded form, but in general the Chinese methods for handling fractions are far superior.

Most of what is known about Egyptian fractions is derived from the information given in a famous document, now known as the Rhind papyrus, which was inscribed in about 1700 B.C. It was bought in Luxor in 1858 by A. Henry Rhind, a Scottish antiquary, and is now owned by the British Museum. The papyrus, a kind of calculator's handbook, opens with a table in which every fraction of the form $2/b$ is expressed as a sum of distinct unit fractions arranged in decreasing order of size, where b is equal to all the odd integers from 5 through 101.

Did the Egyptians have a systematic method for expanding proper fractions in this way? A number of scholars have speculated about the possibility but it seems most probable that they did not, because the expansions given in the Rhind papyrus are not always the "best." There are of course many different ways to define "best." The most obvious way is to call an expansion best if it minimizes the number of terms. Another type of best expansion is one that minimizes the largest denominator in the series. For example, the expansion of 3/7 as $1/4 + 1/7 + 1/28$ has the smallest possible number of terms, but the expansion as $1/6 + 1/7 + 1/14 + 1/21$ has the smallest possible value of the largest denominator. If both the number of terms and the largest denominator can be minimized in the same expression, so much the better. (I shall not consider other types of best expansions such as those that minimize the sum of all the denominators.)

Even stranger than the preference of the Egyptians for such a cumbersome system is that the Greeks adopted it. In fact, the system was widely used in Europe until well into the 17th century! Even the great Archimedes calculated with what are now called Egyptian fractions. The term has come to refer to any expression of a rational number as a sum of distinct unit fractions, traditionally arranged in decreasing order of size. Modern fractions, in which any positive integer can be above or below the line, are derived from Hindu mathematics and were not widely adopted until the 18th century. Some historians have maintained that the long preoccupation with unit fractions was a cultural bias that delayed progress in mathematics as much as the Roman system of writing numerals did.

Investigating the properties of Egyptian fractions is now a small but challenging task in number theory. There are many deep unsolved problems in this area, but there are also many problems well within the reach of any clever novice that have much in common with certain recreational puzzles. For example, consider the old Arabian brainteaser about a man whose will specified that his 11 horses be divided so that his eldest son would get 1/2, his middle son would get 1/4 and his youngest son would get 1/6. When he died, his lawyers were puzzled about how to carry out these eccentric instructions. After all, horses are of little value when sliced into fractional parts. A relative, hearing of the problem, solved it by lending the heirs his own horse. The 12 animals were then easily divided according to the formula in the will, with the three sons respectively getting six, three and two. One horse was then left over, and so the relative got his horse back!

The puzzle has appeared in many different forms, and of course it can be generalized to deal with larger numbers of sons and larger numbers of horses that are borrowed and then returned. If we stick to the story's traditional form involving three sons and one borrowed horse, an interesting question arises. How many variations are possible in the number of horses to be divided and the set of three fractions for dividing them specified in the father's will? One might guess that there would be an infinite number, but there are only seven. They are the seven solutions of the Diophantine equation $n/(n+1) = 1/a + 1/b + 1/c$, where a, b and c are positive, distinct integers, a is less than b, b is less than c and $n+1$ is the least common multiple of a, b and c.

It is easy to show that a must be equal to 2. If a is greater than 2, then the lowest possible least common multiple for a, b and c is 12, obtained when a equals 3, b equals 4 and c equals 6. Therefore $n/(n+1)$ must be at least 11/12. But the sum $1/3 + 1/4 + 1/5$ equals 47/60, which is less than 11/12, and if the denominators are raised, the sum is even smaller. Hence a is not greater than 2,

	n	a	b	c
1	7	2	4	8
2	11	2	4	6
3	11	2	3	12
4	17	2	3	9
5	19	2	4	5
6	23	2	3	8
7	41	2	3	7

All the variations of an old Arabian puzzle

and so a equals 2. A similar argument shows that b must be either 3 or 4, and with that information it is not hard to determine all the possible values for c. The chart in the illustration on the preceding page gives the value of n (the original number of horses to be divided) and the denominators of the three unit fractions for each of the seven possible variations of the puzzle.

It is obvious that any proper fraction can be expressed as the sum of unit fractions if a repetition of terms is allowed. For example, $3/7$ equals $1/7 + 1/7 + 1/7$. It is not obvious, however, that every proper fraction can be expressed as the sum of unit fractions even if a repetition is forbidden. One proof of this fact is the existence of a famous algorithm for writing any proper fraction as the sum of a finite number of distinct Egyptian fractions. The algorithm was first published in 1202 by Leonardo of Pisa, better known as Fibonacci, in his influential book on arithmetic *Liber abaci*. Fibonacci preferred to work with unit fractions, and his book contains tables for converting proper fractions to Egyptian sums. His algorithm for converting a proper fraction to the sum of a finite number of distinct Egyptian fractions is given without any proof that it always works. The eminent British mathematician J. J. Sylvester rediscovered the algorithm, and in 1880 he published the first proof that it does always work.

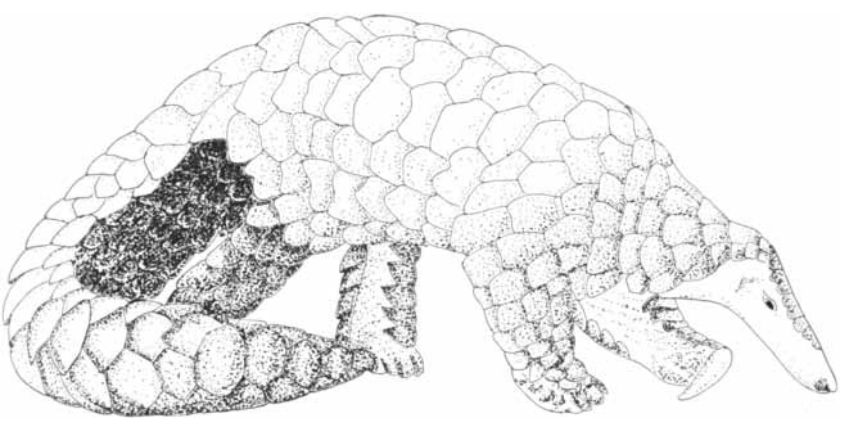
Fibonacci's method is simple. Call the proper fraction a/b. The first term of the expansion is the largest unit fraction not greater than a/b. Now subtract the unit fraction from a/b to obtain another proper fraction. The second term of the expansion is the largest unit fraction not greater than this remainder. Continue in this manner, each time putting down the largest usable unit fraction as the next term in the expansion and then subtracting and repeating the process with the remainder. It is clear that the fractions obtained in this way will grow steadily smaller. It can be proved that the process always terminates. Hence the algorithm always works. (It is also possible to express any irrational number as the sum of an infinite series of distinct unit fractions, but that is too far removed from our topic.) In today's vernacular Fibonacci's method is known as a greedy algorithm, because at each step in the process the largest fraction possible is chosen.

Although the greedy algorithm will express any proper fraction in the Egyptian manner, it does not always give the best expansion in either of our two senses of the word. When the algorithm is applied to fractions of the form $1/b$, however, it does generate the best two-term expansion of $1/b$ in both senses. A little algebraic doodling will convince you that applying the algorithm is the same as replacing $1/b$ with $1/(b+1) + 1/[b(b+1)]$. Thus $1/2$ equals $1/3 + 1/6$; $1/3$ equals $1/4 + 1/12$; $1/4$ equals $1/5 + 1/20$, and so on.

The formula given above for a two-term Egyptian expansion of $1/b$ also serves to prove that any proper fraction can be expressed in the Egyptian manner in infinitely many ways. Consider the expansion $2/3 = 1/2 + 1/6$. By applying the formula to the last term $1/6$ we obtain a new expansion: $2/3 = 1/2 + 1/7 + 1/42$. If we repeat the procedure with $1/42$, we obtain $2/3 = 1/2 + 1/7 + 1/43 + 1/1{,}806$. In this way the expansion of $2/3$ as a series of unit fractions can be continued indefinitely.

The same formula underlies an algorithm called the splitting method, which, like Fibonacci's greedy algorithm, is guaranteed to generate a finite Egyptian series for any proper fraction. There are many other algorithms that serve the same purpose, each with its own advantages and defects. Some algorithms minimize the number of terms and others minimize the largest denominator, but all of them, including the greedy algorithm, are inefficient and difficult to apply to fractions with large denominators and numerators.

When the greedy algorithm is applied



An uncurled pangolin

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to a proper fraction a/b, it always generates a series of Egyptian fractions with a number of terms no greater than a. Thus when it is applied to a proper fraction of the form $2/b$, it generates an expression with one or two terms: $2/4$ equals $1/2$; $2/5$ equals $1/3 + 1/15$; $2/6$ equals $1/3$; $2/7$ equals $1/4 + 1/28$, and so on. At each step the algorithm chooses the largest unit fraction that is smaller than the remainder, but since each step is unaffected by preceding or succeeding steps, the procedure can easily miss an expression with fewer terms when it is applied to a proper fraction with a numerator of 3 or higher. It also tends to generate terms with denominators much larger than necessary.

Michael N. Bleicher, in his section on Egyptian fractions in the book *Excursions into Mathematics* (Worth Publishers, 1969), gives several horrendous examples of how miserably the greedy algorithm can fail to generate the best expansion in either of our two senses of the word. For example, when the algorithm is applied to $5/121$, it generates the series $5/121 = 1/25 + 1/757 + 1/763{,}308 + 1/873{,}960{,}180{,}913 + 1/7{,}638{,}092{,}437{,}828{,}241{,}151{,}744$. Bleicher compares that with the expansion $5/121 = 1/25 + 1/759 + 1/208{,}725$. There is no way to express $5/121$ with fewer than three terms, but Bleicher does not know whether or not a three-term expansion can have a largest denominator smaller than 208,725.

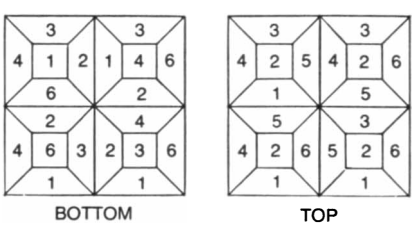
For proper fractions of the form $3/b$ the greedy algorithm is guaranteed to generate an expression of three or fewer terms, and if the fraction has the form $4/b$, it is guaranteed to generate an expression of four or fewer terms. The outstanding unsolved question of Egyptian fractions concerns the case $4/b$: Can a proper fraction $4/b$ always be expressed with three or fewer terms? In other words, can the Diophantine equation $4/n = 1/a + 1/b + 1/c$ always be solved for any integral value of n greater than 4?

Paul Erdös and E. G. Straus have conjectured that the equation can always be solved. Their conjecture has been verified to extremely large values of n, but it has not been proved. Similarly, Waclaw Sierpinski has conjectured that all proper fractions of the form $5/b$ can be expressed with no more than three terms. He has also conjectured that for any given integer k and a variable with integral values b there is a value of b greater than k such that for all larger values of b the proper fraction k/b can always be expressed with no more than three terms.

So far we have considered only proper fractions. What about improper fractions such as $2/1$ and $7/3$? These fractions too can always be expressed by a finite Egyptian series in infinitely many ways. To generate such an expression we start with terms in the harmonic series $1/1 + 1/2 + 1/3 + 1/4 + \ldots$, because they are the largest unit fractions we can use. It is well known that the harmonic series does not converge. In other words, a partial sum (the sum of the first n terms for some n) will exceed any integer we name. The procedure for generating a series of Egyptian fractions equal to an improper fraction consists in using the harmonic series as far as possible and then adding more unit fractions to express whatever fractional part of the desired total remains. The harmonic series diverges with distressing and increasing slowness, however, and for this reason even small improper fractions demand enormously long Egyptian expressions. For example, expanding $10/1$ requires more than 20,000 unit fractions from the harmonic series.

Recently some curious results concerning Egyptian fractions have been obtained. In 1963 it was shown that every positive integer can be expressed by an Egyptian series in which all the denominators are in an arithmetical progression. In 1964 Ronald L. Graham of Bell Laboratories studied the question of what rational fractions can be expressed by Egyptian fractions in which all the denominators are squares. He solved the problem completely, and he also solved the more general problem of determining which rational fractions can be expressed with Egyptian fractions in which all the denominators are powers higher than 2. In the same year Graham also showed that if there is a set of numbers that includes all prime numbers greater than some number and all squares greater than some (possibly different) number, then any rational fraction has an Egyptian expansion that draws all its denominators from the set.

Particularly difficult problems arise when the denominators of Egyptian fractions are limited to the odd whole numbers. It is easy to see that the sum of a series of such fractions cannot be a fraction with an even denominator. It has been shown that every rational fraction with an odd denominator can be expressed as the sum of a finite series of distinct Egyptian fractions, all with odd denominators, for example $2/3 = 1/3 + 1/5 + 1/9 + 1/45$; $2/5 = 1/3 + 1/15$, and $2/7 = 1/7 + 1/9 + 1/35 + 1/315$. There are inefficient algorithms for finding such expressions, but no one has yet proved that Fibonacci's greedy al-



Solution to the "Eight Blocks to Madness"

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gorithm always terminates when it is applied to this task, even for proper fractions. When denominators may be either even or odd, the greedy algorithm generates increasingly small unit fractions, and it can be proved that the series must terminate. If all denominators must be odd, however, the fractions in the series determined by the algorithm go up and down, seemingly at random, and the task of proving that the series terminates is formidable.

The expansion of 1 into the smallest number of Egyptian proper fractions with all odd denominators was not found until 1976. (The expression 1/1 is not allowed.) It turns out that there are five solutions to this problem, each with nine terms. The expansion with the smallest largest denominator is $1 = 1/3 + 1/5 + 1/7 + 1/9 + 1/11 + 1/15 + 1/35 + 1/45 + 1/231$. All five solutions start with the reciprocals of 3, 5, 7, 9, 11 and 15. The other four solutions continue with the reciprocals of 21, 135 and 10,395; 21, 165 and 693; 21, 231 and 315, and 33, 45 and 385. What Egyptian expansion for 1 with all odd denominators has the smallest largest denominator? The only answer is the 11-term series $1 = 1/3 + 1/5 + 1/7 + 1/9 + 1/11 + 1/33 + 1/35 + 1/45 + 1/55 + 1/77 + 1/105$.

By adding 1/1 to each of the series given above we get the best odd-denominator Egyptian expressions for 2. When 1/1 is not allowed, however, I do not know what the best expressions for 2 are (in either sense of the term) or even whether such expressions have been found.

Here are four easy Egyptian fraction problems to which the solutions will be given next month:

1. Express 1 as the sum of three distinct unit fractions.

2. Express 67/120 as the sum of the fewest possible Egyptian fractions, with the smallest largest denominator for that number of terms.

3. The fraction 8/11 is the "smallest" proper fraction that cannot be expressed with fewer than four Egyptian fractions, in the sense that the sum of its numerator and denominator is minimized. Find a four-term expression for the fraction.

4. When the greedy algorithm is applied to a proper fraction of the form $3/b$, what is the smallest value for b such that the algorithm produces an expansion of three terms and that $3/b$ can be expressed as the sum of two distinct unit fractions?

In discussing mathematically interesting animals in my June column I made two mistakes, one out of ignorance and one out of carelessness. I wrote that no real animal propels itself across the ground by rolling like a disk or sphere. That is not strictly true if we include rolling down hills. Readers too

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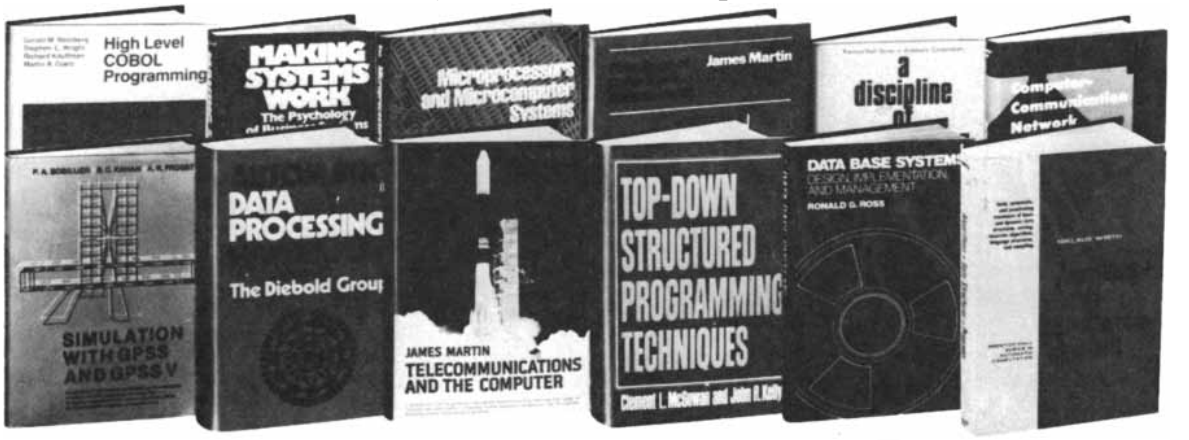

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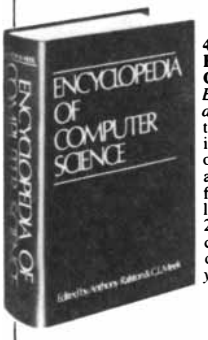

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numerous to identify have written me that earlier this year a National Geographic television special on the Namib desert of Africa showed a small spider that lives in burrows in the sides of sand dunes. When the spider is attacked by a wasp, it extends its legs like the spokes of a wheel and escapes by rolling down the dune. Peter G. Trei of Belgium sent me a copy of a note in *Journal of Mammalogy* (February, 1975) by Richard R. Tenaza, an American zoologist. Tenaza describes how on Siberut, an island west of Sumatra, he witnessed the technique by which pangolins, a species of scaly anteater, elude capture: they curl themselves into a tight ball and roll rapidly down a steep slope. In fact, the name "pangolin" is from a Malay word meaning "to roll." My careless error was placing L. Frank Baum's ork (a bird with a propeller tail) in the wrong Oz book. The ork is in *The Scarecrow of Oz*.

Chandler Davis added to my list of imaginary animals that roll by calling attention to such a creature in George MacDonald's fantasy *The Princess and Curdie*. Rufus P. Isaacs, commenting on the fact that no sphere can be tessellated with hexagons, included a proof of an equally surprising theorem he had worked out many years ago: If a sphere is tessellated with hexagons and pentagons, then there must be exactly 12 pentagons, no more and no fewer.

The first of last month's problems was to use eight specified color cubes to build a larger cube with each face a solid color and no two faces the same color. The top and bottom layers of one solution are shown in the illustration on page 26. The second solution is obtained by shifting the cubes in the top layer so that each cube moves counterclockwise to the adjacent position without changing its orientation. The prototype of the model is cube *Fc* in the matrix of 30 color cubes shown last month.

The second problem was to use the same eight cubes to build a larger cube that has four different colors on each face, with each color represented four times in all. Two solutions (I do not know if there are others) are easily obtained from the two solutions to the previous problem. Simply "triple cut" each cube by exchanging the left and right slabs, the front and back slabs and the top and bottom slabs. The three cuts can be made in any order.

The solutions to the 27-die problem shown in the illustration on page 25 in the August issue are incorrectly oriented. To correct the diagrams each die should be given a quarter turn up (to the top of the page), and then the bottom and top layers should be interchanged. In the same issue the name of Kenneth Jackman, who was the first to solve both problems, was spelled incorrectly.

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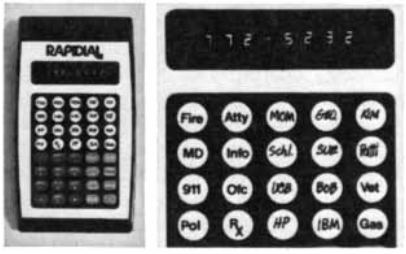

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BOOKS

The archaeology of China, and an artist's keen eye for the mammals of East Africa

by Philip Morrison

ANYANG, by Li Chi. University of Washington Press ($25). THE ARCHEOLOGY OF ANCIENT CHINA, by Kwang-Chih Chang. Yale University Press ($8.95). The winds of change began to blow across the yellow Chinese loess before the turn of the century. They blew up a storm, and now the East is red. These two volumes bear witness to the pervasiveness of that change; they bring the reader (Li's book by a sharp vignette centered on the single most important dig and Chang's by a wide-ranging and up-to-date summary) what is newly won of the ancient history and prehistory of the Middle Kingdom.

At the same time as the Enlightenment in Europe the scholars of China also began to become skeptical. The "studies of bronzes and stones" had an honorable pedigree; there is an erudite and circumstantial catalogue of 13 palace jades and 211 antique bronzes printed at about the time of the Norman Conquest. Should Engineer Yü the Great, who laid out the Nine Provinces and tamed the Yellow River, be taken as real on strength of traditional texts? Plenty of old texts themselves queried details. By the 1920's "Show your proof" became the slogan of Chinese historians. By now they have unearthed and deciphered much proof; China's continuity has been traced far past the golden myths of the Yellow Emperor and his queen, and more richly.

Near the big town of Anyang, not far north of the Yellow River in the great plains about halfway along the main road south from Peking to Hankow, the villagers were long used to digging up "dragon bones." These fragments of old bone were pharmaceutical raw material, sold to the drugstore trade for the equivalent of pennies, to be ground fine as "knife-points medicine" against cuts and wounds. The folklore asserts that the majority of the bones bore inscriptions. "The inscribed pieces at the time had no market value...; so it was the usual practice among the sellers to polish off those inscriptions, before the dragon bones were brought to the market." The polishers did not, however, succeed in removing all the inscriptions, and before 1900 a Peking scholar-statesman, Wang I-yung, began to collect the inscribed dragon bones.

Wang was a student of bronze inscriptions; he at once saw the relation between the bone characters and those of the old bronzes. By 1903 scholars had managed to publish fragments of 1,000 inscriptions from the incised tortoiseshells now identified as bearing the oldest specimens of Chinese characters. Silver instead of coppers began to change hands; potato diggers became bone hunters, and dealers and collectors grew active from Peking and Shanghai to Tokyo, Chicago and Edinburgh. Forgers also flourished, including one opium-smoking genius, more artist than businessman, who duplicated inscriptions "in exact detail" before one scholar's astonished eyes. (Many a museum still proudly displays such elegant frauds.) Conservative scholars rejected on the grounds of fraud all the new finds that threw the traditional history of the characters into disarray. Studies nonetheless continued in depth; the volumes on the fragments grew in insight, confirming some old king lists and upsetting some old guesses on language and form. It became clear that the oracle bones were in fact sacrificial inquiries of the ancient courts of the Shang dynasty, and that their source was what was known in the old texts as the Waste of Yin.

Between the two world wars field archaeology entered China. It was first brought there by such outsiders as Teilhard de Chardin and Franz Weidenreich, to name only two who made "close contact with Chinese minds." It was from the beginning brilliantly successful, establishing for China a prehistory that is still growing apace, from the find of the half-million-year-old Peking man through the Neolithic to Shang and Chou. By 1936, on that hot June day "when the season's work was to have closed," the crown was set on the dozen years of careful, large-scale prewar excavations near Anyang. The royal palaces and tombs had already been found under the flat wheat fields and had been meticulously explored; magnificent bronzes were few (although some were still to be found in situ) because over the centuries the pounded-earth tombs had been rifled for marketable treasure, most recently during the disorder of the years between the wars. The robbers may have got nine-tenths, but the scholars, led by Li Chi himself, took their lucky final tithe, richer in knowledge than all the unprovenanced hoards of the collectors worldwide.

The signal find of 1936 was a mass of closely packed tortoiseshells, three tons of clinging carapaces, 17,000 inscribed documents manifestly buried intentionally. Many of them still bear the original vermilion and black pigments, proof that brush writing preceded incision. We can read of ritual sacrifice and weather, of succession and kinship, of crops and capitals, of eclipses and holidays—all written to record the divinatory quest of meaning in the cracks left by the hot point in the magical shell.

The documents are not fully readable, but they reveal much. Indeed, they broadly bear out the hints in the ancient texts preserved from the old historians of two millenniums ago. The jigsaw puzzles of the tortoiseshell texts have been put together most patiently, using the natural structure of the plastron to assemble simple phrases into full statements. Li Chi and his Taiwan colleagues, parted for 30 years from their grand dig by a gulf deeper than the China Sea, have continued to study and reflect on their finds. An annotated dictionary of oracle-bone characters and a steady flow of inscriptions, volume after volume, attest to the devotion of these scholars. Li Chi includes much more in his overall survey of the Anyang finds than can be mentioned here: from bronze foundry methods to cranial dimensions, from hairpins to ritual music.

K. C. Chang is a Harvard anthropologist; his survey, brought up to date by a photographic and conversational inquiry across China in 1975, puts the Waste of Yin and its finds into the wide and maturing context of a vibrant archaeology currently at work and well displayed over all China. Carbon-14 dates are flowing out of the laboratories of Peking; this book carries the reader through the 1976 reports. The center of interest for Chang and for the busy fieldworkers in China alike is not those timeless Han burials and the splendid art finds so widely viewed on this side of the Pacific; indeed, his volume closes with the Chinese unification under Shih Huang-Ti in 221 B.C. Rather, it is the rise of a distinct Chinese culture through the peaceful Neolithic villagers to the imperial splendors and cruel sacrifices of the Bronze Age.

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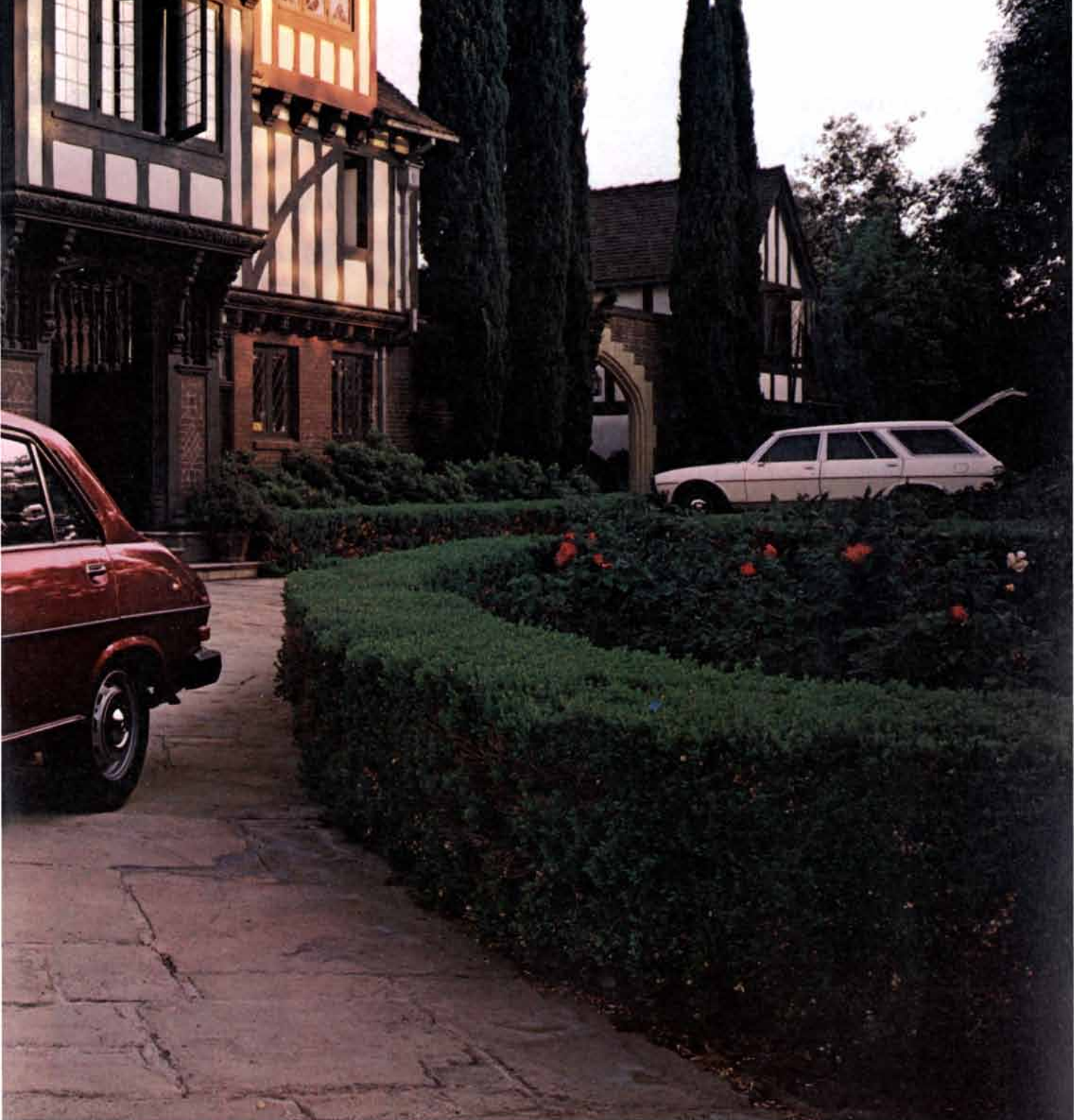

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area in the North China plains, where millet was domesticated and pottery was made in settled villages, was first disclosed to J. Gunnar Andersson, looking for fossils, when his collector brought back "several hundred axes, knives and other objects of stone." The farmers of one village alone, Yang-shao in Honan, made this discovery in their own fields in 1920. By now an entire village of the ancient culture, Pan-p'o-ts'un near Sian in Shensi, has been excavated and is preserved in part under a permanent roof as it looks in the last stages of excavation, a marvelous contribution to public education and a magnet for visitors to China.

Chang now adds strands of early farming from the lower Yangtze, where rice was grown, from the southeastern coast, where root crops were staples, and perhaps from rice areas still farther south. By the time of Ur of the Chaldees (but surely more and more independent of the Euphrates or the Nile) the farming villagers of all China began to show signs of local distinctions, of a more complex society and of war. One Hopei site of the period has a pit containing 10 skeletons, people of all ages, buried without pattern or order and covered with burned clay. Five more skeletons were found in an ancient well nearby, some of them decapitated. It was probably an intervillage raid, "something yet to be found in the peaceful Yang-shao village settlements."

Today the annals of historical Chi-

An inscribed Chinese tortoiseshell, from **Anyang,** *by Li Chi*

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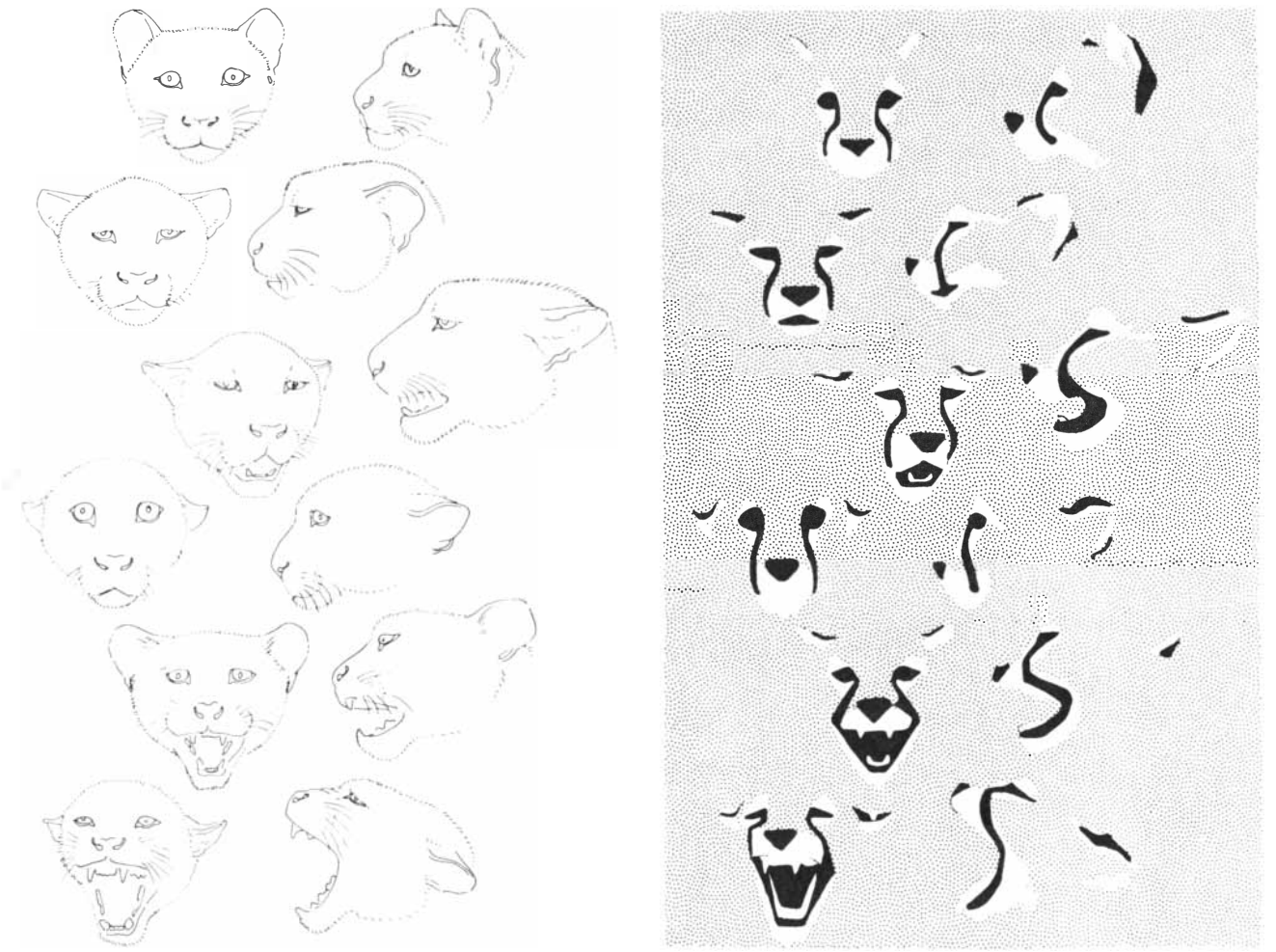
na are linked back through the Shang (about 1800 B.C.) to the Neolithic. The links are formed by the chariots and the seers, the kings and their haughty retainers, the varied and monumental flanged bronzes so cunningly made by the unique and complex ceramic piece-mold technique (as has been experimentally demonstrated by colleagues of Li Chi's) and fluent notations on the oracle bones. In Anyang the wood chariots (or rather their traces in the soil) were found in the 1930's surrounded by sacrifices of horses and charioteers in place. Yet their big wheels were absent, like the heads of some sacrificial victims. (Professor Chang provides a photograph that shows a chariot with big spoked and dished wheels, more recently uncovered at Anyang.) The horse-drawn two-wheeled wood chariot with its intricate bronze fittings and furnishings is "the only Shang innovation that may have originated in the Near East." The potters of the little villages had already used marks that increasingly seem to have provided the basis for the Shang written word.

Bronze was everywhere in the Shang, but its farmers plowed and delved with wood and stone; almost no bronze tools have been found after long search. Costly bronze was a royal monopoly, saved for war and ritual. A halberd with an iron blade has been found at a Shang site, and the experts argue about whether or not the iron is meteoritic. Then in about the sixth century B.C. metallurgy began to emerge as a productive tool-making industry for civil life. Chinese metalworkers could cast iron with precision early, millenniums before those in the West. With the feudal Chou, no longer a slave society, and its iron, irrigation, jade figures and tiled cities the centuries began to recognizably weave the almost seamless brocade of Chinese culture.

EAST AFRICAN MAMMALS: AN ATLAS OF EVOLUTION IN AFRICA, VOLUME 3, PART A (CARNIVORES), by Jonathan Kingdon. Academic Press ($74.25). A dozen beautifully rendered facial masks of cheetahs look out of the page, some in repose, some watchful, a couple angrily agape, grim teeth prominent. On the opposite page two smaller drawings each repeat the same 12 heads. But in one of the smaller drawings there are only outlines, sans the black spots and stripes that characterize the cat. In the other small drawing those strong black markings of the face appear alone, all the rest of the head suppressed. The visual pleasure of the presentation is immediate, and the analysis supports the argument of the text, namely that the black arabesques that surround and link the expressive features serve to emphasize the facial display, mainly for the benefit of other cheetahs (although "a spectacular snarl might also be advantageous against a competitor").

This volume (the fourth of a planned set of six) is well represented by the cheetah faces. Led by visual delight, sensitive to the animals he studies, this brilliant artist-naturalist employs the richness of individual animals not only to strengthen our understanding but also to gain that reward in itself: "the contemplation of physical beauty in mammals." In sketch page after page the ani-



Cheetah heads **(left)** *and corresponding facial markings* **(right),** *from* **East African Mammals,** *by Jonathan Kingdon*

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mals tumble over themselves, burrow, fawn, sleep, arch, scratch, intimidate. Along with these informal sharings of his own long years in the field he supplies large, elegant and meticulous formal renderings supplemented by many careful drawings of skeletons and of the subtle musculature, in the poses of life.

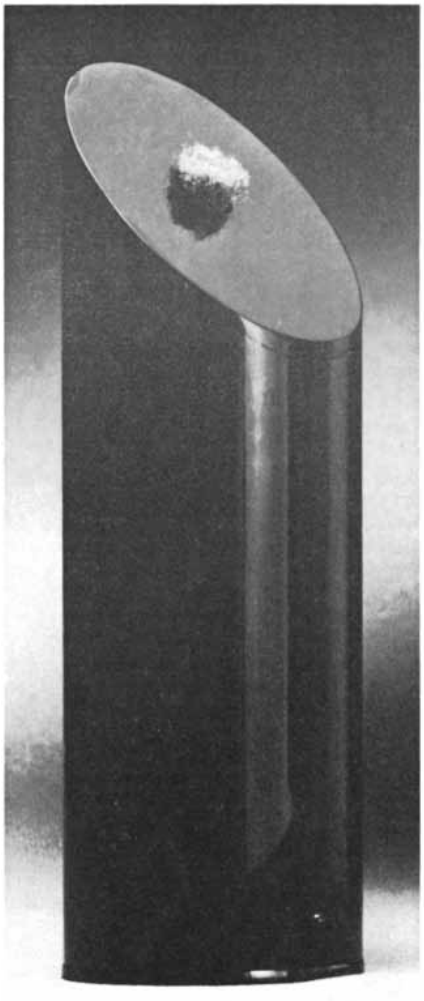
Forty carnivore species are described by families: the dogs, the cats, the civets, the hyenas, the mongooses and more. For each species there is an essay, usually based on Kingdon's own attentive study of the animals in the field, including a learned yet personal summary of the literature about the form. Range maps, size and even local names are always included.

The strong, plucky, intelligent honey badger—the ratel—earns a fascinating treatment, particularly of its fragile link to the honey-guide bird, "a relationship that probably needs to be learnt by both." Kingdon has followed the bird to a bee's nest more than once, but he has not yet seen the bird and the honey badger together, and he preserves a little skepticism sotto voce.

The cheetah has a long history of human intimacy; the swift cats were coursed by Ghenghis Khan, Akbar and Charlemagne. The spotted one (so the name means in an Indian tongue) has clearly caught the artist's eye. So has the bigger spotted cat; one color plate displays 10 aberrant leopard patterns. Indeed, no two leopards are the same in pattern. That rosette of black spots around an orange patch is a module replicated with extraordinary variety. It seems possible that the big cats all arose from a common ancestor, an early form of leopard, because all their coat patterns can be derived from the leopard rosette. (Lion cubs have leopardlike blotches.)

If the ur-leopard came, as appears likely, from the smaller forest cats, then the modern felines and our primate selves are fellow actors in the slow adaptation of forest fauna to life in the savannas, "one of the grand evolutionary dramas." We human beings were certainly social predators, like hyenas, lions and wild dogs, and some of the mongooses and otters. "The banded mongoose is one of the most highly social of mammals. To encounter one on its own can only be due to a mishap; its proper place is amongst a scatter of grunting gleaners in the leaf litter or in a skirmishing line returning to sleep together in a packed mass of bodies in the den."

Recent ethological field studies of wild dogs, the spotted hyena and the lion are made the basis of Kingdon's pieces on those animals. His brief essays cannot, of course, offer the detail of the monographs, but the openness of Kingdon's interest and the width of his experience give his text unexpected value.



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Although it has no moving parts, you can actually feel a wind produced from the fuzz. This wind is ionized oxygen which spreads to fill a 1500 cubic foot room or about 15 feet square.

EFFECTS FELT QUICKLY

You will feel the effects immediately. The Energaire will clean your room of odor-causing bacteria and stale, musty or smoky air. Energaire will keep you alert. With a fresh supply of ionized oxygen, you will have more energy, be less fatigued, and you will sleep better.

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His lion piece, for example, centers on the role of this largest of cats as a source of symbols for human beings. The lion's hairs win love, its whiskers overcome enemies, its claws promise luck, its heart confers courage—every part of the lion's body has magic even in cultures where the real lion is at some distance. Imperial symbols are more remote still from the living cat. Thunderous roar and proud mane, and the special "lion strut" toward subordinate animals, are certainly the sources of this ancient hold over the human mind, through their promise of dominance by martial force. The male lion's mane is a visual device, not a physiological or protective one. It makes him look bigger than he is, adds a majestic symmetry and grants instant recognition, an evolutionary trump card in a long suit of tricks from fluffing of fur to facial ruffs. Lion society, like our own, does offer "advantages to the male that can intimidate his conspecifics." The real continuity of lion society rests, however, with the maneless but powerful lionesses. The male lions mark, patrol, roar and sometimes fight to establish the pride territory. Actually both sexes roar, generating a series of eight or nine reverberating sounds, audible "up to eight kilometers away on a still night, followed by a declining series of grunts."

The entire set of these volumes of art and science is beginning to glow on the shelves of natural history.

THE CHANGING AMERICAN DIET, by Letitia Brewster and Michael F. Jacobson, Ph.D. Center for Science in the Public Interest, 1755 S Street Northwest, Washington, D.C. 20009 ($2.50). The "tireless USDA economists" who annually compile the statistics on food consumption, prices and expenditures are the source of the data in this small paperback brochure. Its authors have translated the volumes of statistics into digestible form: two dozen graphs plot the foods Americans consume, from alcohol to vegetables, reckoned per head for the years from 1910 through 1976. (A few series cover other epochs.) They add a dozen more curves and graphs, based not on foods but on the nutrients they contain, and intersperse among their graphs brief but often incisive analyses of the causes of change, done in entirely popular language. The result is full of interest, a source for argument and conjecture, for instructive and interesting conversations around the dinner table (where else?). A few calculations by any scientific reader will take him further into this or that corner of the meaty issues raised; the booklet is a handy and accessible source, reform-directed.

It is constancy rather than change that somehow stands out in these curves. En-

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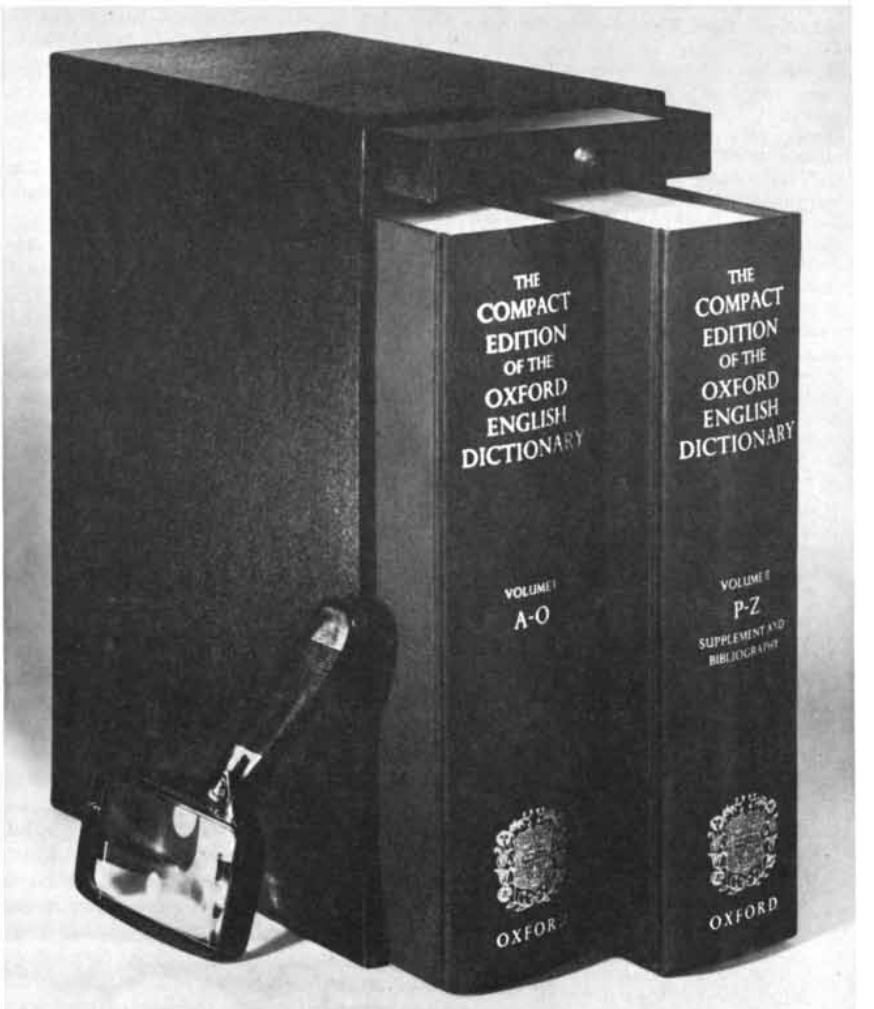

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ergy content and protein intake have never shown more than 10 percent changes (always per capita) since 1910, except for the years of the Great Depression, when protein consumption fell off about 12 percent. Of course, these are averages; the baby boom and the food-stamp program are only two of the many recent factors that somehow make up this stability. Two changes are clear and strong in the nutrient pattern: we take in more fat than ever before, by 27 percent, and we have reduced our intake of carbohydrate to compensate for that energy increase.

It is wheat flour we no longer eat as our grandparents did: total cereal use is down from 300 pounds per person per year in 1910 to about 130 in 1976. Corn meal and corn flour have fallen off sevenfold. Rice use is dead flat; pasta has doubled. Bread is plainly much less the staff of our life than it once was; we seek sweeter, fattier foods.

The sweeteners have risen steadily, although sucrose seems to have plateaued a generation ago, and the rise since 1950 has been in corn syrup. Three-fourths of that sweet stuff has been added to the prepared foods we buy, not only to what is frankly sweet, such as the soft drinks (a fourth of all the sucrose), but also to just about everything else, even buns, hot dogs, mustard and catsup. Corn syrup is almost exclusively encountered as an industrial sweetener; it was the high-fructose form developed in the 1960's that gave it its current popularity with the manufacturers.

Fats and oils are the other side of the story. They are diverse, and even the basic data are not as complete as one would like. It is pretty clear, however, that most of the increase in fats has come from the use of oils in our food—salad oils, mayonnaise—and the widespread popularity of deep-fried snacks of many kinds. Table spreads, solid cooking fats and dairy products have stayed more or less constant or have even fallen. A third of the fat increase can be assigned to the remarkable doubling of our beef intake; meat now offers us almost a third of our fat. Pork has fallen a little, and the use of lard and butter fat has dropped to a fourth or thereabouts.

Evaporated and condensed milk? It lost favor as refrigeration spread to most kitchens. Melons? They fall steadily, strangely enough, perhaps because they are hard to manage in the supermarket. Chocolate (nearly all of it as candy) was rare in 1910, but it has stayed about level since the 1930's. Coffee has slid steadily from its 1946 peak, although the cola drinks bring us another big dose of caffeine.

Alcohol is most interesting: our use of this ancient and dangerous drug is down from seven gallons per head per year (reckoned as absolute alcohol content) during the Mexican War to less than three gallons today. The temperance movement of the 1830's seems to have worked: the universal use of 20-proof hard cider went down by an order of magnitude well before the Civil War. Then beer began to replace cider and consumption slowly returned to about the same volume (but now with much less alcohol content) as the post-1848 wave of German immigration converged on Milwaukee and St. Louis. The use of distilled spirits is rising, but it remains below a third of the peak it reached in hard-drinking 1840.

Chicken? Peanuts? French fries and ice milk? They are all here.

MAJOR MEDICINAL PLANTS: BOTANY, CULTURE AND USES, by Julia F. Morton. Charles C Thomas, Publisher ($49.50). MEDICAL BOTANY: PLANTS AFFECTING MAN'S HEALTH, by Walter H. Lewis and Memory P. F. Elvin-Lewis. John Wiley & Sons ($27.50). The tradition of the herbal, bearing the therapeutic lore of herbs and simples, is still green. These two comprehensive volumes stand as examples, both published within the past year. They stand at two poles of approach. Morton offers a botanist's treatise, arranged by plant families, with exact descriptions plant by plant and much attention given to the husbandry or collection of the plant. The Lewises, on the other hand, arrange their book by expected effects, treating "injurious" plants, "remedial" plants and "psychoactive" plants (their quotation marks) in 19 chapters with medically oriented labels such as cancer, heart and circulation, panaceas, stimulants and depressants. Their subject is in fact botanical medicine. The quasi-magical appearance of the subject—the remarkable specific activity of many plant substances—survives to the present day, based, one infers, on the modularity of biochemistry.

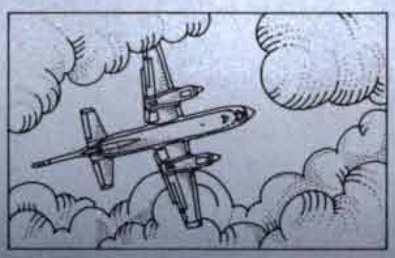
The molecular phrase spelled out by the alkaloid of Egyptian henbane in "all parts, including the roots," turns out to command the dilation of the pupil. Such an effect is certainly not directly adaptive for the plant. That the deadly nightshade was called belladonna, and is the close European relative of the wild Egyptian species, traces the origin of the widely used atropine, the racemized form of the plant substance L-hyoscyamine. Atropine, usually administered as the sulfate, is now obtained mainly from the wild henbane collected by the shepherds of Egypt for the export trade. That the European plant formed a chief ingredient of the flying ointment of the early Renaissance witches is broadly understandable: the two plants are of the same family, they share fat-soluble alkaloids, and the nervous-system effects are made plain by the quenching of the pupillary reflex.

MOTOROLA MAKES A TREASURE

Nigeria has more people than any other nation in Africa. Indeed, it's one of the ten largest nations on earth.

Yet, incredibly, vast stretches of its 357,000 square miles had yet to be adequately mapped.

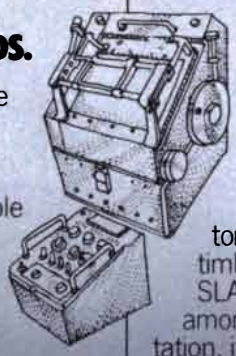
For years, the government of Nigeria tried to get the job done with conventional aerial photography.



But much of this part of the world swelters under an almost continuous cloud cover. And in northern Nigeria, near the Sahara, a dust cloud twelve thousand feet high obscures the earth for months at a time.

They turned the problem over to Motorola—and got the job done in only five months.

ELECTRONICS SEE THROUGH CLOUDS.



The equipment that made the difference was Motorola's Side-Looking Airborne Radar: SLAR.

It has three remarkable virtues.

It can see through the cloud cover, day or night.

It looks sideways, to allow simultaneous mapping from both sides of the aircraft. The images that result show the land in striking detail.

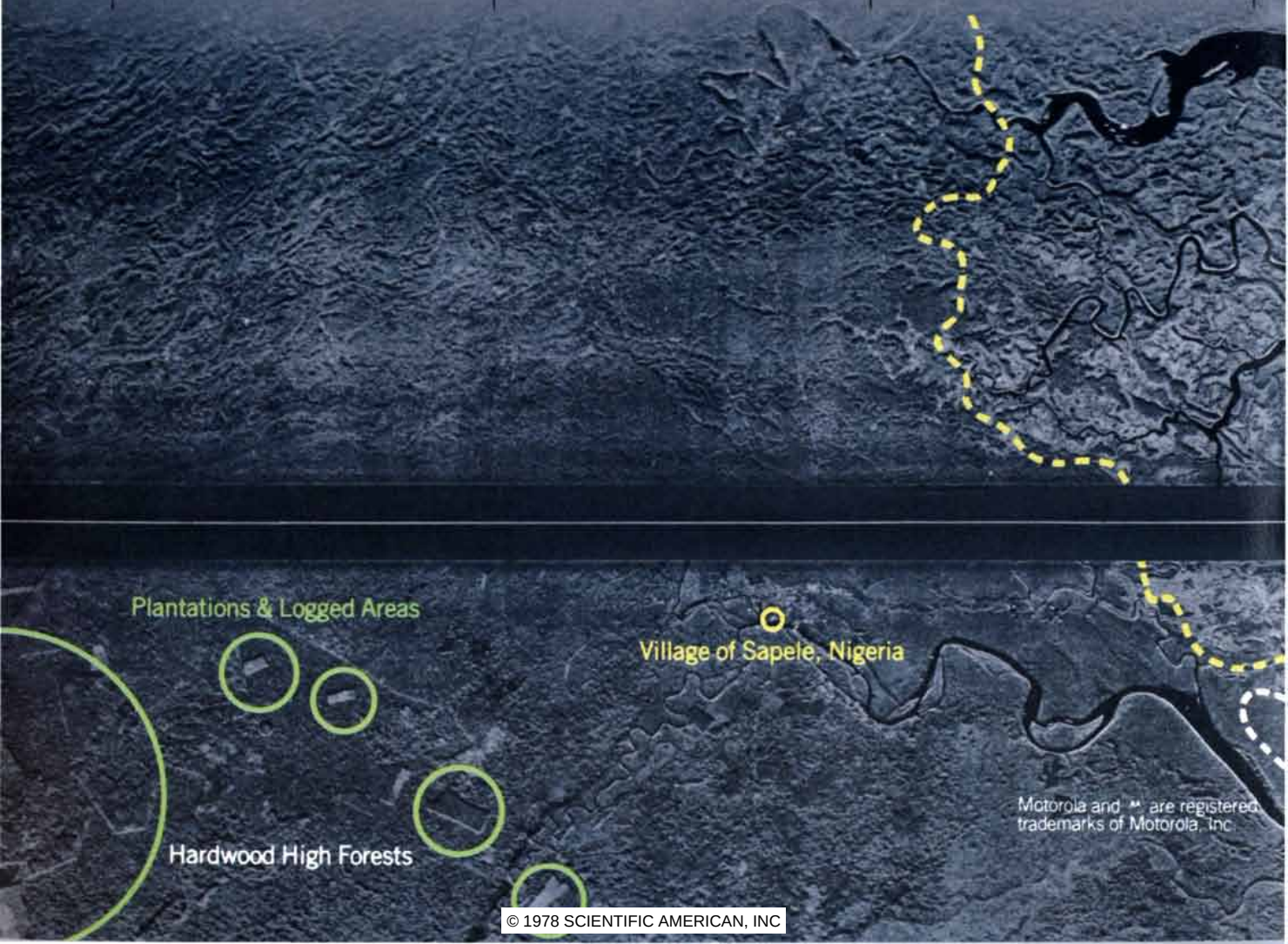
And SLAR displays its images instantly to the sensor engineer aboard the aircraft. Instead of having to wait for pictures to be developed, he knows immediately whether or not he has to make another pass over the same terrain.

ELECTRONIC EYES FIND TREASURES.

SLAR mapping gave Nigeria a new assessment of her natural treasures.

For instance, an inventory of her farmland and timber resources. Since SLAR can actually differentiate among several types of vegetation, it helped identify forests containing ebony, mahogany and rubber trees.

And it helped identify geological structures that could mean

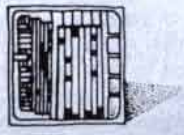


MAP OF NIGERIA.

the presence of unexploited oil, gas and mineral deposits.

THE ELECTRONIC MIRACLE: A MICROCOMPUTER.

Further developments have been made on this remarkable system. At the heart of Motorola's most advanced SLAR is a tiny electronic miracle: a Motorola microcomputer.



A microcomputer, drawn larger than life.

The microcomputer is one of the latest demonstrations of Motorola's fifty years of electronics expertise. And you'll find the technology that made it possible in many of the things we make today.

For Motorola is no longer just the company that put radios into cars nearly fifty years ago—although we now market hundreds of models of two-way radios.

Nor are we just the company that put popular-priced TV sets into American homes—in fact, we no longer make home TV sets here at all.

AN ARRAY OF ELECTRONIC ADVANCES.

Now, Motorola is not only one of the world's largest manufacturers dedicated exclusively to electronics, but also one of its foremost designers of custom and standard semiconductors. And Motorola microelectronics are working in a remarkable array of products.

For instance, a coronary observation unit that enables paramedics at the scene of an accident to transmit a victim's EKG directly to a nearby hospital.

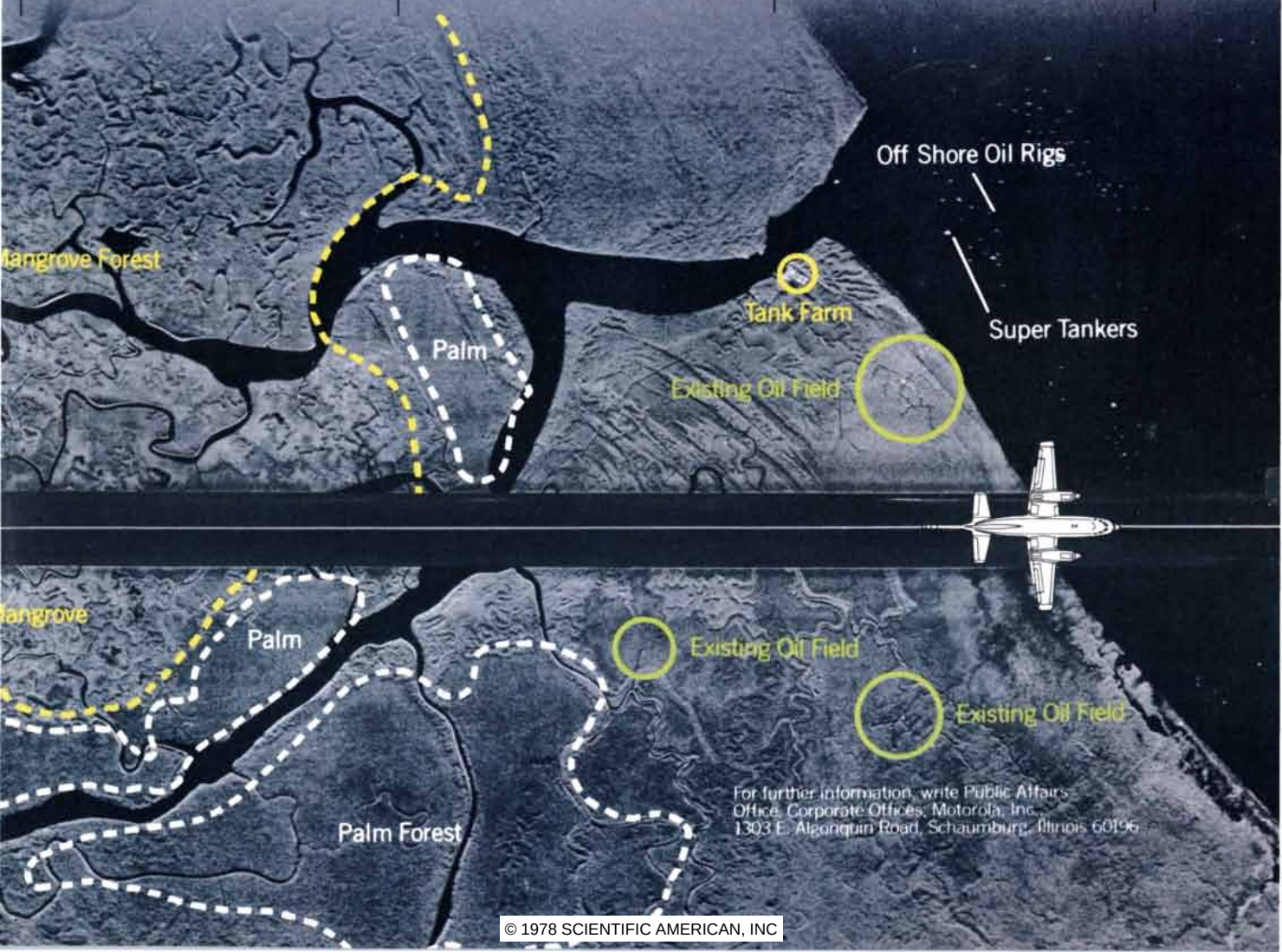
A Digital Voice Protection system that keeps criminals from tuning in on police radio communications.

Even lightweight pagers that help busy people keep in touch while they're on the go.

And, of course, a device that's helping a nation like Nigeria take a realistic inventory of hidden natural resources.

MOTOROLA

Making electronics history since 1928.



For further information, write Public Affairs Office, Corporate Offices, Motorola, Inc., 1303 E. Algonquin Road, Schaumburg, Illinois 60196

The Lewis book gives a structural formula for the nightshade drug, a number of pages on its history, with accounts (from a popular current work of fiction) of the subjective effects of the related *Datura* ointment and a couple of old prints of the preparation for the Sabbat. Such rather trendy, if wide-ranging, treatment is not found in Morton's book; she provides the reader instead with three or four pages, condensed texts and good photographs or drawings for each of the half-dozen species worldwide that are sources for this family of drugs. The botanist's book sticks much closer to the official dispensatory, although it does so with appropriate accounts of folk usage; the more medically oriented authors have gone further afield. Indeed, they even seem impressed by assertions that the Amazonian liana-bark infusion can intensify the "ability to telepathize" and "enhance extrasensory perception."

One surely touches here on origins of the magic seen in herbs. More abstract magical theories, say from the human form suggested by the forked roots of mandragora, a European relative of henbane, no longer have much support. Another basis for the herbal art is less arcane still: the uses of licorice, menthol, coca, poppy and ipecac, for example, are easily rationalized. All of them are important drugs today, with their administration often less therapeutic than sensory. The Lewises include alcohol among their drugs, although its crop sources are not regarded as being medicinal. Of course, chemists today elaborate the work of the plant enzymes. Perhaps the most important substances for which the plant supplies intermediate molecules are the steroids of cortisone and of the Pill, and heroin, the product of the acetylation of the poppy alkaloid morphine.

In a year the pharmacists of the U.S. dispense about a billion and a half prescriptions. A consistent 25 percent of these still contain one or more active constituents that have been extracted from the higher plants. (Add 15 percent for the microbial products and those derived from animals.) These books illuminate that large area: the one a readable, if concentrated and tabular, medical textbook, the other an encylopedic work of botanical reference. Both books have large bibliographies, indexes and other useful apparatus.

A MILLION GALAXIES: COMPUTER PHOTO-MAP OF THE GALAXIES BRIGHTER THAN 19TH MAGNITUDE VISIBLE FROM EARTH'S NORTHERN HEMISPHERE, edited by P. James E. Peebles and Steward Brand. The CoEvolution Quarterly, Box 428, Sausalito, Calif. 94965 ($4.50). On a square yard of glossy black this poster image, profound, enigmatic, beautiful, presents in a clotted

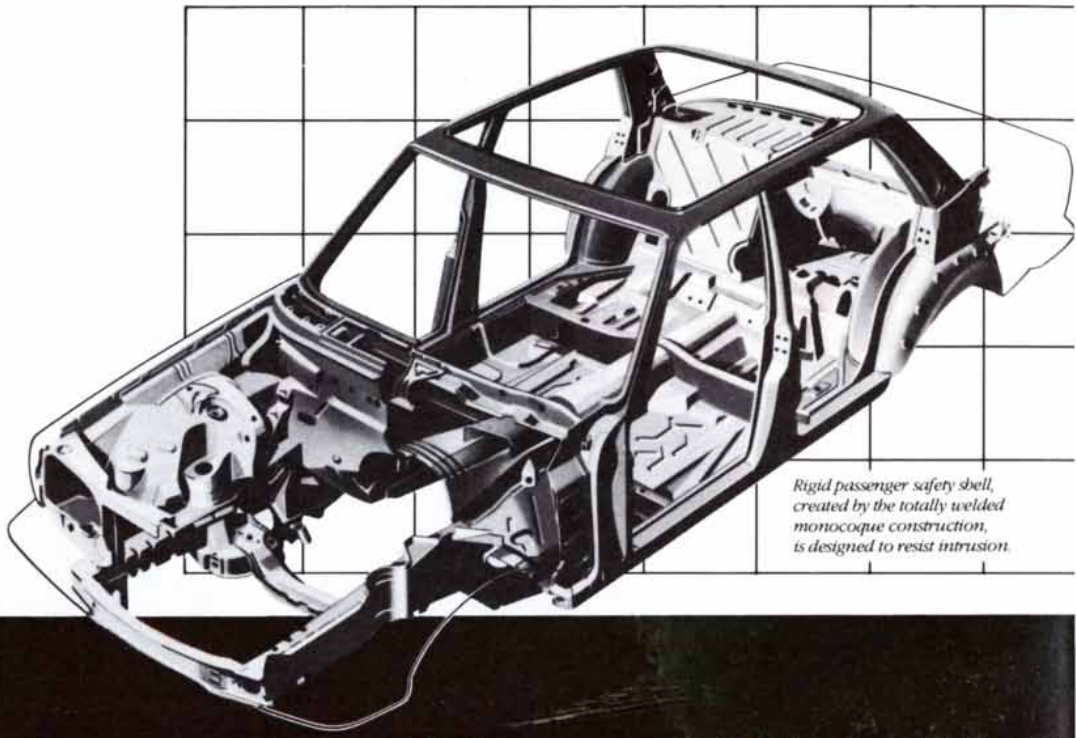
tangle of tiny gray squares one abstract but faithful view of the entire thing. It maps onto the plane about half of the great sphere of galaxies around us out to a billion light-years away. Not a photograph, it presents no galaxy form, no glowing globes or spindles; rather, in each of a million squares less than a millimeter on an edge the computer and its peripherals have recorded the presence of galaxies, coding the count on a scale of brightness values from black representing no galaxy up to white representing 10 or more galaxies.

It has been 20 years since Donald Shane and Carl Wirtanen began to use the Lick Schmidt camera on and off for a decade to record the whole of the sky they could reach from Mount Hamilton on some 1,300 overlapping big glass plates, each plate 17 inches square. They counted down to a fixed limit all galaxy images, most of them so small as to be visible only in a low-power microscope, entering on their data sheet for every big plate the number of images found in each of 1,296 subsquares. They published a contour map but in much less detail; it is just too slow to plot a million points by hand. Professor Peebles and his students took another look at the Lick counts with present-day computer power, and they prepared (after much thoughtful data massage to correct for plate variations, obscuration and the like) the rich map we see here. It was modestly presented in the pages of an archival journal (and in this magazine about a year ago) as a photograph small, grayish and retiring.

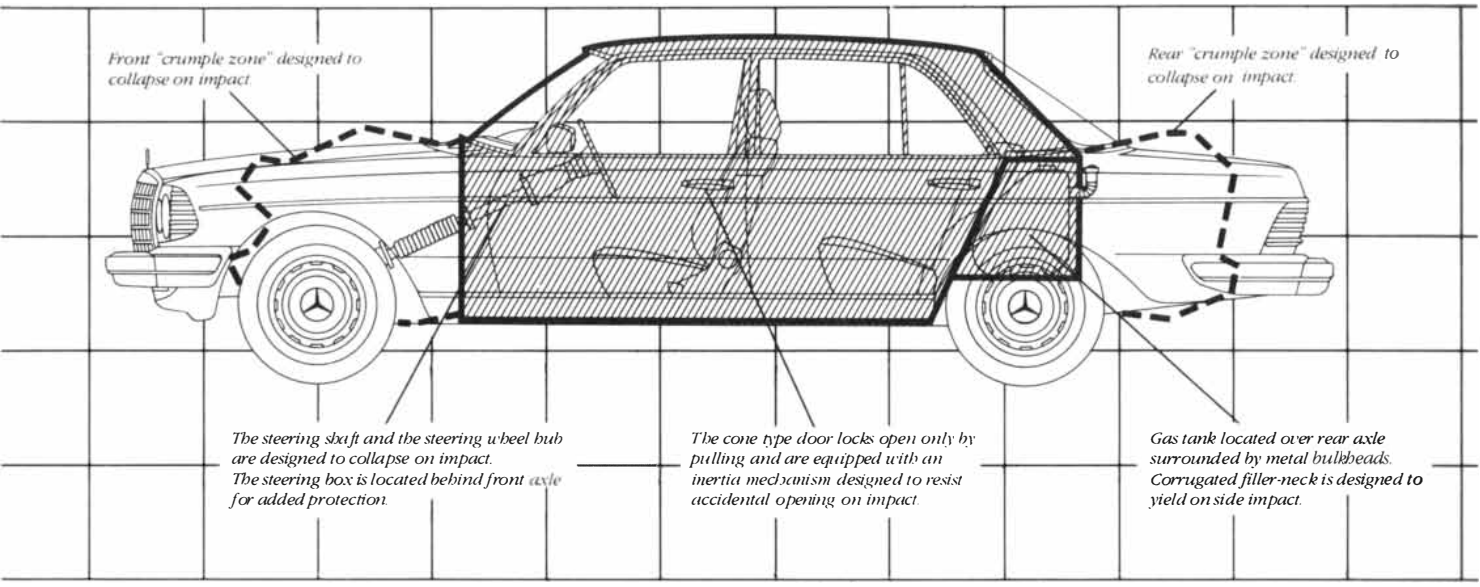
Now the map is offered grandly, not for the scientific record alone but in visual celebration of the world. No Tantric demon or benign celestial choir provides a more vivid symbol of the vastness of the universe in which we live. The clusters and filaments and voids that form the texture of this striking halftone speak volumes, even though, like the oracle herself, their speech is enigmatic. Clusters of galaxies are real enough at several levels, but how much of all that the scanning eye reads from this plot is mere happenstance and how much is dynamical inevitability remains to be established.

There is no wider map; if none of those squares marks the location of any fellow observers, ours is a lonely and immense desert. If others dwell somewhere in space, their unimaginable cities are well marked here. It is a philosophical pleasure to view and reflect on these million galaxies. (Of course, our earthborne telescopes can sample small fields for fainter images; maybe in all a billion galaxies and more lie within present optical reach, although they are mostly still unseen. From observatories in space we expect to sample many more than that.)

You may never need all 120 safety features in your Mercedes-Benz. But it's comforting to know they're there.



Rigid passenger safety shell, created by the totally welded monocoque construction, is designed to resist intrusion.



Of the 120 safety features built as standard equipment into every new Mercedes-Benz, those designed to meet U.S. safety standards represent less than half. Those designed to meet Mercedes-Benz safety standards represent the rest.

The washboard principle

For instance, the engineers wanted to keep the car's taillights visible in foul weather. Solution: taillight lenses ribbed like washboards. Wind tunnel tests showed that most dirt and slush tend to collect on the outer surfaces – leaving the recessed grooves cleaner, longer.

Because a side impact *might* activate a push button and this in turn might pop open a door, the engineers designed push buttons out of the door handles of a Mercedes-Benz. They will open only by pulling.

The engineers even found a way to make the mouldings that frame the windshield work in the cause of safety.

They are actually designed to deflect rainwater away from the side windows as you cruise along in the wet.

The windshield wipers, on the other hand, are aerodynamically designed to sweep across the windshield *with* the airflow and thus resist "lifting," even in high-speed turbulence.

Seeing is surviving

Mercedes-Benz takes a dim view of styling that obstructs driver visibility; you can't avoid what you can't see. Result: a Mercedes-Benz driver is surrounded by as much glass as possible – in the sedans, for example, by a sweep of 85 percent unobstructed visibility.

Notice that the fuel filler flap of a Mercedes-Benz is placed far ahead on the right rear fender, almost above the wheel. No random act: it leads to a fuel tank mounted so deep inboard that it sits above the rear axle – as far from exposure to a rear-end impact as possible.

Strong law, stronger locks

You may be heartened to know that the door locks on a Mercedes-Benz conform not just to the letter of the law but to its spirit. They far *exceed* the strength demanded by U.S. federal law.

No law dictates it, but "crumple zones" at the front and rear of a Mercedes-Benz body are designed to yield accordion-like, to absorb kinetic energy in a heavy impact and lessen its effect on the passenger compartment.

The steering box in a Mercedes-Benz sits *behind* the front axle, for extra protection. The steering column is designed to yield and collapse on impact. The steering wheel itself is deformable and its flat, padded center is meant to help dissipate the effect of a heavy impact over a large area.

Every new Mercedes-Benz is safety-padded in the usual places, plus some unusual ones: e.g., the underside of the instrument panel and the knob of the shift lever. The engineers didn't want the glove-box door to pop open on an impact and become a menace to the front seat passenger – so the lock on the glove-box door isn't a push button but a *sliding* mechanism.

The search goes on

These are some examples of the 120 safety features built into every new Mercedes-Benz. Imposing as that number may seem, it is by no means a final one. Safety research and development at Mercedes-Benz have not stopped – and it is intended that they never will.

Electric sunroof (shown) available at added cost.

Established 1845 SCIENTIFIC AMERICAN October 1978 Volume 239 Number 4

A New Strategy for Military Spending

An analysis of U.S. military forces finds that they so far exceed actual military needs as to be unsafe for the nation and the world. A program for prudently decreasing these forces is here described

by Philip Morrison and Paul F. Walker

In the 33 years since the end of World War II, Americans have periodically perceived the Russians as standing 10 feet tall. This is such a period. It is said, for example, that the day is close at hand when a small fraction of the U.S.S.R.'s growing number of land-based nuclear warheads will be able to hit more than 75 percent of the 1,000 silos containing Minuteman missiles, the most reliable and accurate U.S. nuclear deterrent. It is proposed that the U.S., at a cost of $20 billion or more, therefore press ahead with the development of the mobile Missile X, 200 of which would be shuttled at random among 4,000 silos spread over an area as large as Connecticut. It is urged that the U.S. not accept a new treaty based on a second round of Strategic Arms Limitation Talks (SALT II) that would interfere with Missile X or with the development of cruise missiles, the highly accurate jet-powered weapons carriers that can be launched from land, sea or air.

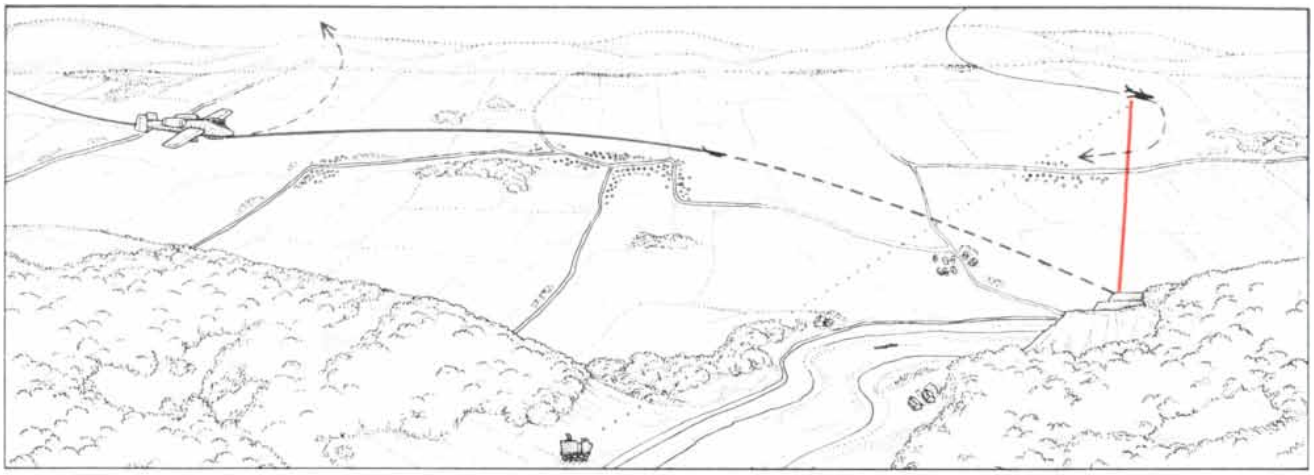
It is also urged that in order to counter the 20,000 tanks of the Warsaw Pact forces in Europe the U.S. deploy enhanced-radiation weapons ("the neutron bomb") for tactical purposes. With or without neutron bombs, the U.S. has asked its partners in the North Atlantic Treaty Organization (NATO) to increase their defense spending by at least 3 percent per year, in constant dollars, into the 1980's. In spite of a presidential veto, pressure continues for a fifth nuclear-powered aircraft carrier at a cost of more than $2 billion. (The U.S. already has 13 blue-water aircraft carriers; the U.S.S.R. has no comparable vessels.) At this writing the Department of Defense budget before Congress for the fiscal year 1979 is $126 billion in total authorizations, about 40 percent of net Federal spending.

There is no evidence that the Carter Administration, in drawing up the first defense budget for which it is entirely responsible, has followed the method of zero-base budgeting, which President Carter so strongly recommended when he was a candidate for the office. In this method each agency of the Government would have to review and justify every one of its programs from scratch, regardless of the previous level of spending or of how many people are entrenched in the performance of particular duties. The method has been widely adopted in business as a means of controlling costs, which in all organizations tend to rise inexorably. Because we believe with President Carter that zero-base budgeting has substantial merit we have followed its precepts in trying to answer the question: How much does the U.S. really need to spend to maintain its national security? The answer summarized in this article is given at full length in a book soon to be published, *The Price of Defense: A New Strategy for Military Spending*. The book has been prepared by the informal Boston Study Group, of which we are members. (The names of the other members are given in "The Authors," page 20.)

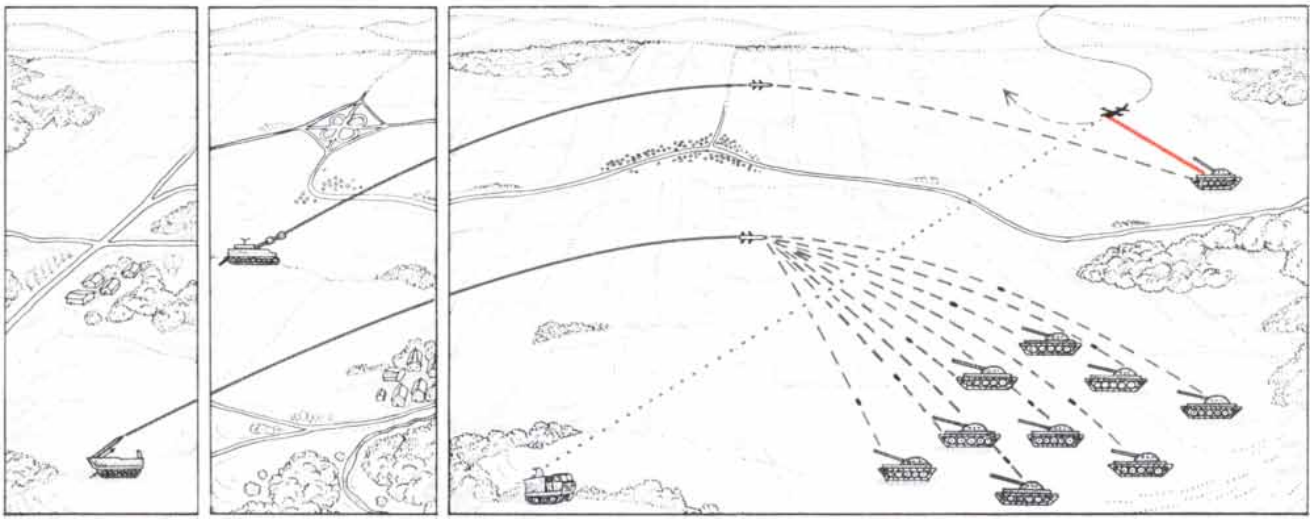
Since the end of World War II the U.S. has put more than $2 trillion into its military establishment, including the cost of the wars in Korea and Vietnam. With this expenditure the U.S. has become by any reasonable measure the world's foremost military power. The U.S. "triad" of 1,054 land-based missiles, 656 submarine-based missiles and 380-plus long-range bombers could theoretically deliver more than 6,500 megatons of nuclear explosive on more than 11,000 targets. Over a four-year period following the signing of the SALT I agreement in May, 1972, the U.S. increased the number of nuclear warheads in its constant inventory of land- and submarine-based missiles at a rate of more than 100 per month, three times the rate achieved by the U.S.S.R. in the same period. The total strategic-warhead count now stands at 9,000 for the U.S. to 4,000 for the U.S.S.R. Overall the U.S. has more than 30,000 nuclear weapons, of which 22,000 are designed for tactical purposes.

Not only does the U.S. have many more nuclear weapons than the U.S.S.R. but also its weapons are more advanced. Indeed, the U.S. leads the world technically in nearly every significant aspect of military hardware, non-nuclear as well as nuclear. This proficiency contributes to the power of the traditional elements of the U.S. Army, Navy and Air Force, but it is not the sole source of their strength. What makes U.S. general-purpose forces—apart from strategic forces—uniquely powerful is the combination of technical advantage with size and structure. The general-purpose forces are capable of bringing non-nuclear power to bear in any part of the world. In this respect the U.S. stands alone as the world's only truly global power.

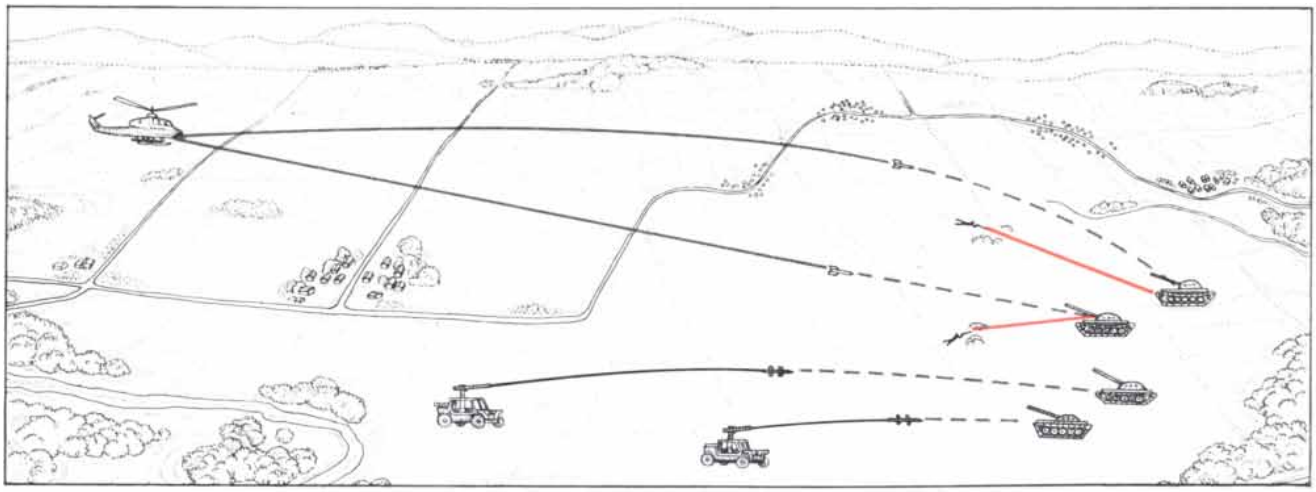
In the view of most Americans the vast U.S. military establishment is a benign force with only one goal: to preserve the freedom of the U.S. and of its long-standing allies whatever the cost.



NEW BATTLEFIELD TECHNOLOGY increasingly favors the defense over the offense, largely because of precision-guided munitions, or "smart weapons." The three scenes on this page depict the use of smart weapons in hypothetical engagements. Here a laser "designator" beam (*color*) is directed against an enemy bunker by a Firebee remotely piloted vehicle (RPV). The pilot of the RPV, who is hidden from enemy view, controls the vehicle by radio (*dotted line*). An A-10 attack aircraft (*left*), several miles away and flying low for concealment, launches a Maverick missile in the general direction of the target. The missile homes on the laser spot held on the target.



TWO SURFACE-LAUNCHED MISSILE SYSTEMS, both smart weapons, are depicted in action against tanks. At top center a Copperhead projectile launched from a 155-millimeter howitzer homes on a target, which can be as much as 12 miles away, that has been designated by a laser beam from an RPV. In middle center a Lance missile, with a range of 160 kilometers, releases six to nine terminally guided submissiles (TGSM's) that respond to infrared emission of vehicles. RPV may have helped to spot column of advancing tanks.



SMART WEAPONS OF SHORTER RANGE are fired from helicopters and jeeplike vehicles. The Cobra helicopter launches laser-seeking Hellfire missiles, with a range of up to five kilometers, that home on targets designated by lasers aimed by infantrymen. Other infantrymen in light vehicles fire tube-launched, wire-guided, optically tracked Tow missiles, which have a range of three kilometers.

Proponents of larger defense expenditures—the advocates of Missile X, enhanced-radiation weapons, the B-1 bomber, a new arsenal of cruise missiles and an additional nuclear aircraft carrier—have often observed that if their "present danger" scenario is in error, all that is lost is a few billions (or perhaps tens of billions) of dollars. They have further observed that if the advocates of restraint in the growth of military forces are in error, the U.S. may one day face irresistible pressure to make some repugnant accommodation. Given that choice, the arms budget continues to grow.

It is our thesis that the simplistic pursuit of military growth has after three decades passed the bounds of reason, even setting aside the externalities of inflation and fiscal soundness. In a world whose surface area does not grow at all, military forces whose physical power grows steadily are in the long run profoundly unsafe. Step by step, in the name of "realism," the U.S. has moved from a dangerous situation into one even more dangerous. Every step upward in potential damage and in speed of response has added genuine risk, the risk of unreasonable or mistaken leadership, of an error in judgment. Such is the clear history of warfare. The spring has been wound tighter and tighter each decade. The greatest real cost is not the wasted billions but the never ending escalation of technique and the growing complexities of the tautened balance. The risk is that the overwound spring will break, and the nations with it.

It is much to be wished that a winding down could be achieved by mutual agreement. Diplomacy, however, lags in seeking solutions by formal agreement; those on both sides who either do not trust the other side or have something to gain by military growth will find some imbalance in every formula for negotiation. For example, a recent report funded by the Defense Nuclear Agency asserts that the U.S. is behind in the majority of 41 "measures of Soviet-American strategic military power," regardless of whether these indexes are militarily relevant or not.

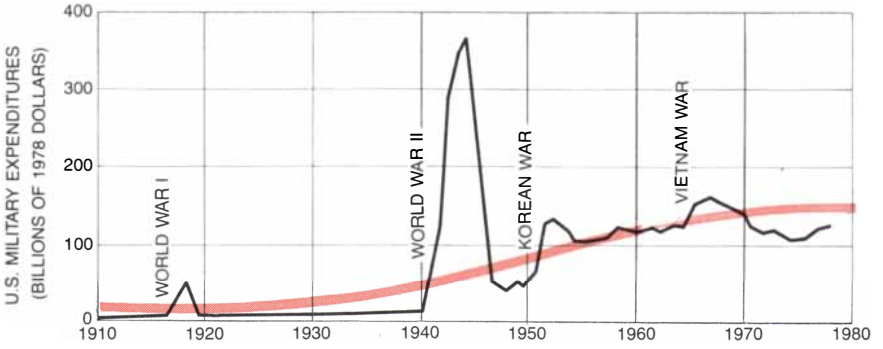
We believe the time has come for a new arms-control approach, one that can be adopted unilaterally on its merits. Our proposal is that the U.S. buy as much force as it needs but not more, that it prepare prudently for military contingencies but not overprepare and that it recognize it is too late for the rule of simple slogans such as "Peace through strength" or "Always assume the worst." The policy we propose is not based on any one axiom of military preparedness. It is based on an issue-by-issue and weapon-by-weapon examination of the world of warfare today and in the near future. We have reached the conclusion that a very different structure of military forces would better meet the ends the country seeks. Our goal has been to describe this structure.

We do not think any taint of isolationism should be, or can be, imputed to our effort. The new force structure we shall describe would defend directly and indirectly, as it does at present, all U.S. territory and the territory of our chief allies, that is, the NATO powers and Japan, against any plausible dangers of the next decade. The new forces we shall describe are safer forces because they would not generate in others, who may misread U.S. purposes, as great a perceived need for enlarging their forces.

The prudential military structure we propose would reduce the U.S. defense budget by about 40 percent, or some $50 billion a year. At the very least, even if the U.S. initiative we advocate fails to spark a constructive response abroad, we shall have removed from this country the onus of contributing to the forward momentum of military growth. If a reversal of such growth can be achieved, one can hope for a reduction in the fraction of world income spent on arms from the 5 to 10 percent of recent decades to the 3 percent that was typical between the world wars, or even down to the 1 percent prevailing before World War I. Such a reduction in arms expenditures would transform the world in innumerable ways; it would free an enormous volume of material and human resources for more constructive ends. Most important in our view, it would reduce the probability of a war among the industrialized nations that could be their last.

Military forces need to be judged in relative terms. They usually imply the existence of at least one major adversary; his force level goes far in determining the scale of one's own forces. To be sure, there are absolute criteria of geography and history as well. The long frontier the U.S. shares with Canada, for example, bears no comparison with the one the U.S.S.R. shares with China. Perceived threats, real or otherwise, act as the catalysts for military structures. A look at some facts of military life worldwide will demonstrate the point.

Today the four most populous nations muster the largest land forces: China, the U.S.S.R., India and the U.S. Yet immediately behind the U.S. in the size of their land forces come the Socialist Republic of Vietnam, South Korea, North Korea and Pakistan, with armies ranging from 600,000 to 400,000. The next four largest armies, ranging from 375,000 to 300,000, are those of Turkey, the Federal Republic of Germany, France and Taiwan. The U.S., with an army of 790,000, would not plan to match the Indian army of close to a million, much less the Chinese army of more than three million. Similarly, although American concern with Russian forces is persistent and intense, the relative strengths of the two countries cannot be evaluated by a count of guns, tanks, aircraft, naval vessels and missiles. Rather one must try to estimate the strength of the forces one might actually face at the time when and in the place where the contest might be joined if deterrence were to fail.



U.S. MILITARY EXPENDITURES show a rising trend punctuated by the peaks of four wars. The figures are plotted in constant dollars to allow for inflation. The central concern is the plateau on which the U.S. now stands, which is unprecedented in history. In effect military costs have scarcely declined from the Korean-war peak of 1952. The defense budget for the 1978 fiscal year ending September 30 was $116.8 billion in "total obligational authority." The Carter Administration's proposed budget for fiscal year 1979 is $126 billion. Military spending can of course be portrayed as declining since the height of the Vietnam war as a percent of other indexes, such as gross national product or total public outlays. The greater cause for concern is the steady upward ratcheting of military costs over the longer term of the past half century.

Secretary of Defense Harold Brown emphasized this point in a talk to the Commonwealth Club of San Francisco in June. The goal, he said, was effective defense without the "ideological baggage" of simplistic quantitative comparisons interpreted in spurious political terms. "We don't necessarily care," he said, "whether the Soviets have more tanks than we do.... We do care whether, in the event of Soviet attack, we are able to throw it back.... That, rather than simply outdistancing the Soviets in numbers of tanks or any other single

item, is what you should demand of the U.S. and allied defense establishments."

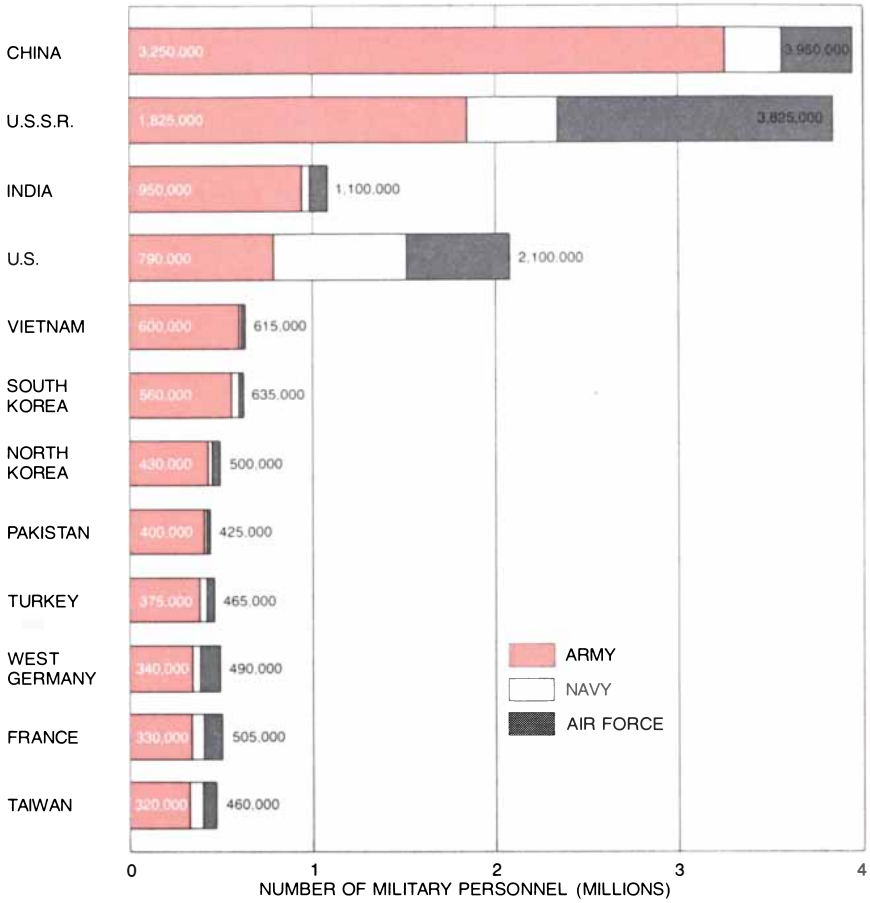
"We could," Brown continued, "go out and simply try to duplicate Soviet capabilities, but it would not make sense to do so.... Our interests are different. We do not need four million men, 45,000 tanks or 10,000 surface-to-air missile launchers. We need whatever it takes to protect our interests. Basically we want to forestall or deter conflicts that could jeopardize those interests."

In seeking to assess accurately the "Soviet threat," Brown pointed out: "It is no secret that a quarter of the Soviet non-nuclear capability is on the Chinese border; that many aspects of the Soviet logistic capability remain fragile; that current Soviet operating doctrines require larger forces than we could use for the same purposes, and that we have stronger, more reliable allies than the Soviets."

The large differences between the structures of American and Russian military forces become clear when the two are compared function by function. Such a comparison was made two years ago by Congressman Les Aspin of Wisconsin and his staff and was subsequently verified and improved by the Defense Intelligence Agency. As is shown in the illustration on the next page, the contrasts are substantial. The U.S.S.R. has a long border with an estranged great power that ties down at least 600,000 men. Another 700,000 Russian uniformed personnel are employed in support functions for which the U.S. prefers to use civilians. The U.S.S.R. has 500,000 military personnel engaged in border patrol, coastal protection and internal security, five times the number employed by the U.S. The U.S.S.R. has about 550,000 people in a large special organization, the Air Defense Forces (PVO-Strany), devoted to protection against the long-range bombers of the U.S. Strategic Air Command.

This Russian organization mans as a defense against high-altitude bombers more than 12,000 surface-to-air missile launchers, some 2,600 interceptor aircraft and 6,000 radar installations. In a missile age the U.S. requires no equivalent defense against the far smaller Russian bomber force. The U.S. Air Defense Command (with Canadian help) flies a tenth as many interceptors, and U.S. surface-to-air launchers for continental defense have dwindled to a few active Nike batteries in Alaska and Florida and a number of newer Hawk batteries also in Florida. The entire air-defense force amounts to about 1 percent of its Russian counterpart.

Even in the case of strategic offensive forces the U.S. requires only about a fifth the personnel employed by the U.S.S.R. to operate and maintain the land, sea and air armadas that embody each nation's nuclear deterrent. When the above assignments are subtracted from a total U.S.S.R. military establishment of 4,850,000, only about 2,100,000 Russian soldiers and airmen are available for a possible confrontation in Europe. It is a remarkable fact that out of its significantly smaller military force of 2,200,000 the U.S. has 1,900,000 available for such a confrontation. The lesson is a general one: what matters is not input but output. Little is gained by head counts that ignore functional commitments.



WORLD'S 12 LARGEST LAND ARMIES are plotted in descending order of strength, according to plausible recent estimates. Although the U.S. stands fourth in the size of its army, it has the largest navy and ranks third in total military manpower. Because of different counting procedures the totals given here for the U.S. and the U.S.S.R. differ somewhat from the totals given in the functional breakdown of forces presented in the illustration on the next page. In that breakdown the total for the U.S.S.R. is raised to 4,850,000 by including 700,000 paramilitary personnel assigned to civilian jobs and another 300,000 or so assigned to internal security.

The irrational momentum of the arms race is seen most vividly in the 25-year history of the intercontinental ballistic missile (ICBM), which began with fragile liquid-fuel rockets sitting above-ground and progressed to solid-fuel missiles in hardened (and then rehardened) concrete silos and finally to missiles ferried through the ocean deeps on endless voyages to nowhere. In this fateful contest each of the superpowers tried to maximize its particular technological abilities and advantages. The U.S.S.R. concentrated on throw weight and nuclear megatonnage; the U.S. emphasized accuracy and multiplicity of warheads. Each side tried to match its adversary and then, if possible, to take two steps for the other's one. The feedback loop was positive and dangerous.

At this point it may be useful to put before the reader some up-to-date information about the nature of a nuclear attack. Let us imagine a single strike by one missile with 14 reentry vehicles, or warheads, on one U.S. city, Boston. If each warhead carries 40 kilotons of nuclear explosive, about three times the power of the Hiroshima bomb, the overlapping circles of the 14 warheads would kill or seriously injure about 40 percent of the three million people living in the metropolitan area. Bombs falling in the harbor would send huge waves of radioactive water pouring over the city center. The prevailing wind from the northwest would carry a radioactive fallout plume over all southeastern Massachusetts and much of Cape Cod, causing as many as 100,000 delayed deaths.

It is not difficult to extrapolate this picture to hypothetical full-scale strikes aimed at many cities in either the U.S.S.R. or the U.S. A decade ago Sec-

retary of Defense Robert S. McNamara put into the record an estimate of the destruction that would be caused by attacks on Russian cities by ballistic missiles launched from U.S. submarines. An attack by five submarines, each submarine carrying 16 missiles, each missile with 10 40-kiloton warheads (800 warheads in all), would kill 37 million people and destroy 59 percent of Russian industry. An attack by 20 submarines with 3,200 warheads would kill 74 million people and destroy 76 percent of Russian industry.

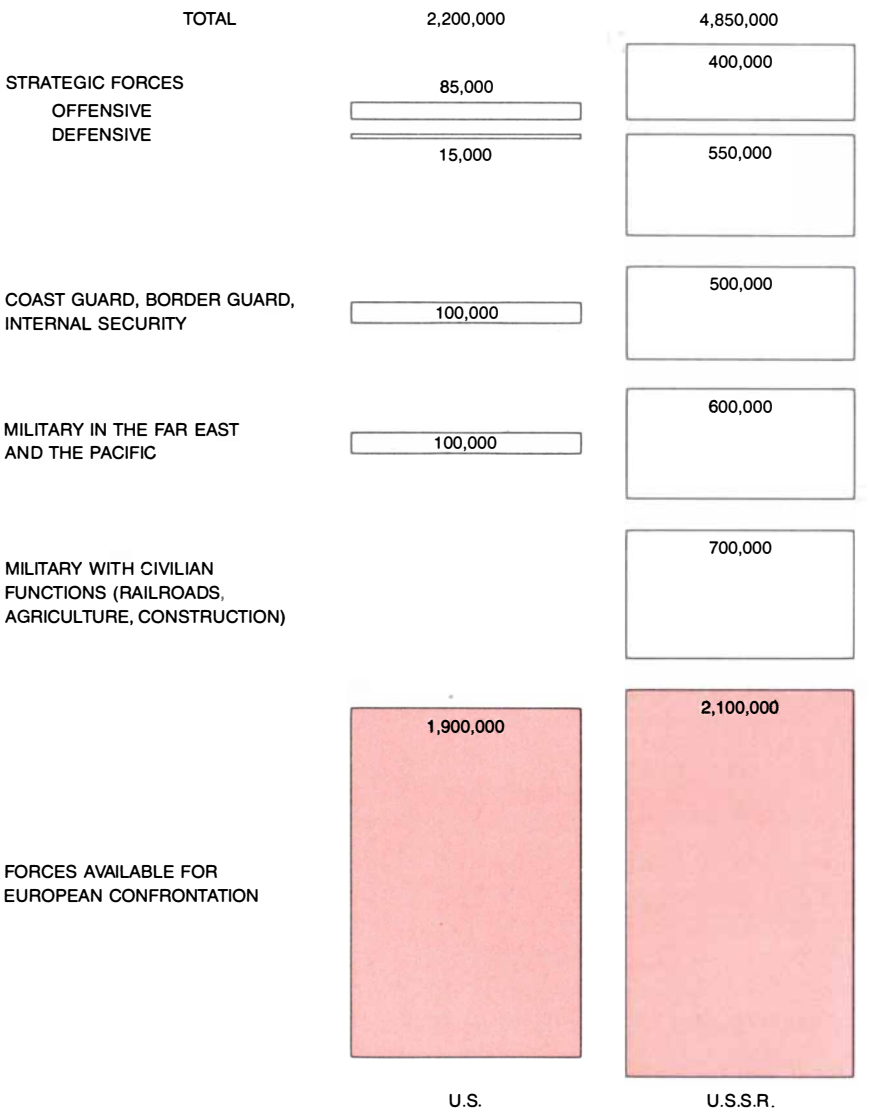
Although McNamara offered no estimate of the death and destruction that would result from a comparable U.S.S.R. attack on U.S. cities, we have made simplified estimates of our own, partly to verify with U.S. demographic data, more available to us, the extraordinary numbers given by McNamara for an attack on the U.S.S.R. A single Russian submarine, if it carried 160 40-kiloton warheads similar to those on U.S. Polaris and Poseidon submarines, would probably kill or seriously injure some 18 million Americans living directly within the target areas and perhaps another two million caught in the track of the fallout plumes. An attack by nine submarines with 1,200 warheads could well kill or gravely injure 70 to 90 million people, counting delayed deaths from radioactive fallout. The destruction of industry would be massive but essentially irrelevant to the human holocaust.

How is it possible that for a generation the leaders of the U.S. have rationalized the creation of such catastrophic forces? The answer is clearly that no sane leader expects that such weapons will ever be used. His intention is to let them remain unused, as they have been so far, but nonetheless to exploit them in other ways: as a symbol, as a bargaining counter, as a prize of domestic and Pentagon politics and ultimately as a latent threat of massive retaliation against an adversary's military adventures.

From the earliest days of the ICBM's it has been recognized that a couple of hundred missiles would suffice as a second-strike deterrent, to be launched if an adversary should strike first without warning. That number can be found today in the latest reports of the Department of Defense. The U.S., however, maintains at least 9,000—45 times 200—strategic missile warheads, and its leaders are reluctant to reduce that number. They adhere to the concept of the triad of land-based, submarine-based and airborne strategic nuclear weapons, maintaining that it provides a prudent diversity and hence a hedge against some unforeseeable breakthrough in antimissile technology. In addition but with less conviction, they argue that the triad also provides for "flexible options" in the selection of targets, including "conventional forces, lines of communication, war-supporting industry and targets of increasing hardness: from aircraft runways and nuclear storage sites to command bunkers and ICBM silos." In short, the mission of U.S. strategic forces goes far beyond simple deterrence, even making wide allowances for all kinds of system failure.

The argument that the present triad is necessary to carry out this broad mission fails quantitatively. The safe undersea missiles have ample capability for reaching hundreds of subsidiary targets. Can the Department of Defense seriously maintain that the destruction of so many targets represents a "flexible option" short of an all-out nuclear war?

The Air Force is hard pressed to perpetuate its two legs of the triad: land-based missiles and long-range bombers. All the existing ICBM silos have long since been mapped to within a few meters or less by orbital-satellite cameras and will soon be vulnerable to newly accurate Russian warheads. The present ICBM's will be viable only if they are launched on the mere warning of a nuclear strike. Bomber aircraft, the third leg of the triad, are not much better. Although they have the virtue of being recallable, they would need hours to reach the standoff distances at which their cruise missiles could be launched. In a missile age they are less than relevant. The Administration has shown no enthusiasm for a new bomber, the B-1, to replace the aging fleet of B-52's, hence the Air Force's request for a new land-based system of Missile X's shuttling around many empty silos or shelters. Such a system would temporarily confound targeting, but it would also



MILITARY MANPOWER OF U.S. AND U.S.S.R., two countries quite different in geography and history, cannot be adequately compared by a simple head count. The functional comparison presented here is drawn from studies by Congressional and Department of Defense agencies. The U.S. has no border with an estranged power, a much smaller requirement for air defense, a tradition of employing civilians in jobs for which the U.S.S.R. employs "civilians in uniform" and a strategic force second to none with a fifth the personnel needed by the U.S.S.R.

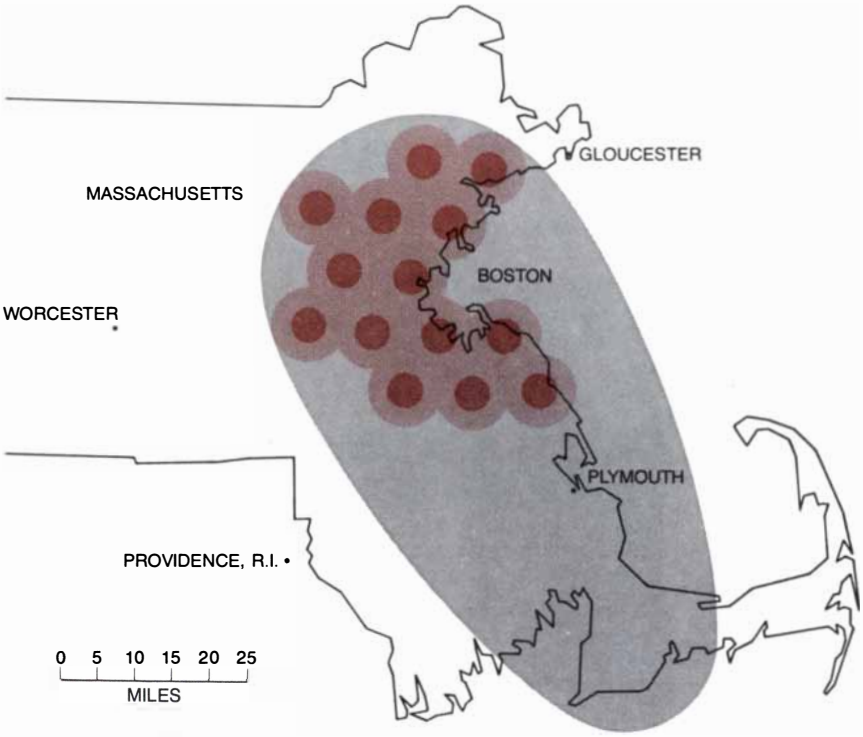
make the verification of arms agreements all but impossible.

In our view the triad is more force than is safe. It would be far safer to reduce year by year the present bomber force and the land-based silos until few bombers and silos remain. As a hedge against the possibility (which no one currently takes seriously) that the submarines could be knocked out one could keep 100 of the 1,054 silos, their missiles ready to be launched on warning if and only if the submarines were mysteriously overcome. One would build no new missiles, no new bombers and no new missile-carrying submarines while the present Poseidon fleet remained serviceable. One would give up the concept of the flexible option (even though the Poseidon fleet would continue to provide many options in targeting) as being unsafe for the country.

Making the civilian population of each nation the hostage of the other, cruel as it is, is the safest course for the time being, so strange has the nature of arms become. A stable balance is the safest stance today, and it could be achieved even better by a slow reduction in the nuclear loading of the submarine force, since the Poseidon force of 31 submarines we propose should be kept carries 496 missiles with upward of 5,000 warheads. A tempered reduction in that force is what we should be discussing, not Missile X, cruise missiles and a new submarine fleet of Tridents.

The U.S.S.R. improves and expands its strategic missile forces too. Two-thirds of those forces, however, are land-based. Russian missile submarines are still not nearly as good as American ones, and Russian long-range bombers are few. Although the U.S.S.R. has about 850 seaborne missiles (as against our present 656), they are distributed among some 80 submarines, of which only 55 are nuclear-powered. Because of the long distances these submarines must travel to reach their stations, a lack of regular double crews and a slow repair cycle only eight or 10 first-line boats are on station at any one time, many fewer than U.S. hunter-killer submarines are capable of shadowing. In contrast the U.S. tries to keep its 41 Polaris and Poseidon submarines on a tight schedule: normally two months at sea submerged and a third month spent in base for refitting, with two complete crews taking alternate tours of duty. In practice repairs that take more than a month reduce the number of boats on station from the planned 60 to 65 percent to a little more than 50 percent, which is still an enviable record of skill and devotion.

On land the U.S.S.R. was allowed more ICBM's than the U.S. by the terms of the SALT I agreement. The two countries agreed that the U.S.S.R. could deploy a total of 2,498 land-based and un-

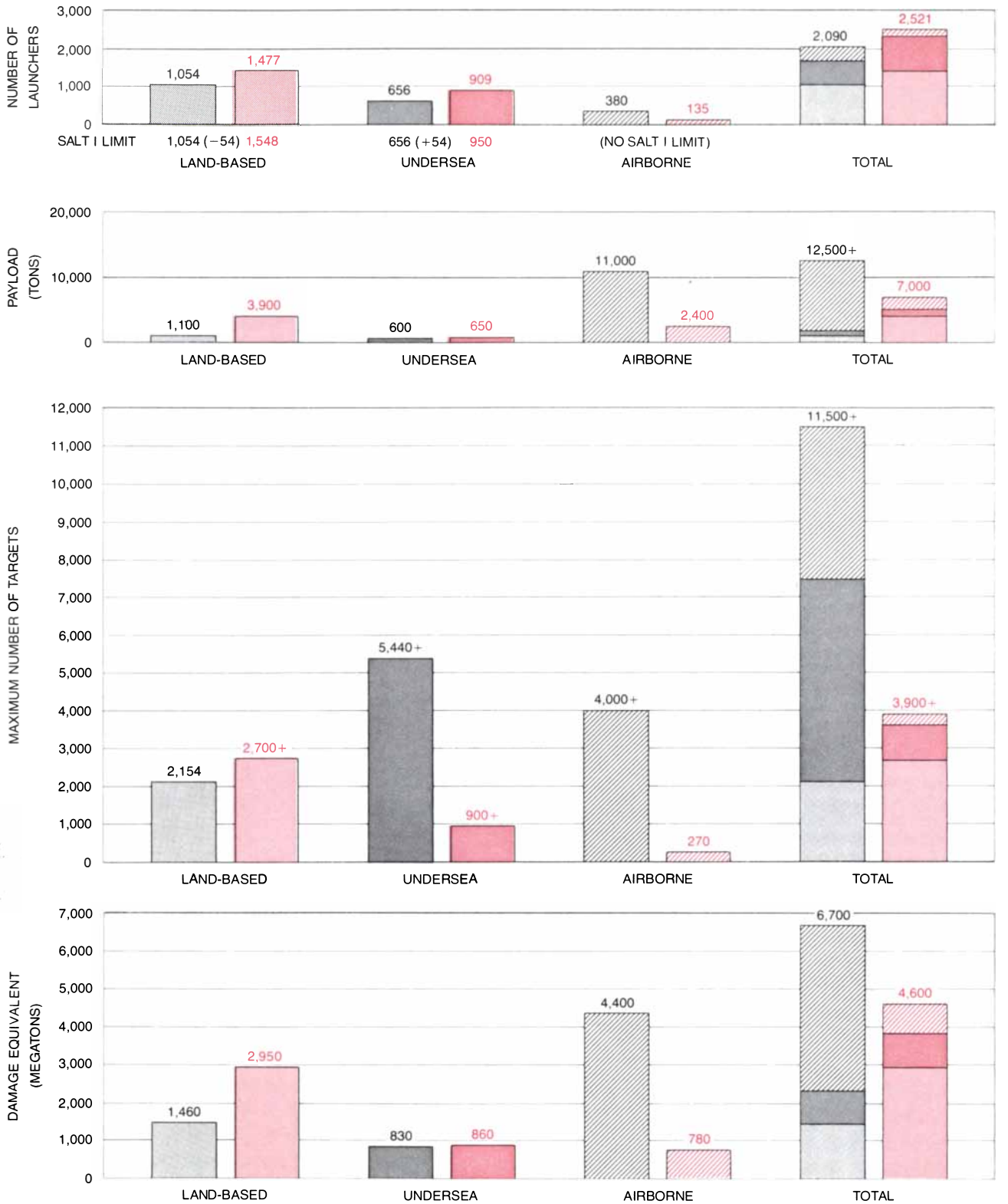


HYPOTHETICAL NUCLEAR STRIKE on a U.S. city (Boston) by a single missile with 14 warheads would kill or seriously injure about 1.2 million of the some three million people living in the metropolitan region. The damage circles are conservatively sized for warheads of 40 kilotons each, roughly three times the size of the bomb that destroyed Hiroshima. Within the inner circles, 3.6 kilometers in radius, the probability of death is 50 percent. In the region between the inner and the outer circles, 7.6 kilometers in radius, the probability of death is greater than 20 percent. The radioactive plume, driven southeast by prevailing winds, could cause 100,000 delayed deaths. Explosions in harbor would create huge waves of radioactive water.

HYPOTHETICAL ATTACK ON RUSSIAN CITIES BY U.S. MISSILE SUBMARINES			
SIZE OF ATTACK (NUMBER OF SUBMARINES)	5	10	20
NUMBER OF 40-KILOTON WARHEADS	800	1,600	3,200
DAMAGE EQUIVALENT (MEGATONS)	100	200	400
DESTRUCTION OF INDUSTRY (PERCENT)	59	[70]	76
NUMBER OF DEATHS (MILLIONS)	37	[56]	74

HYPOTHETICAL ATTACK ON U.S. CITIES BY MISSILES LIKE THOSE ON U.S. SUBMARINES			
SIZE OF ATTACK (NUMBER OF SUBMARINES)	1	4	9
NUMBER OF 40-KILOTON WARHEADS	160	600	1,200
DAMAGE EQUIVALENT (MEGATONS)	20	75	150
NUMBER OF DEATHS, TARGET AREAS ONLY (MILLIONS)	16	48	60
TOTAL DEATHS, INCLUDING THOSE IN FALLOUT PLUMES (MILLIONS)	18	55–60	70–90

HYPOTHETICAL ATTACKS BY MISSILE SUBMARINES could lay waste to either the U.S. or the U.S.S.R. The upper table indicates what is to be expected from nuclear strikes of various intensities on the U.S.S.R. The estimate of the destruction of industry and the number of deaths from attacks by five submarines and by 20 submarines was put into the official record a decade ago by Secretary of Defense Robert S. McNamara. The numbers in brackets for a 10-submarine attack are interpolations. The lower table contains the authors' estimates of the consequences of attacks on U.S. cities by a smaller number of Russian submarines, assuming that they are equipped (which they are not yet) with missiles and warheads comparable to those carried by U.S. boats. The authors undertook the estimate partly as an exercise to see if Secretary McNamara's projections would be confirmed if U.S. demographic data that were not available to him at the time were used as a basis for the calculations. The authors' table includes estimates of the number of delayed deaths that would be caused by radioactive plumes.



U.S. AND U.S.S.R. NUCLEAR STRATEGIC FORCES are divided into land-based, undersea-based and airborne components. Each nation thus follows a "triad" policy, but each has its own modes of warhead delivery. U.S. forces are in black, U.S.S.R. forces in color. The Strategic Arms Limitation Treaty (SALT I), signed in May, 1972, set a limit on the total number of land-based and undersea-based launchers each side could deploy: 1,710 for the U.S. and 2,498 for the U.S.S.R. Each side was allowed more submarine launchers than it has so far put to sea (*top set of bars*), a total of 710 for the U.S. and 950 for the U.S.S.R., but if the maximum number of undersea missiles were to be deployed, the number of land-based missiles would have to be adjusted accordingly. Actually the U.S.S.R. still appears to be about 110 launchers short of its allowed total. The inequality in numbers of launchers recognized in SALT I points to the military irrelevance of missile parity in an era of mutual assured destruction. The U.S. fleet of 380 long-range bombers is much larger and more capable than the U.S.S.R. fleet of 135, an imbalance left untouched by SALT I. The agreement placed only indirect limits on the payloads of ballistic launchers (*second set of bars*) and no limit on the number of warheads that could be lofted by each launcher, translated here into "Maximum number of targets" (*third set of bars*). The U.S. superiority in warheads, including both airborne bombs and missiles, is now roughly three to one. In megatons of explosive that can be delivered the U.S. lead is smaller but still impressive (*bars at bottom*).

dersea-based launchers and the U.S. a total of 1,710. The agreement also set a limit on submarine launchers of 950 for the U.S.S.R. (in a maximum of 62 nuclear-powered boats) and 710 for the U.S. (in a maximum of 44 boats). Since the U.S. actually has 656 submarine launchers, it is permitted 1,054 land-based launchers—exactly the number it has had since 1967. According to the most recent estimates, the U.S.S.R. has now put to sea 909 submarine-launched missiles and has deployed 1,477 ICBM's in silos on land, for a total of 2,386 launchers, which is roughly 110 short of the 2,498 allowed by SALT I.

The apparent advantage that SALT I gave the U.S.S.R. in strategic launchers was more than nullified by the U.S. fleet of some 380 long-range bombers, which the treaty left untouched. Perhaps more significant, the U.S. had already begun adding extra warheads—multiple independently targetable reentry vehicles (MIRV's)—to its inventory of 1,710 launchers as early as 1970 and accelerated their introduction after SALT I was signed. The U.S.S.R. made no significant progress in adding MIRV's to its land-based launchers until the Vladivostok accord of November, 1974, and it may not yet have added extra warheads to any of its submarine-launched missiles [*see illustration at right*]. The Vladivostok accord, which was never ratified, would have allowed each side 2,400 strategic launchers of all types, including long-range bombers. It would also have set a limit of 1,320 on missiles with MIRV's.

The Russian force of 1,477 land-based launchers embraces seven different types of missiles, of which more than 1,200 are obsolescent liquid-fuel models. The U.S.S.R.'s introduction of new solid-fuel systems, widely viewed with alarm, can be at least partly understood as a continuing effort to catch up with U.S. technology, to reach allowed SALT I levels and to help offset the marked asymmetry in the U.S.-U.S.S.R. submarine missile forces actually on station and ready to fire.

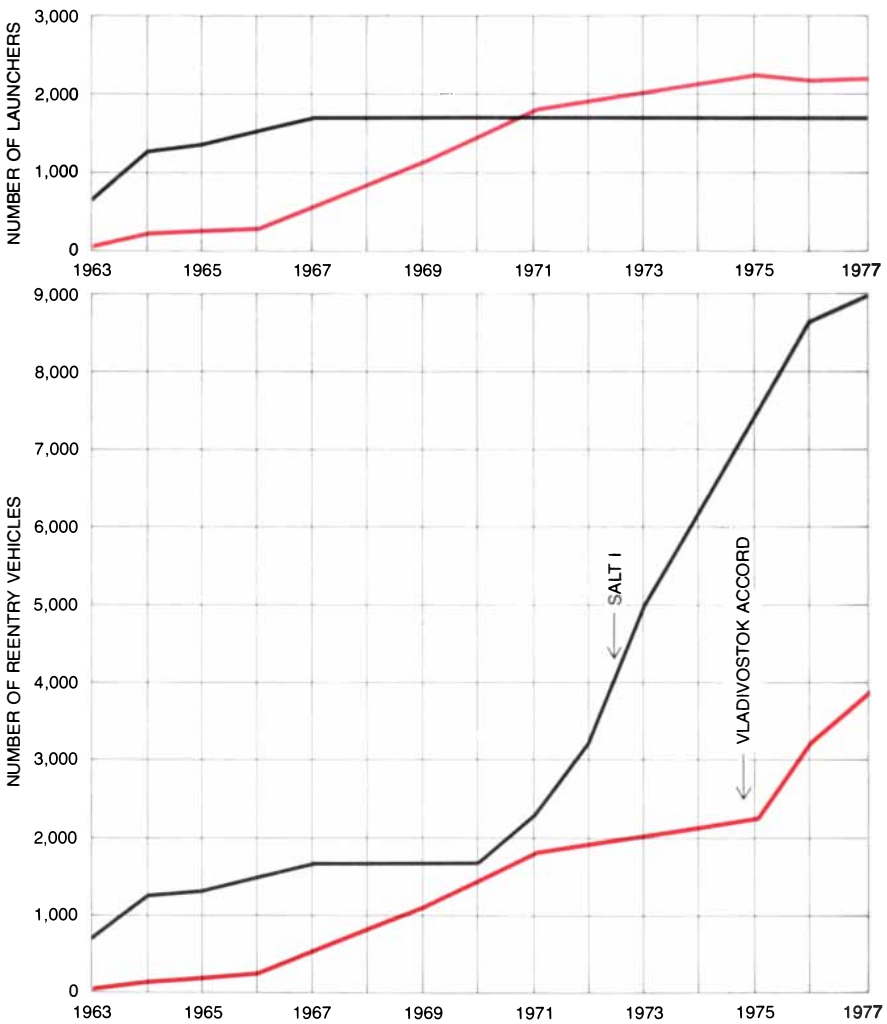
What governs nuclear war is the terrible ascendancy of the offense. In conventional ground warfare too the offensive team of the tank and airplane has had an advantage over the defense. It is this ascendancy, demonstrated vividly in World War II, that has aroused concern about the possibility of an attack on NATO Europe by the U.S.S.R. and its allies. Here NATO has organized a deterrent defense, with the result that most informed observers are satisfied there is a crude balance of forces along the frontiers of Europe. Our proposals for a new U.S. force structure recognize the unlikely contingency that U.S. general-purpose forces could be tested in Europe. There U.S. forces could be reduced only marginally, and the reduction would be symbolic. It should be evident to an adversary that offensive intentions do not begin by reductions in force, even small ones.

If one looks 10 years ahead, however, a new evolutionary development appears on the horizon, a development already perceived by the more farsighted in the Department of Defense. It is a profound change of weapons technology for the land battlefield (and also for the sea one) that for the first time since World War II promises a dramatic advantage to the defense.

The promise lies in the continuing advance in military technology based on microelectronics, symbolized by the ubiquitous pocket calculator. Colloquially it is called smart weaponry; the Pentagon prefers "precision-guided munitions," or PGM's. The adroit combination of small and sensitive sensors of many kinds, with effective computation and guidance made possible by miniaturized circuits, together with new explosives and new materials, offers the individual soldier or small teams of soldiers the odds-on probability of being able to destroy with one shot a formidable target: a tank, an airplane or even a ship.

As recently as the war in Vietnam thousands of aerial bombs, tens of thousands of artillery shells and millions of small-arms rounds were expended with a low probability of kill. It is reckoned that in World War II it took 300,000 small-arms rounds to kill a single soldier. Those were cheap projectiles, very numerous but very simple; the smart weapons fire fewer and more expensive but far more effective projectiles, and their hit rate has risen by orders of magnitude.

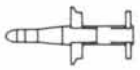
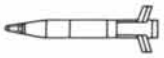
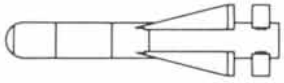
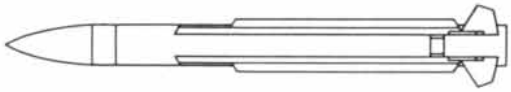
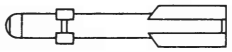
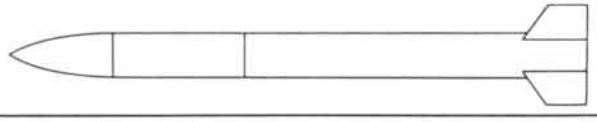
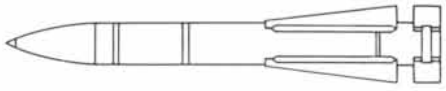
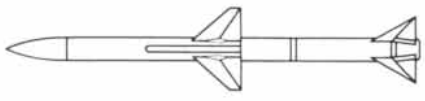
Perhaps the first widely publicized hit under operational conditions was made by a not particularly smart weapon in the Middle East war of 1967. A Rus-



MOMENTUM OF MISSILE RACE was originally expressed in the number of land-based and submarine-based strategic missiles possessed by the U.S. (*black curves*) and the U.S.S.R. (*color*). The number of strategic-missile launchers (*top curves*) was frozen by the SALT I agreement of May, 1972. The agreement placed no prohibition, however, on the equipping of individual missiles with multiple independently targetable reentry vehicles (MIRV's), or warheads, a practice initiated by the U.S. two years earlier (*bottom*). Between 1970 and the end of 1976 the U.S. added new warheads to its inventory of 1,710 missiles at the rate of nearly 100 a month, a rate the U.S.S.R. approached only after the Vladivostok accord of November, 1974.

sian-developed Styx surface-to-surface cruise missile, 20 feet long, first deployed in 1959 and able to fly 20 nautical miles at subsonic-jet speed, was used by the Egyptians to sink an Israeli destroyer, the *Elath*. The cost-effectiveness of the weapon startled military planners. One missile that cost $20,000 launched from a small patrol boat out of gun range had destroyed a ship worth $150 million. The Styx was then used by Indian ships against Pakistani vessels in December, 1971. Israel has now developed and deployed its own improved smart antiship missile, the Gabriel.

In May, 1972, there was another vivid demonstration of smart weapons. For six years American F-4 fighter-bomb-

	MISSILES	LENGTH (METERS)	WEIGHT (KILOGRAMS)	RANGE (KILOMETERS)
SURFACE-TO-SURFACE				
TOW, ANTITANK		1.2	18	3.8
TGSM, ANTITANK		.9	16	160
COPPERHEAD, ANTITANK		1.3	63.5	20
AIR-TO-SURFACE				
MAVERICK, ANTIARMOR		2.5	209	CLASSIFIED
STANDARD, ANTIRADAR		4.5	635	25
HELLFIRE, ANTIARMOR		1.8	43	5
SURFACE-TO-AIR				
REDEYE, ANTIAIRCRAFT		1.2	13	3
STINGER, ANTIAIRCRAFT		1.5	13.4	CLASSIFIED
PATRIOT SAM-D, ANTIAIRCRAFT		5.2	CLASSIFIED	CLASSIFIED
AIR-TO-AIR				
PHOENIX, ANTIAIRCRAFT		4	380	165
SIDEWINDER, ANTIAIRCRAFT		2.8	85	1–18
SPARROW, ANTIAIRCRAFT		3.7	200	25

TACTICAL SMART MISSILES will give U.S. and allied ground forces powerful means for stopping an attack by armored forces. Smart weapons exploit microelectronic technology in combination with small and sensitive sensors based on television, infrared or laser techniques. They also carry warheads in the configuration of the "shaped charge," which can punch through a depth of steel five times

ers had tried without success to knock out the well-defended Than Hoa bridge in North Vietnam with conventional bombs; it also took them many sorties to destroy the first Paul Doumer bridge near Hanoi in 1967. Eighteen aircraft had been lost in those raids. Yet in 1972 the two bridges were knocked out with smart weapons in single strikes without the loss of a plane. The rather simple Hobo homing glide bomb and the Maverick missile, viewing its target with a television camera and guided by laser beam, cost in the range of $10,000 to $20,000.

CHARACTERISTICS
TUBE-LAUNCHED, WIRE-GUIDED, OPTICALLY TRACKED. CREW OF FOUR. ADAPTED TO WHEELED AND TRACKED VEHICLES AND HELICOPTERS.
UNPOWERED TARGET-SEEKING MINIMISSILE; PACKED IN CLUSTERS OF SIX TO NINE PER PROJECTILE, SUCH AS LANCE STORABLE-LIQUID-FUEL MISSILE.
CANNON-LAUNCHED PROJECTILE; HOMES ON TARGET DESIGNATED BY LASER. DESIGNED FOR USE IN 155 MM. HOWITZER: 1979 DELIVERY.
AIR-LAUNCHED, HIGH-PENETRATION EXPLOSIVE. INITIAL 1968 MODELS SELF-GUIDED BY TELEVISION. NEW MODELS GUIDED BY INFRARED SENSOR OR LASER DESIGNATION.
HOMES ON RADAR EMISSIONS; DUAL-THRUST MOTOR FOR VARIOUS PURSUIT COURSES. MARKS IMPACT AREA WITH VISUAL SIGNAL FOR FOLLOW-UP STRIKES
HELICOPTER-LAUNCHED, SEEKS LASER-DESIGNATED TARGET. SHAPED-CHARGE EXPLOSIVE WARHEAD. FOR DEPLOYMENT IN 1980.
SHOULDER-FIRED, SUPERSONIC, INFRARED-HOMING MISSILE WITH HIGH-EXPLOSIVE WARHEAD. FIRST DEPLOYED IN 1964.
MAN-PORTABLE; PASSIVE INFRARED-HOMING SYSTEM; "FIRE AND FORGET" TYPE. DISTINGUISHES FRIEND FROM FOE. NEW VERSION USES PASSIVE OPTICAL SCANNING.
LAND-MOBILE MISSILE WITH HIGH PROBABILITY OF SINGLE-SHOT KILL AGAINST HIGH-PERFORMANCE AIRCRAFT OF 1980'S. AVAILABLE 1979.
LONG-RANGE; SEMIACTIVE, MIDCOURSE GUIDANCE; ACTIVE RADAR TERMINAL GUIDANCE, INFRARED AND PROXIMITY FUZING. DEPLOYED IN 1971.
FOR VISUAL ENCOUNTERS, INFRARED HOMING. MACH 2 AND ABOVE. MANY MODELS SINCE 1956. HIGH-EXPLOSIVE WARHEAD.
DESIGNED FOR CLOSE-IN DOGFIGHTING; ALL-WEATHER, RADAR-GUIDED. HIGH-EXPLOSIVE, 30-KILOGRAM WARHEAD. NUMEROUS MODELS.

the diameter of the warhead. Primitive smart weapons were introduced at the end of the Vietnam war and in 1967 Middle East war.

The most remarkable example of the effectiveness of such weapons, which were getting smarter all the time, came in the Middle East war of October, 1973. General Sa'ad al-Shazli, chief of staff of the Egyptian armed forces, concluded after the war that it was now impossible to guarantee the success of any armored attack until the antitank weapons of the defense were neutralized. For example, the Israeli 190th Armored Brigade had attacked the Egyptian Second Army under cover of strong air support in the Sinai. After a few hours of fighting the Israeli force had been effectively destroyed. More than 130 Israeli tanks had been killed by Russian-made Sagger antitank missiles: 25-pound wire-guided rockets carried by lightly armored vehicles, widely deployed since 1965 by the Warsaw Pact forces and others. Over the Middle East battlefields second-line Russian-made surface-to-air missiles brought down 90 Israeli fighters in two days.

Maj. Gen. Chaim Herzog of the Israeli army, who has closely chronicled the war in his book *The War of Atonement: October, 1973,* points out the mistake of the Israelis in assuming that the best antitank weapon would be the tank: "Again there was a failure to take into account available intelligence—such as that on the Sagger antitank missile—and apply its lessons organizationally and operationally." Herzog describes one Sinai battlefield on the second day: "Hundreds of guiding wires of antitank missiles lay strewn across the road as if a giant spiderweb had collapsed." These weapons all came out of the 1960's; what will the electronics world have created by the 1980's?

The lessons of such experiences have not been lost on military planners. Director of Defense Research and Engineering William J. Perry asserts in his fiscal 1979 report to Congress that technology is America's "strongest advantage" and that "precision-guided munitions" offer the "single greatest potential for force multiplication" and "the potential of revolutionizing warfare." Perry argues that "we can greatly enhance our ability to deter war without having to compete tank for tank, missile for missile with the Soviet Union."

Smart weapons, in particular battlefield antitank weapons, have now gone through several generational developments. Their precursors were systems of the bazooka type, which had to be aimed at the target; once they were fired their course could not be corrected. They were therefore effective only at unusually close range. The first generation of smart missiles were wire-guided; they changed course according to commands automatically transmitted as the firer held the target in his sights until impact. The next generations have improved guidance (although many are still wire-guided), with computerized control located in the missile rather than in the launcher. The latest models of smart weapons are "fire and forget" and "shoot and scoot" designs; the firer no longer has to keep steady aim on the target but rather can take aim, fire and run for cover, or select still another target. The smart antitank warhead is then guided to its destination by a terminal-guidance system based on infrared, optical or radar sensing. In some cases the terminal guidance is achieved by a laser spot held on the target by someone other than the firer of the missile.

Smart weapons appear to offer high probabilities of kill with a single shot. It is estimated that the Tow heavy antitank weapon, a wire-guided, optically tracked missile that can be launched from a jeep or helicopter, in wide service with U.S. forces since 1972, has a kill probability of 80 percent up to its maximum range of 3.8 kilometers. The Hughes Aircraft Company advertises that its 1974 Maverick air-to-surface, television- or infrared-tracked antitank missile has made 92 percent direct hits in 226 production firings at "tank-size targets in operational-performance incentive firings." The success of all Maverick firings (about 500) has been 90 percent. A third example of a smart weapon for which data are publicly available is the German Kormoran, an aircraft-launched, radar-homing antiship missile designed in the early 1970's. In seven test firings last year six were exactly on target and the seventh met "specification requirements." Even allowing for commercial hyperbole, these are impressive performances.

What are the keys to the success of the new weapons systems? The first is the new sensors, powerful target-acquisition systems that can pinpoint the position of an artillery battery, a ship or a tank. Perhaps the most elaborate example of target acquisition is being embodied in a U.S. computerized system designated BETA (battlefield exploitation and target acquisition). It will incorporate satellite surveillance, airborne reconnaissance, side-looking airborne radar, moving-target indication systems, infrared systems, thermal and acoustic sensors and night-vision scopes. BETA should be able to locate with precision anything sizable that moves, emits heat or presents a radar image above the general background: aircraft, ships, tanks, armored vehicles. Only those targets too numerous to follow or too cheap to

bother about will remain unobserved.

The second key to the success of smart weaponry is precision servo-guidance of low weight and reasonable cost. The systems now here and improving allow little chance for a miss. What can be seen can be hit, and more and more can be seen, night and day.

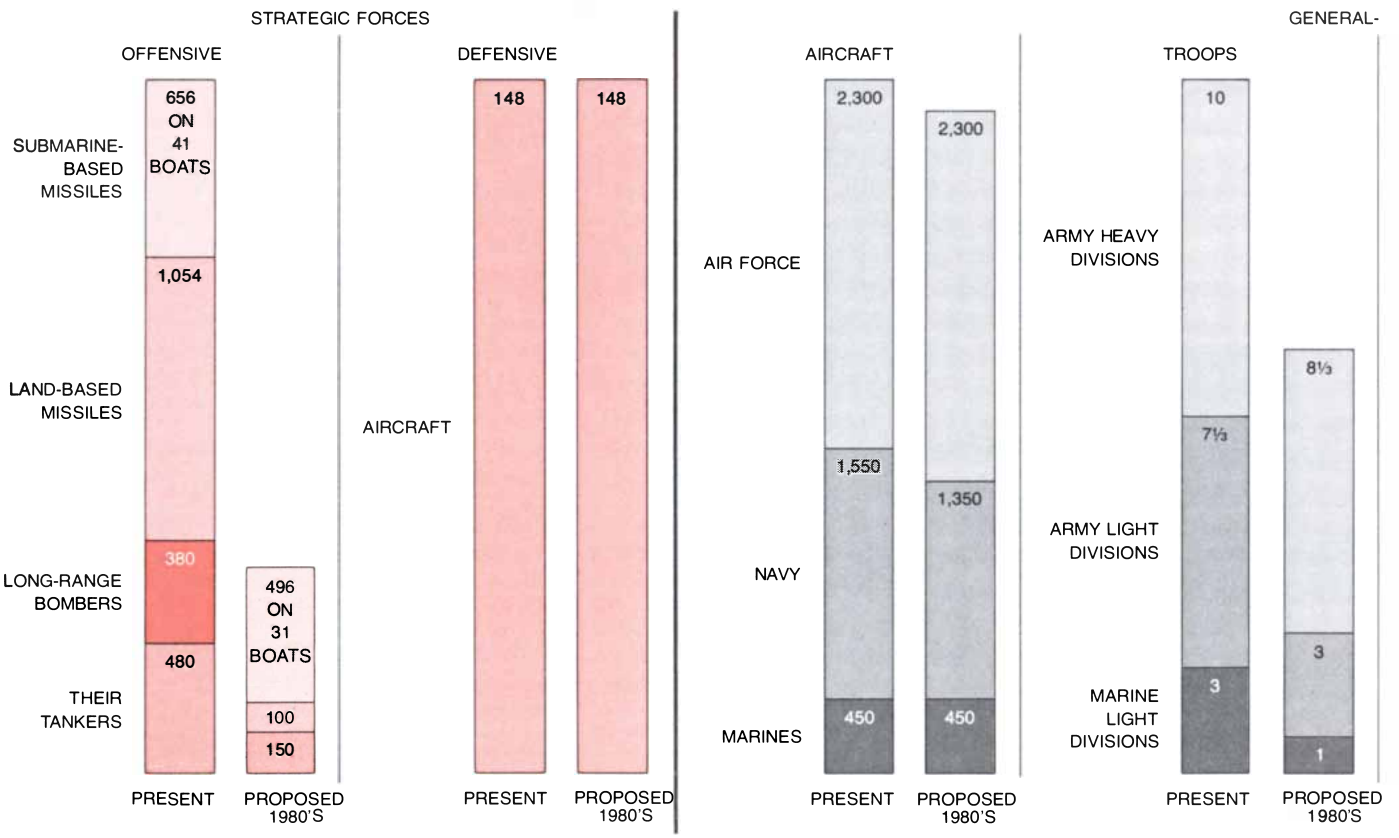
The third key is the design of small warheads. The conventional artillery shell has been modified in a number of ways; dense armor-piercing slugs that discard lighter components in flight and high-explosive rounds with contact fuzes give the warhead a much better chance of piercing composite armor.

As Perry explains it, the U.S. is now "converging very rapidly" on the following three objectives: "To be able to see all high-value targets on the battlefield at any time; to be able to make a direct hit on any target we can see, and to be able to destroy any target we can hit." Today's munitions, "combined with appropriate intelligence and delivery support, can make the battlefield untenable for most modern forces."

Although the future for precision-guided munitions seems bright, counterdevelopments will come. New composite materials for armor on tanks and aircraft are said to provide better protection against both explosive warheads and attack based on the total kinetic energy of many nonexplosive projectiles. One such material is a sintered aluminum oxide in the form of ceramic tiles that have "unique kinetic-energy-dissipation properties." The British boast of a new tank armor, still highly classified, a plastic-steel laminate named Chobham (for the military laboratory where it was developed) said to absorb the energy of penetrating rounds. Israel asserts that its new 56-ton Chariot tank, a front-engine, low-profile vehicle, is capable of withstanding any shell in the Arab arsenal. The project manager for the new U.S. XM-1 tank maintains that its survivability is enhanced by extended armor protection (such as skirts to cover tracks and wheels) and by improved agility, speed and acceleration.

Critics of smart weapons hope for additional countermeasures. Heavy suppressing fire from increasingly accurate artillery may disrupt smart-weapon attacks by infantry. Countereffects may also be offered by camouflage and deception techniques, such as smokes and fogs, nets to prevent night infiltration and radar-signal reflectors. In both Vietnam and the Middle East it was learned that if the slower antitank and antiaircraft missiles were spotted in time, they could be outmaneuvered. Armor enthusiasts assert that the tank has yet to meet its match, even in smart weapons.

It seems fair to conclude, however, that as smart weapons become more versatile, more reliable, faster-moving, relatively cheap and still more accurate they will overcome expensive armor protection and the power-intensive tactics of evasion. Tanks and aircraft close to the battlefield will cost more, will have to expend more effort and time in their own defense and will attempt to survive by evasion. Around them many men and cheap pilotless vehicles with cheap but deadly weapons will be seeking their fewer and more expensive targets. It is late for the massed tank offensive; even command of the air may pass from the pilot to the ground-based soldier. The overall judgment is not in, but the fate of the battleship seems in store for the little battlecraft of the land and the strafing gun-and-rocket aircraft of present wars. They will increasingly depend on evasion; then they will be seen as not being worth their cost, and in the end they will surrender their offensive superiority.



WINDING DOWN OF U.S. ARMED STRENGTH recommended by the authors would chiefly affect the scale of U.S. strategic forces but would still leave the U.S. with a credible nuclear deterrent and the ability to defend directly and indirectly all the territory of the U.S. and its chief allies against any plausible threat for the next decade. The submarine deterrent, the most secure of U.S. missile-launching systems, is retained with only a small initial reduction, from 656 missiles to 496, each equipped with 10 to 14 independently targetable warheads, subject to future reduction. The number of land-based Minuteman missiles would be cut to a precautionary 100. The strategic-bomber fleet would be decommissioned, but some of its refueling tankers would be retained to support tactical forces. There would be

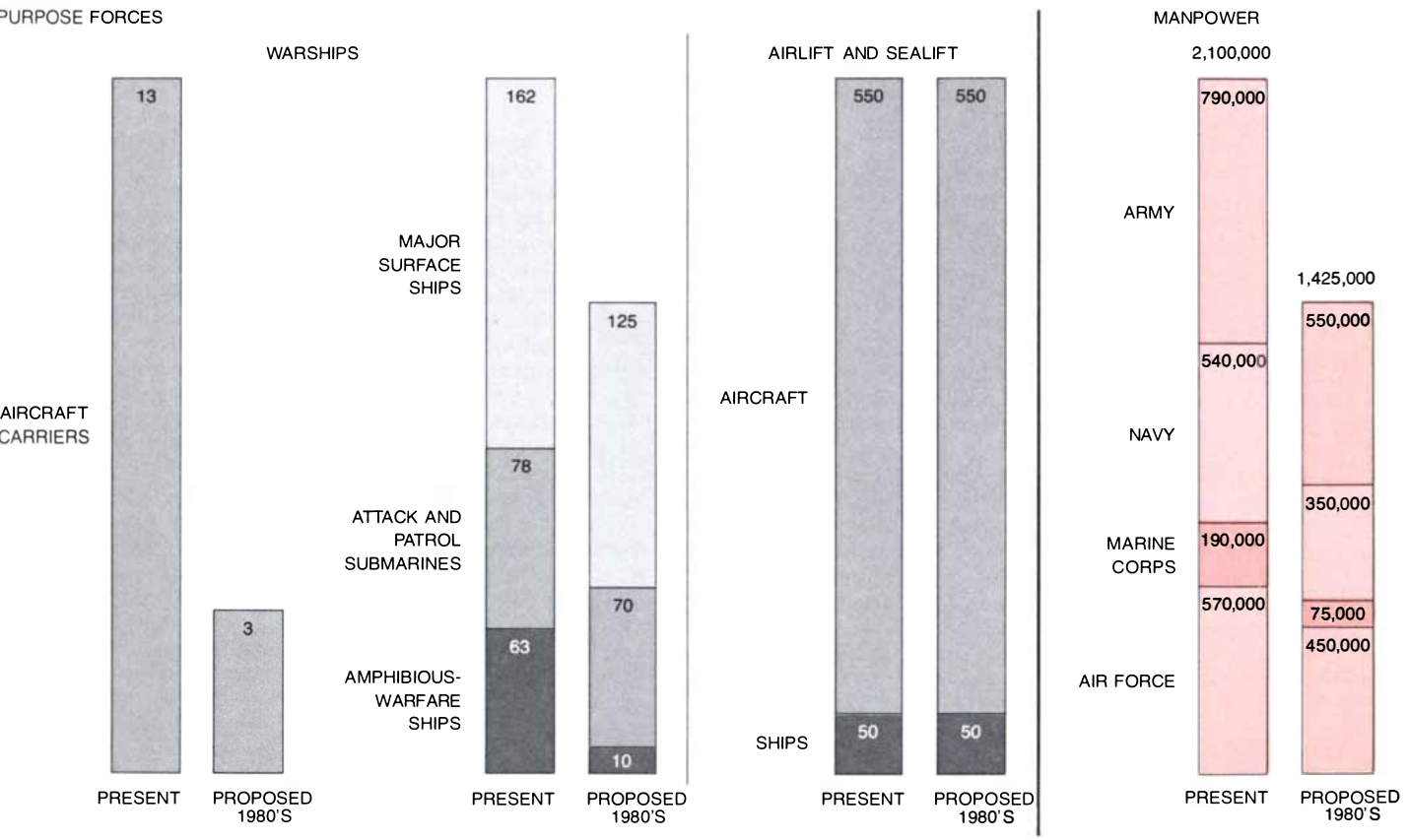
The advances in smart weaponry are putting a premium on concealment and dispersion. The weapons will be lighter and smaller and will be moved and fired by small teams on the battlefield. In World War II each step was hard: detecting the enemy, identifying him, hitting him and then destroying him. That is no longer valid; once a tank, an aircraft or a ship can be found it can be identified and hit and probably knocked out of action. The trend was visible during a tour of an armored unit at Fort Carson, Colo., made by the authors of this article. The unit commander explained that in war games points are no longer given just for hypothetical hits by the tanks; since the experience of the Middle East war of 1973 points are subtracted for the number of seconds during which tanks and armored vehicles are visible to the enemy. The trick is to remain hidden until advance seems possible. Any detectable concentration of force or logistics becomes vulnerable.

During the 1973 Middle East war more tanks were thrown into battle than in any other past engagement (except for one battle near Kursk on the Russian front in World War II). Close to 3,000 tanks were destroyed and more than 600 aircraft were downed. This led Russian Marshal Andrei A. Grechko to call for debate on the future role of the tank, a Russian specialty. Citing the Middle East experience, Grechko has noted that "modern defense ... has acquired greater stability.... Tanks have become more vulnerable and the use of them on the battlefield more complicated.... It is obvious that the traditional method of increasing the viability of tanks—directly strengthening their armor—is far from the only and, if you like, not the best way out of the situation that has built up."

Within the next decade or two the battlefield may well become untenable for all but the most agile and best concealed. This would appear to be a stabilizing development, since in most engagements it will give a decisive advantage to the tactical defense. The costly offensive force must typically come out into the open to advance; this now puts it in serious danger of taking many hits from the hidden and protected defense with cheap, numerous smart weapons. The new U.S. Army Field Manual (FM 100–5, *Operations*) recognizes this "superiority of the defense." Of course, it all depends greatly on the adequacy and the deployment of the defensive systems; it is always possible to overwhelm a defense with sheer numbers.

The future of land battle nonetheless seems to lie not with ponderous, powerful armored vehicles, which are expensive and therefore few in number, easily detectable and easily destroyed, but with light, mobile, less heavily armored, cheap and numerous jeeps or reconnaissance vehicles. They would carry a powerful punch in new smart weaponry. There is some evidence that armies are heading in this direction; the French, the British and the Russians have all developed several models of small, armored scout vehicles. Just a year ago the U.S. sought proposals for AHAM, an advanced heavy antitank missile, vehicle-mounted, extremely accurate and deadly. Moreover, a good part of the $44.5 billion for research and development and for the procurement of new equipment this year is going toward precision-guided munitions.

The aircraft for supporting ground forces have also grown in cost, performance, firepower and vulnerability over the past decade. In World War II it took 2,500 P-47 and P-51 fighters and B-25 and B-26 bombers to destroy 60 to 70 tanks a day; today 100 F-4, A-7 and A-10 fighters carrying smart antitank mis-



no reduction in strategic-defense aircraft. The general-purpose forces, which embody the nation's main capacity for defending itself and its allies, would be reduced modestly except for a sharp reduction in the number of aircraft carriers, which are virtually indefensible. There would be an accompanying gradual retirement of major surface ships, many of which are now assigned to the protection of carriers. The rapidly growing capacities of smart weapons should help to allow a prudent reduction in the number of divisions from about 20 to about 12. The overall effect on military manpower is shown in the last pair of bar graphs: a reduction from 2,100,000 to about 1,425,000 in uniformed personnel. The authors' recommendations are calculated to provide the U.S. with as much force as it needs.

siles can theoretically knock out 600 to 700 tanks a day. Yet the aircraft themselves are now highly vulnerable to surface-to-air missiles; in 1973 many Israeli fighters were hit at various altitudes by a variety of Russian-made surface-to-air missiles (SAM's) and radar-directed guns. Indeed, ground forces with pilotless drones and plenty of smart antiaircraft weapons may well be able to contest piloted planes for air superiority in the not too distant future. Helicopters seem even more vulnerable, although they now carry more armor than the faster fighters. All aircraft are costly and getting costlier as they are given more protection.

For the modern smart missile the most inviting target of all may well be the aircraft carrier. The U.S. currently deploys 13 such vessels; the largest is nuclear-powered, displaces 94,000 tons, is 1,100 feet long, has a deck with an area of six acres and carries a cargo of 100 combat aircraft and 6,100 sailors and airmen. These costly vessels can be targeted at all times by enemy missiles, given their high visibility on the surface and their small number. Some Navy officers still argue that the big carrier is defensible: it is mobile, it can detect enemy aircraft several hundred miles away, it has antisubmarine capability and it can absorb several good-sized hits without sinking. Soon, if not already, it may carry powerful lasers to direct against incoming missiles. But can it do much more than survive?

Experience indicates that the fighting carrier is delicate: flight-deck accidents have put carriers out of commission for months. Every carrier hit in World War II by two or more kamikaze planes was forced to retire for repairs. Prolonged carrier defense seems doubtful; cheap antiship missiles are getting more sophisticated daily. They will fly low, fast and in large numbers against carrier task forces. A couple will surely get through.

The aircraft carrier is conceivably useful in two situations: "showing the flag" in peacetime and fighting a poorly armed opponent. Carriers would be of little use in a major non-nuclear war of the future, if such a war is possible. In fact, they might be a giant liability, needing constant heavy convoys and frequent repair. Even today the carrier task force devotes much effort to self-defense: of the 100 aircraft on each carrier only a third are attack planes. The planes are capable of delivering a few hundred tons of bombs on targets a day, not exactly a cost-effective non-nuclear explosive punch. It is hardly necessary to mention the fate of carriers in a nuclear battle.

Ships, planes and tanks are all steadily more expensive and more sophisticated but more vulnerable. Each basket of eggs is more expensive but more breakable. The nuclear aircraft carrier costs $2 billion to build and another $3 billion to fit out; more than half of the $42 billion Navy budget goes in some way to supporting the 13 carrier task forces. Fighter-aircraft costs have risen in some cases to $25 million per plane; the real cost of the F-14 Navy fighter, for example, is more than that of a couple of carrier squadrons in World War II. Tank costs have also risen steeply. Five years ago the U.S. M-60 main battle tank cost $300,000; today it costs $650,000, and the cost of the new XM-1 tank fully equipped is estimated to be close to $1.5 million. Yet each of these pieces of expensive manned equipment—the tank, the airplane and the ship—can be destroyed by one precision-guided missile costing a few thousands of dollars. Cost-effectiveness is clearly shifting to smart weapons with small, lower-performance carrying vehicles.

Defense Secretary Brown has predicted purchases over the next five years of 5,000 tanks and 2,000 tactical aircraft, mainly for NATO support, at a respective cost of roughly $7 billion and $30 billion. The same amount would buy several million smart weapons for infantrymen, a formidable deterrent to anybody's tank assault. Such a conclusion is of course overdrawn; there will always be need for a balance of high-cost and low-cost weaponry. It nonetheless makes graphic the differential in costs between the high-performance manned target and the smart weapon attacking it.

The foregoing observations have emerged from a study of the entire force structure of the U.S. that we and our colleagues of the Boston Study Group have conducted over a four-year period. We became convinced that a better and safer defense for the U.S. and its allies can now be bought for much less than the proposed $126 billion for fiscal 1979. Tradition, employment, service rivalries, political hyperbole and covert intentions ought not to dictate force planning, particularly in the face of changing technologies. If such shibboleths as "triad," "essential equivalence," "forward defense," "flexible response" and "power projection" continue to dominate military planning as they do now, the U.S. runs two grave risks: (1) sporadic interventions leading to smaller or larger Vietnams and (2) eventual nuclear destruction.

The charts on the preceding two pages summarize the reductions in land, sea and air forces that we suggest could be made step by step over a period of years and that would leave the U.S. with a prudent military structure, prepared for any eventuality short of an all-out irrational nuclear attack. Against such an attack there can be no preparation and no defense for any nation, and the attacking power is as doomed as the one attacked. The major reductions would be in nuclear strategic forces; the proposal is to eliminate all long-range strategic bombers, to reduce to 100 the number of land-based Minuteman ICBM's, to reduce the number of missile-launching submarines from 41 to 31 and gradually to reduce the number of missiles and warheads carried on each. The next-largest force reduction would be made in the fleet of aircraft carriers, from 13 to three. The number of major surface ships would be cut from 162 to 125, mainly ships now included in carrier task forces. There would be only minor reductions in the number of aircraft assigned to general-purpose forces. With the accelerated development and introduction of smart weapons the number of Army heavy divisions could prudently be reduced from 10 to 8⅓ and the number of light divisions from 7⅓ to three. In addition two of the present three Marine light divisions could be eliminated. Total military manpower would be cut a third, from 2,100,000 to 1,400,000.

The budget for the new and safer military structure would come to about $73 billion, or about 40 percent less than the U.S. defense budget of $120.4 billion originally proposed for the fiscal year just ended. The accompanying bar charts [*opposite page*] show our budget for the 1980's broken down in the two ways defense budgets are presented to Congress: by military program and by appropriation title. Our estimates include an interim rise in retirement pay to cover the transition period of manpower reductions. If one excludes such pay, the overall budget reduction comes closer to 45 percent than to 40.

What effect would our proposals have on U.S. employment, military and civilian? We assume that at the end of a 10-year period our proposal would result in a reduction of about three million people engaged in military activity directly or indirectly. We would foresee a gradual transition to the lower spending level in part because the change would be gradual and in part because it would take time for the proposals themselves to win acceptance. It is likely, then, that the number of jobs eliminated each year would be no more than 400,000. Much of the shrinkage could be absorbed by normal shifts in jobs and by retirement. Each year probably fewer than 200,000 people would actually lose their jobs and be forced to enter the civilian labor market. Compared with the rapid ups and downs in employment characteristic of American economic life, and particularly compared with the demobilization at the end of World War II, the problem of finding new jobs for 200,000 people a year should not be daunting.

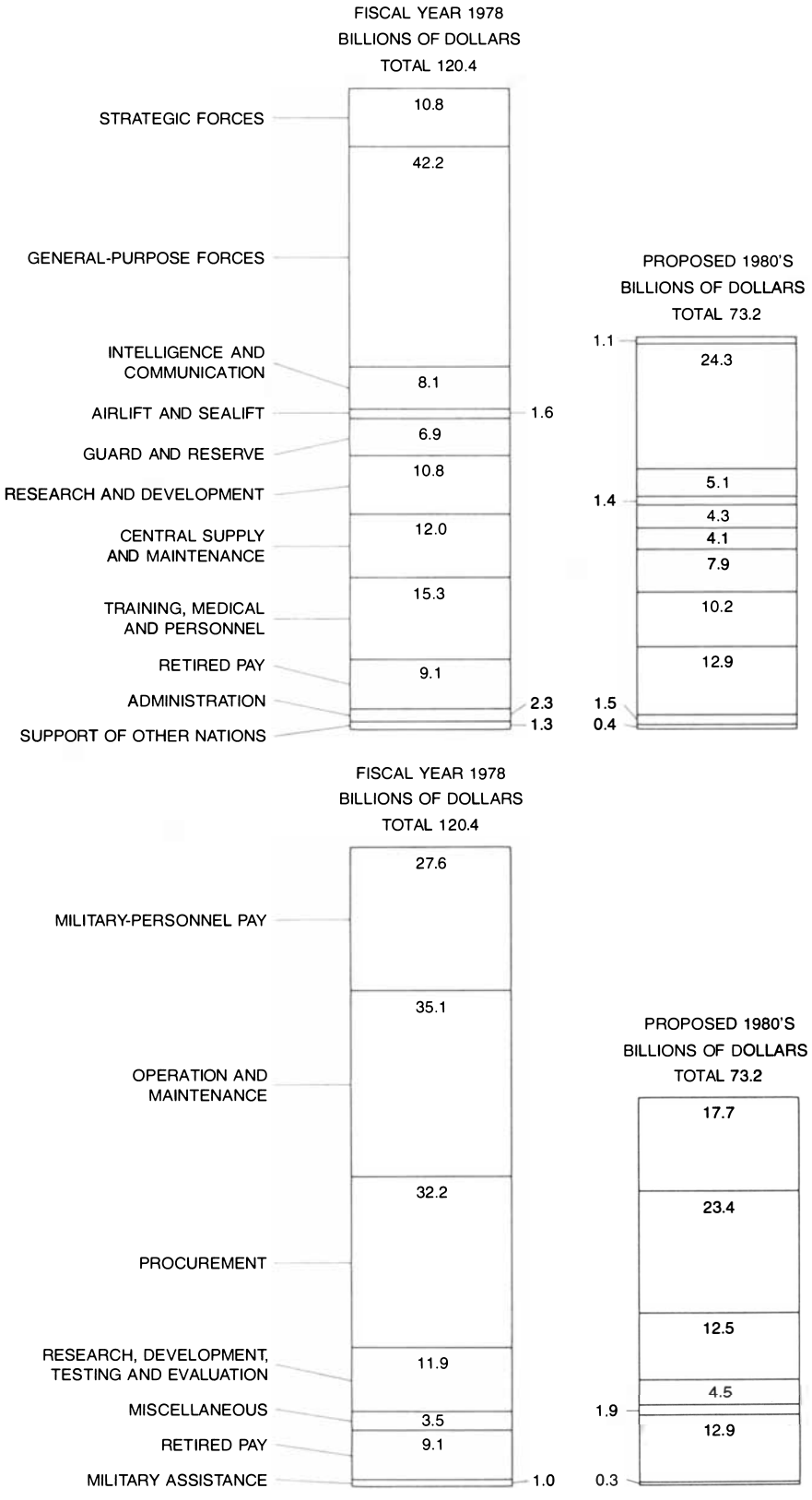
As for the effect of military cuts on industry, we believe the gradual pace of the reduction and the ability of American industry to adapt to new con-

ditions should minimize the need for large-scale public aid to distressed companies. We might also observe that several economic studies have shown that, far from creating jobs, military expenditures provide fewer jobs than equal levels of spending for civilian goods and services do. For example, the Bureau of Labor Statistics recently analyzed the effect on unemployment of shifting $1 billion from military expenditures to a variety of nonmilitary expenditures. If similar proportions hold true for the reduction in military spending we are proposing, the transfer of an equivalent sum to the civilian economy would create a net two million new jobs.

In this article we have not, of course, been able to present the detailed analysis contained in our book. There it will be seen we have tempered our judgments in two ways. First, we recognize that in complex human affairs it is not always prudent to change too rapidly, even when one is convinced of the need for change. Second, we have looked for paths of retreat from our own proposals, if they turn out to have undesirable results. Insofar as it is possible the changes we are recommending incorporate a built-in scheme for returning to an earlier state.

In the more than 30 years since the reduction in U.S. military forces at the end of the last great war those forces have steadily increased in size, firepower and cost. Bilateral and multilateral efforts at arms control and disarmament have not slowed the upward trend in armaments. In some instances they have even encouraged it. It is incumbent on the U.S., which is largely responsible for setting the technical pace, to break the spiral. We can play the role of catalyst for less risky world military policies.

A better, safer defense for the U.S. and its allies can be bought with much less risky forces and rather less money. Our analysis and recommendations are meant as tentative first steps in that direction; they are offered for broadened and serious debate. We believe our recommended force structure would (1) adequately deter nuclear and non-nuclear attack on the U.S. and its allies (NATO, Japan and allies in the Middle East), (2) make it harder for the U.S. to be tempted to intervene in the kind of foreign situation history has shown to be disastrous, (3) set standards for decreases in armaments, (4) catalyze diplomatic progress in arms control and disarmament, (5) make U.S. forces and policy understandable and less threatening to the outside world and (6) release new economic energies in the U.S. against inflationary trends. The country could begin to fulfill President Carter's campaign pledge to reduce military spending, to limit the upward-spiraling arms trade and to lighten the thermonuclear sword that still hangs over all mankind, sharper and heavier each decade.



U.S. MILITARY BUDGET is presented to Congress in two breakdowns: by military program (*top*) and by appropriation title (*bottom*). These figures are based on the Administration's proposed budget for fiscal year 1978, the latest available in sufficient detail for analysis. The final budget for fiscal year 1978 was reduced to $116.8 billion, in large part by eliminating $1.6 billion for the B-1 bomber and transferring $1.3 billion in military assistance (arms and training) to the Department of State budget. The bars at the right show the effect of the authors' proposed military structure on the various budget categories, broken down the same way. If the authors' recommendations were implemented over the next five to 10 years, it would be possible to reduce the defense budget by about 40 percent, or some $50 billion in 1978 dollars. The proposed budget includes a rise in retired pay to cover period of accelerated retirements.

Brain Function and Blood Flow

Changes in the amount of blood flowing in areas of the human cerebral cortex, reflecting changes in the activity of those areas, are graphically revealed with the aid of a radioactive isotope

by Niels A. Lassen, David H. Ingvar and Erik Skinhøj

The phrenologists of the early 19th century believed that the moral qualities of an individual, such as "creativity" and "aggressiveness," could be inferred from the pattern of bumps on the skull, presumably reflecting a hypertrophy of particular regions of the brain within. Although this fanciful but persistent view is now totally discredited, it did, ironically, contain a germ of truth. Studies of the effects of brain damage on behavior and of electrical stimulation of the brain during surgery have revealed that specific sensory and motor functions (rather than personality traits) are localized in discrete regions of the cerebral cortex, the five-millimeter layer of nerve cells that constitutes the surface of the cerebrum. In our laboratories at Bispebjerg Hospital in Copenhagen and at the University of Lund in Sweden a new radioactive-isotope technique has made it possible for us to observe the localization of function in the human cerebral cortex directly.

The first serious efforts to localize functions in the cortex were made in 1861 by the French physician Paul Broca, who made a postmortem examination of two paralytics, both of whom had been paralyzed only on the right side and had suffered from a severe aphasia that rendered them speechless. In the autopsies Broca found a serious deterioration of the brain tissue in a part of the left hemisphere, and he concluded that the speech function is localized in that region of the brain. Later investigators adopted Broca's indirect approach to localize many other cortical functions on the basis of the neurological and mental defects resulting from brain damage.

In the 1940's and 1950's a number of neurosurgeons, notably Wilder Penfield and his colleagues at the Montreal Neurological Institute, mapped cortical areas by electrically stimulating the cortex during surgical procedures in which the surface of the brain had to be exposed because of the nature of the underlying disease. The response characteristics of each stimulation were determined from the verbal report of the patient, who was conscious throughout the procedure. For example, when points on the somatosensory area of the cortex were stimulated, the patient reported sensations of numbness or tingling in specific regions of the body surface.

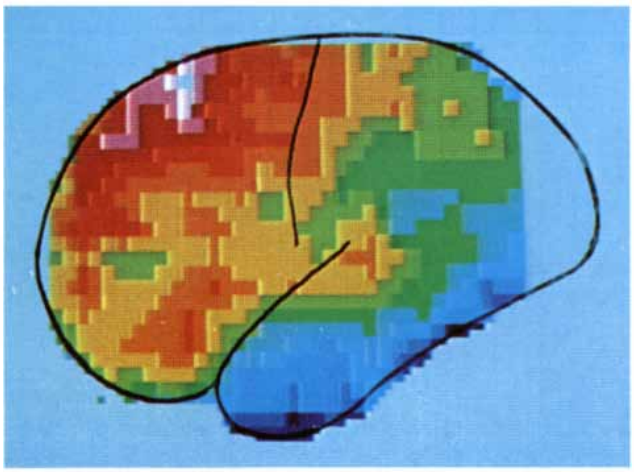
Such localization studies, supported by numerous observations in animals, gave rise to a basic set of relations between cortical areas and function: the occipital lobe in the rear of the cortex mediates vision, the rear-central cortex mediates skin and muscle senses, parts of the temporal lobes mediate hearing, the front-central cortex mediates motor control and Wernicke's area and Broca's area (which in practically everyone are located in the left cerebral hemisphere) respectively mediate the comprehension and synthesis of speech. Relatively large areas of the cortex are neither activated by sensory stimuli nor involved in directing motor activity; these regions, including what are called association areas, are involved in the detailed processing of sensory inputs, in the planning of motor actions and perhaps in purely mental functions.

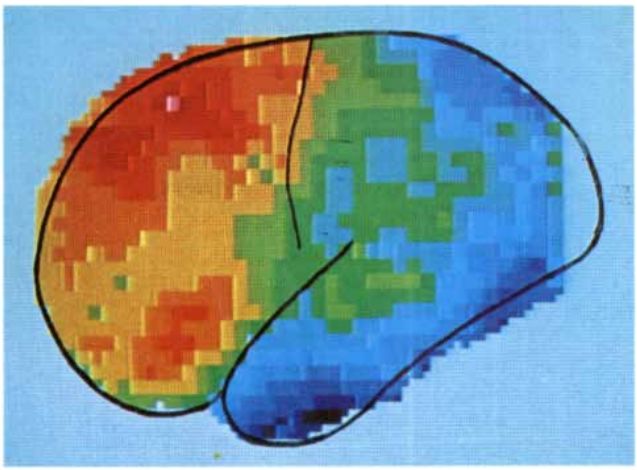
Although brain-lesion and electrical-stimulation studies have provided a great deal of information about the localization of function in the cortex, such studies are inherently limited. As was realized as early as 1874 by John Hughlings Jackson of the National Hospital for Nervous Diseases in London, "to locate the damage that destroys speech and to locate speech are two different things." For example, as will emerge in this article, the right hemisphere is much more active during speech than the tissue-damage approach had suggested. A more direct approach to the localization problem is to study the intact cerebral cortex in various functional situations: during "brain work." One technique is to record with minute electrodes the altered firing rate of individual nerve cells in the cortex. Yet not even large arrays of microelectrodes are adequate for deciphering the vastly complex interplay among the 10 billion nerve cells in the brain. We have taken an entirely different and more holistic approach: the measurement of the enhanced blood supply to cortical areas that are activated by the performance of specific sensory, motor and mental tasks.

Our method is based on the fact that the flow of blood through the tissues of the body varies with the level of metabolism and functional activity in those tissues. The interrelation between function, energy metabolism and blood flow was first postulated in 1914 by Joseph Barcroft of the University of Cambridge, who contended that an enhanced functional level in a tissue can be sustained only by increasing the rate at which oxygen is consumed. Most of the usable energy in the body comes from splitting the energy-rich molecule adenosine triphosphate (ATP) into the lower-energy products adenosine diphosphate (ADP) and inorganic phosphate (P_i). ATP is then reconstituted from its split products in a reaction requiring oxygen and glucose (oxidative phosphorylation).

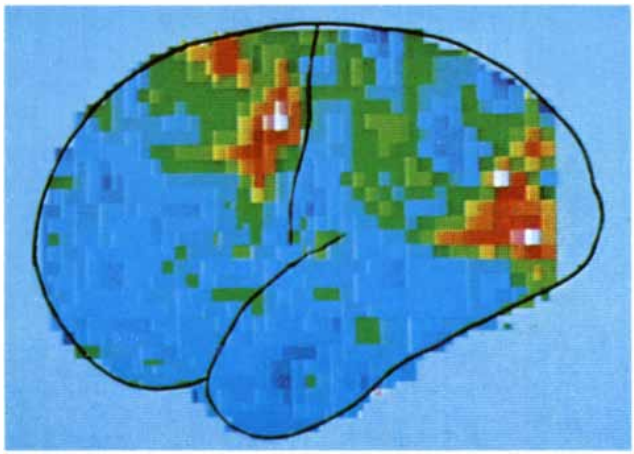
Because there is a constant ratio between the number of ATP molecules regenerated and the number of oxygen molecules taken up in the process the functional level of a tissue is tightly coupled to its oxygen uptake. Oxygen is supplied to the tissues by the bloodstream, and a rise in oxygen demand is met by an increased flow of oxygenated blood. During intense muscular activity the flow of blood through the muscle tissue may rise to as much as 20 times the normal level, and the blood flow in other organs has also been found to be finely adjusted to variations in oxygen demand. Since this fine tuning of blood flow continues when the organs are isolated and completely denervated, it appears to be governed by chemical factors released by local metabolic processes, although the precise mechanism is not yet understood.

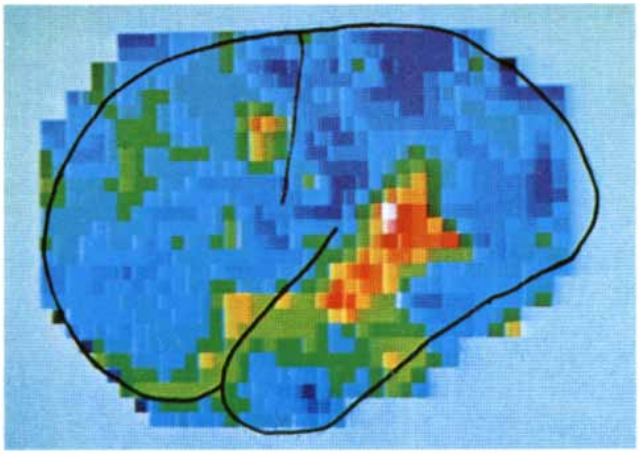
In the case of the brain the interrelation between functional activity, metabolism and blood flow was first suggested in 1890 by Charles S. Roy and Charles S. Sherrington, working in the Cambridge Pathological Laboratory. They



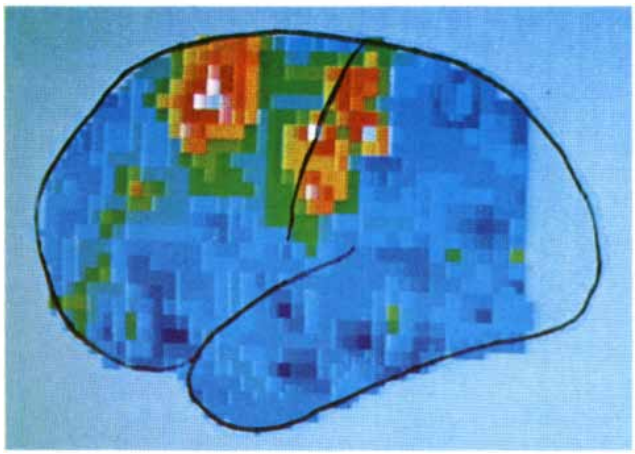


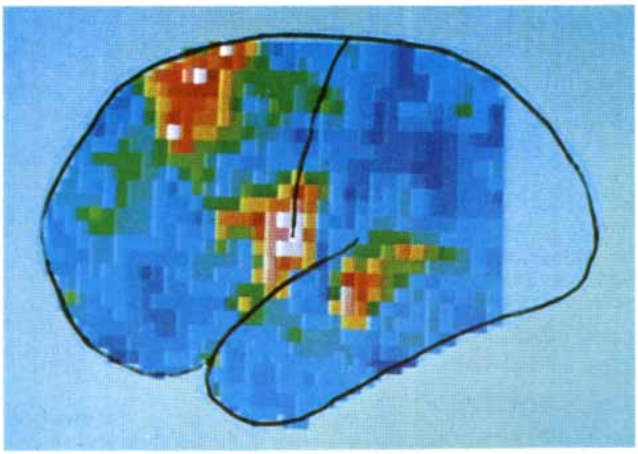
RESTING PATTERN of nerve-cell activity in the left and right hemispheres of the normal cerebral cortex was revealed by measuring regional blood flow, which is closely coupled to metabolic rate and hence to functional activity. The images were generated by a computer from data obtained by detecting the passage of the radioactive isotope xenon 133 through the cortex. Each pixel, or picture element, represents a square centimeter of cortex. On the color scale the mean flow rate is green, rates up to 20 percent below the mean are shades of blue and rates up to 20 percent above the mean are shades of red. Images suggest that in resting state the frontal areas are notably active.



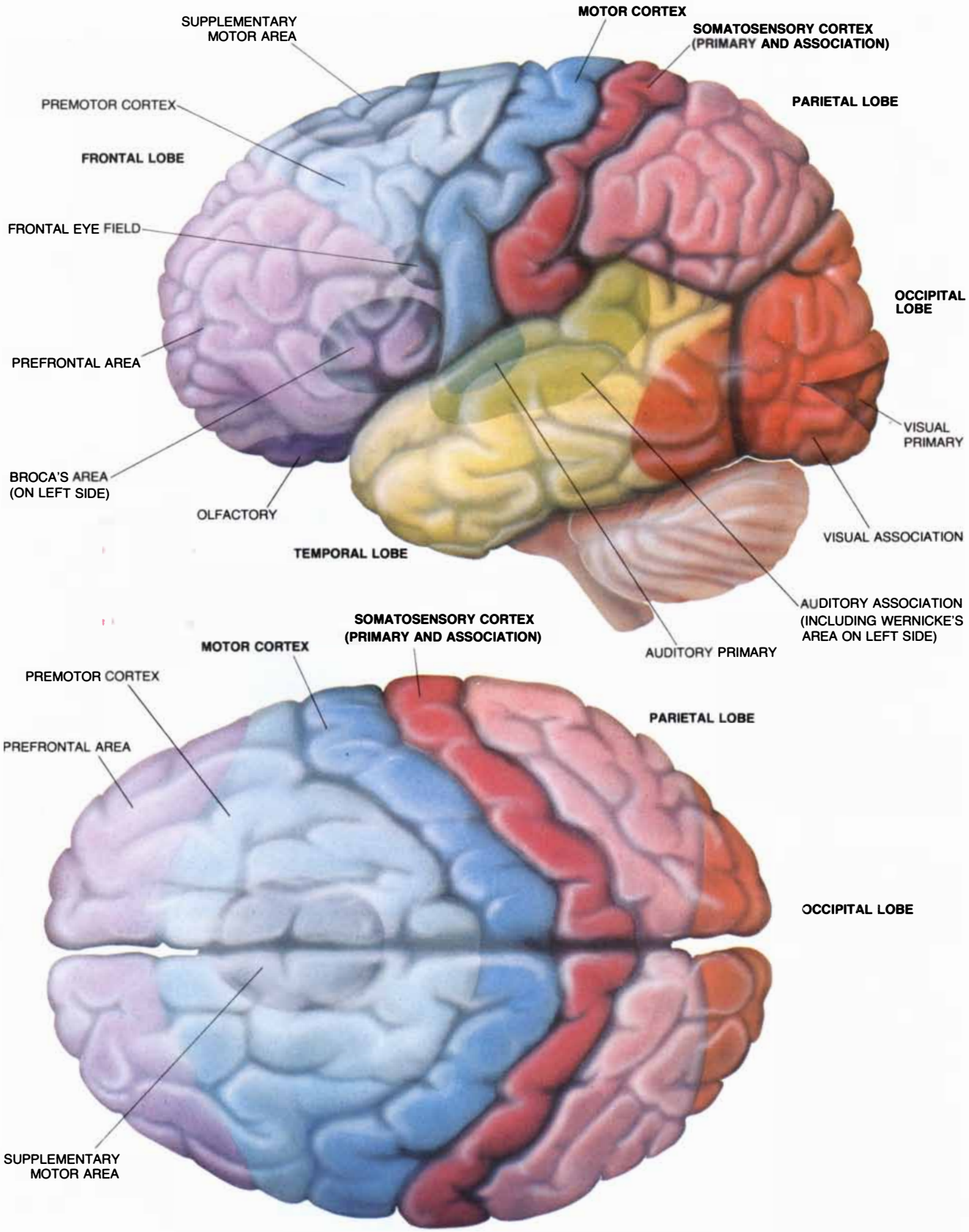


SENSORY PERCEPTION changes the pattern of blood flow in the cortex, revealing the localization of areas that mediate the processing of sensory information. In these images only departures in flow rate from the hyperfrontal resting pattern appear. During the study at the left the subject followed a moving object with his eyes; the visual association cortex in the rear of the brain is active, as are the frontal eye field and the supplementary motor area in the upper part of the frontal lobe. During the study at the right the same subject listened to spoken words; auditory cortex in the temporal lobe is active, as is the adjacent Wernicke's area, which mediates understanding of speech.





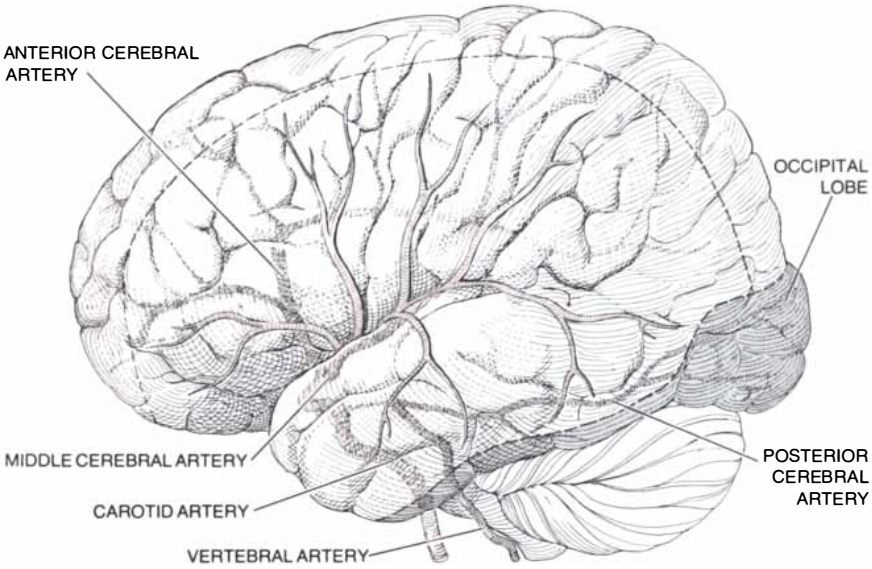
VOLUNTARY MOVEMENT activates different parts of the central cortex depending on the part of the body involved. During the study at the left the subject moved his fingers on the side of the body opposite the hemisphere being examined; the hand-finger area in the central cortex and the supplementary motor area are active. During the study at the right the subject was asked to move his mouth by counting to 20 repeatedly; the mouth area of the central cortex, the supplementary motor area and the auditory cortex are all active.



FUNCTIONAL MAP of the human cerebral cortex was obtained by a combination of approaches: studies of the effects of brain damage, stimulation of the exposed cortex during brain surgery, microelectrode recordings of cortical activity evoked by behavior or sensory stimuli, and the radioactive-isotope technique described in this article. Each sensory modality has a primary cortical area that receives projections from a peripheral receptive surface (such as the retina or the skin) and an association area that processes the sensory input and stores modality-specific memories. The premotor area is involved in complex motor activity such as operating a typewriter. The supplementary motor area programs sequential voluntary movements. Broca's area controls coordination of the muscles involved in speech.

observed that within seconds after the onset of an epileptic seizure (a synchronized hyperactivity of brain cells manifested by muscular convulsions) there was a swelling of the brain, suggesting that there had been a massive increase in the supply of blood.

Subsequent investigations have revealed that cerebral metabolism and blood flow are also enhanced during the normal activation of regions of the cerebral cortex involved in the performance of specific tasks. In 1937 Carl F. Schmidt and James P. Hendrix of the University of Pennsylvania School of Medicine recorded with thermocouples a strictly localized increase in the blood flow through the visual cortex of a cat when a small spot on the animal's retina was illuminated. Many other examples of localized increases in cerebral blood flow have since been reported in animals and in man, and it is now apparent that during a test involving a specific type of cerebral function there is a local change in nerve-cell activity and hence in metabolic rate that gives rise to an increase in blood flow in the active region. This discovery has made it possible to localize brain functions by studying regional variations in blood flow. One could equally well deduce the same information by mapping out changes in local metabolism (by measuring the uptake of either oxygen or glucose), but so far the functions of the human cerebral cortex have been systematically localized only with blood-flow measurements.



MAJOR ARTERIES that supply the cerebral cortex are outlined. The speech and auditory regions are nourished by the middle cerebral artery. The frontal and midline regions are supplied by the anterior cerebral artery. Both of these arteries are fed by the carotid artery in the neck. The primary visual area in the rear of the cortex, however, is supplied by the posterior cerebral artery, which is fed by the vertebral artery in the neck. Because the radioactive xenon is usually injected into the carotid, the primary visual cortex does not appear in the blood-flow images.

The average blood flow in the human brain was first determined in 1944 by Seymour S. Kety, who was then working with Schmidt. Kety's method was to observe the rate at which the brain was saturated or desaturated with an inert gas. The subject inhaled 15 percent nitrous oxide for 10 minutes, during which time the concentration of the gas was followed by drawing samples of arterial and venous blood from the brain. The area between the arterial and the venous saturation curves yielded a measure of the average blood flow, which is normally about 50 milliliters of blood per 100 grams of brain tissue per minute. Kety also measured the difference in the oxygen content of the arterial and the venous blood, which is normally about .07 milliliter of oxygen per milliliter of blood. Multiplying flow by oxygen difference yielded the average cerebral metabolic rate for oxygen, which is normally about 3.5 milliliters of oxygen per 100 grams of tissue per minute.

Later it became possible to measure the blood flow in circumscribed regions of the intact human brain with the aid of radioactive isotopes. In 1961 the three of us developed this principle from studies in cats, and its application to diagnostic examinations in man soon followed. The method involves the use of xenon 133, a radioactive isotope of the inert gas xenon. The radioactive gas is dissolved in sterile saline solution, and a small volume (two to three milliliters, containing from three to five millicuries of radioactivity) is injected as a bolus into one of the main arteries to the brain. The arrival and subsequent washout of the radioactivity from many brain regions is followed for one minute with a gamma-ray camera consisting of a battery of 254 externally placed scintillation detectors, each of which is collimated to scan approximately one square centimeter of brain surface. Information from the detectors is processed by a small digital computer and is displayed in graphical form on a color-television monitor, with each flow level being assigned a different color or hue. Owing to the attenuation of radiation from structures deeper in the brain, the gamma radiation detected comes from the superficial cerebral cortex. Thus the radioactive-xenon technique provides a fairly specific picture of the activity of the cerebral cortex directly below the detector array.

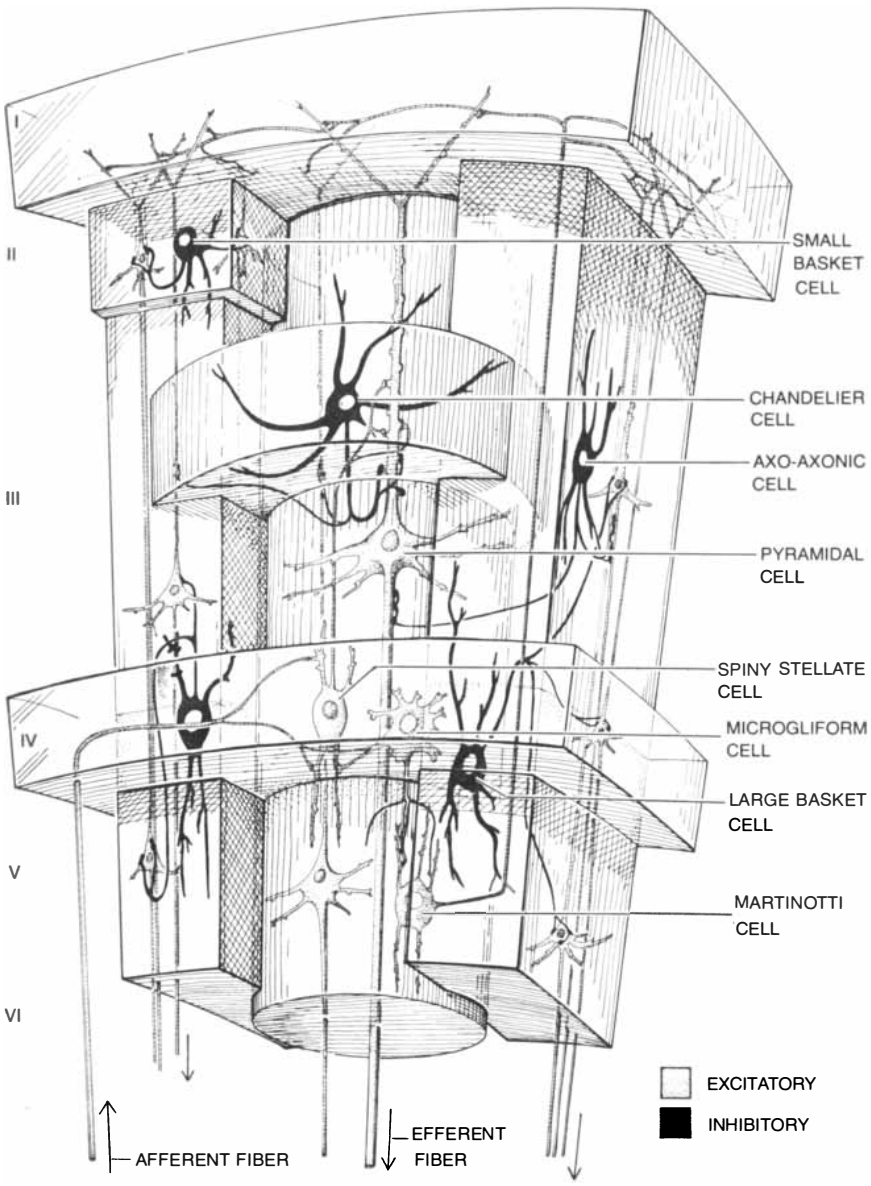
We use the technique routinely on patients in whom cerebral arteriography has to be performed. Cerebral arteriography involves making an X-ray plate of the blood vessels in the brain after an X-ray-opaque medium has been injected into the arteries. This injection is made through a catheter (a fine plastic tube) placed directly in the internal carotid artery through a puncture in the neck or passed up the femoral artery through a puncture in the groin. Since the same catheter is used for the radioactive-xenon injections, the measurement of cerebral blood flow incurs no independent risk to the patient. (The low level of the gamma radiation emitted by xenon 133 is not considered harmful.)

In our laboratories in Copenhagen and Lund some 500 patients have had their brain examined with the radioactive-xenon technique for diagnostic purposes such as the study of strokes, tumors or epilepsy. In retrospect we can say that about 80 of these patients had a normal brain at the time of measurement. This group consisted of patients who suffered from severe headache attacks, generalized epileptic seizures and other transient neurological symptoms that turned out not to be associated with permanent brain lesions or abnormalities. Electroencephalography ("brain wave" recordings) and other tests also served to confirm the normality of their brains. Our studies of the regional cerebral blood flow in these patients therefore enabled us to draw some conclusions about the localization of function in the normal cerebral cortex.

The resting pattern of blood flow in the brain of a normal subject is highly characteristic and reproducible, and it serves as a point of departure for the interpretation of the functional patterns recorded during different types of sensory, motor and purely mental activity. Surprisingly, when the subject is at rest and awake, in a comfortable supine position with eyes closed in a silent laboratory and neither spoken to nor touched, the pattern of blood flow throughout the cortex is not uniform. On the contrary,

the flow is always substantially higher in the front part of the cortex than in the central and rear parts. Although as we have mentioned the mean flow in normal subjects is 50 millimeters per 100 grams of brain tissue per minute, the flow in the front part of the cortex is as much as 20 to 30 percent above this mean, and the flow in the rear regions, particularly in some parts of the temporal lobe, is correspondingly lower. The density of both the capillaries and the nerve cells in the various regions of the cortex is about the same, and so the remarkable difference in flow rate suggests that the overall activity level of the front part of the resting brain is about 50 percent higher than that of the rear parts.

This "hyperfrontal" resting flow pattern may contribute to an understanding of conscious awareness. It is well known that the frontmost parts of the frontal lobe, the prefrontal areas, are responsible for the planning of behavior in its widest sense, whereas the remaining regions of the cortex subserve motor and sensory functions. The hyperfrontal resting flow pattern therefore suggests that in the conscious waking state the brain is busy planning and selecting different behavioral patterns. In the same state the motor and sensory regions of the cortex are not very active; they are perhaps even inhibited. This interpretation seems to agree with subjective experience. While one is at rest one is not continuously aware of one's sensory input; only occasionally does one perceive distinct visual, auditory or tactile signals that stand out from the background "noise" of the resting state. Most of resting awareness is focused on inner thoughts, particularly on reflections on one's own situation and its relation to past events and to possible future ones. The resting conscious brain can therefore be said to be primarily engaged in the simulation of behavior.

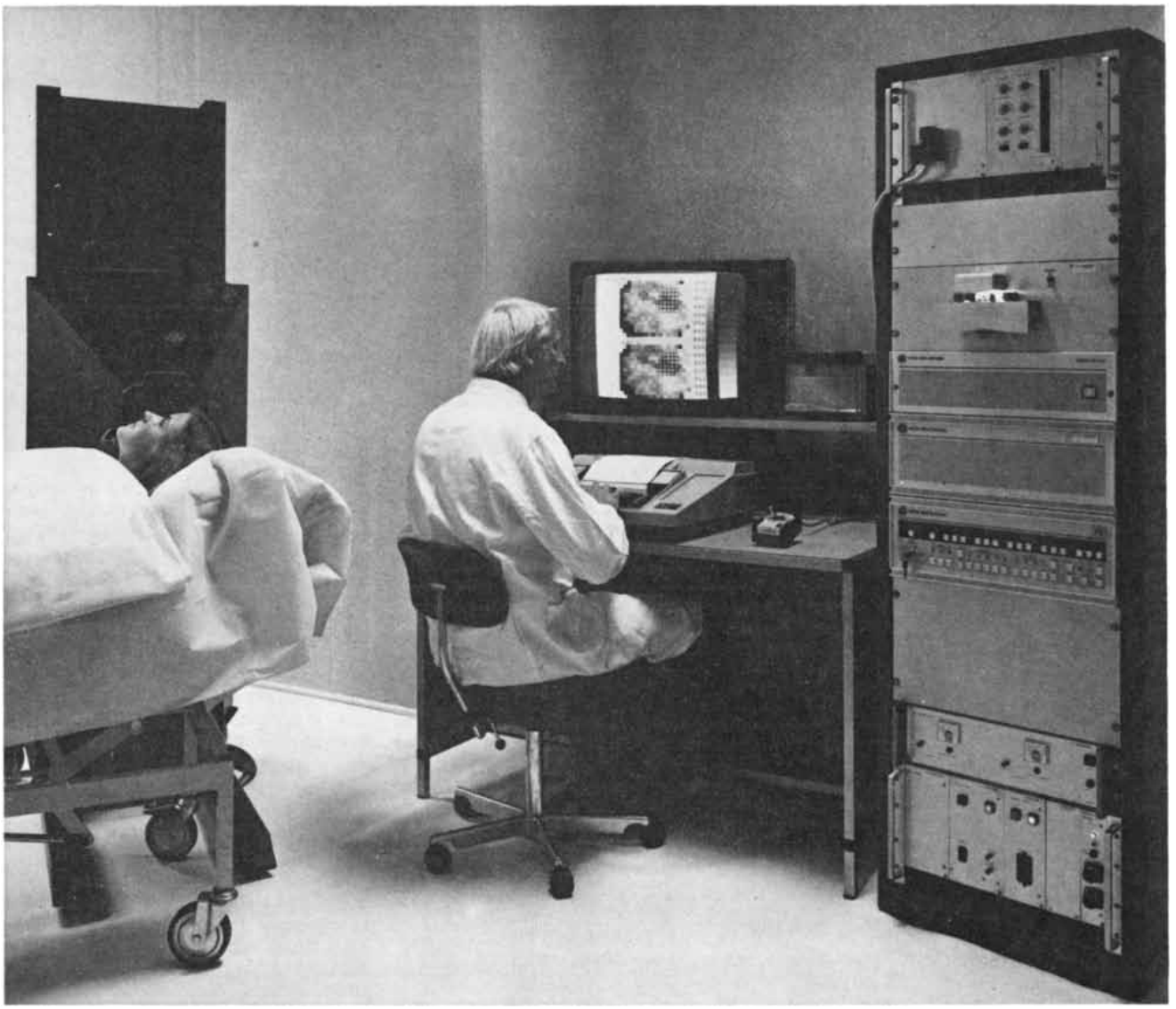


CELLULAR ARCHITECTURE of the cerebral cortex is organized into columnar modules made up of vertically arranged circuits of nerve cells. A typical column, some 250 micrometers (10^{-3} millimeter) in diameter, is shown in this highly simplified diagram based on one by János Szentágothai of the Semmelweis University Medical School in Budapest. Hundreds of incoming nerve fibers carrying sensory information converge on the spiny stellate cells in Layer IV of the cortex. The vertical circuits of interneurons, arranged in a highly specific spatial configuration, transform these raw data into the subtleties of conscious experience and behavior.

What is the effect of simple sensory stimuli on the pattern of regional blood flow in the cortex? For these experiments our computer was programmed so that only departures from the resting pattern of blood flow were displayed in colors on the screen. When the subject opened his eyes and looked at an object, the pattern of the cortical blood flow changed dramatically: an increase of about 20 percent was seen in the visual association cortex, located in the temporal and the occipital lobes. (The primary visual cortex deep in the occipital lobe at the rear of the brain was not seen because this area is supplied by the vertebral artery and hence did not receive the radioactive xenon injected into the carotid artery.) In addition a well-localized part of the premotor cortex, the frontal eye field, became active.

Auditory stimulation in the form of a loud, meaningless noise increased the blood flow near the upper rear part of the temporal lobe on each side of the brain, where the primary auditory cortex and the auditory association cortex are located. Flow in these areas was further increased by hearing simple spoken words such as "bang," "zoom" and "crack." The activated region includes Wernicke's area in the left hemisphere, which is involved in the understanding of spoken language. When spoken words were heard with the eyes closed, the frontal eye field in the premotor cortex was slightly activated. More complex verbal stimuli caused an increase in the regional blood flow in the lower rear part of the frontal lobe, where Broca's speech center is located on the left side.

The effects of tactile perception were studied by Per Roland in Copenhagen, working in collaboration with one of us (Lassen). The subjects were asked to indicate verbally which was the larger of two objects (small metal bars) placed one after the other in the palm of the hand, with the fingers kept motionless. This tactile stimulus activated the hand area of the primary somatosensory cortex in the central part of the opposite



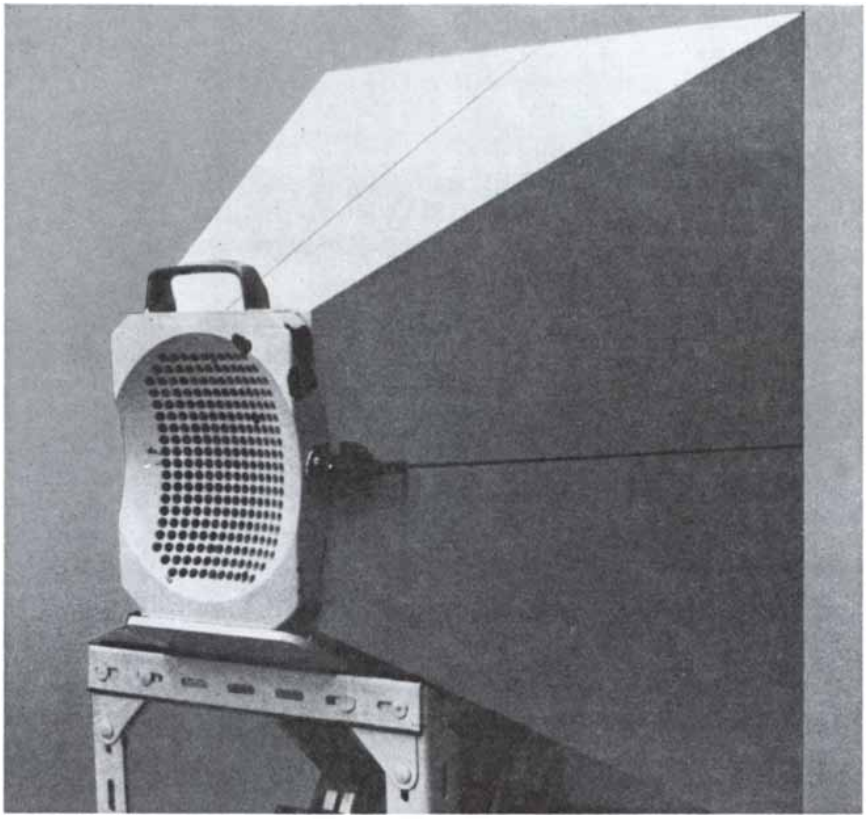
BRAIN-SCAN APPARATUS employed by the authors in their laboratories at Bispebjerg Hospital in Copenhagen and the University of Lund in Sweden is shown during a typical experiment. A few milliliters of saline solution containing xenon 133, a radioactive isotope that emits gamma rays, is injected into the subject's carotid artery. A battery of 254 externally placed scintillation detectors (located in the box behind the subject's head) then records the arrival and subsequent washout of the radioactive isotope from the cortex during the two minutes after injection. The scintillation data are processed by the computer and are then displayed on the color-television screen.

cerebral hemisphere, as well as the adjacent association cortex in the parietal lobe. (As is well known, the sensory and motor functions of the limbs are controlled by the hemisphere on the opposite side of the body.)

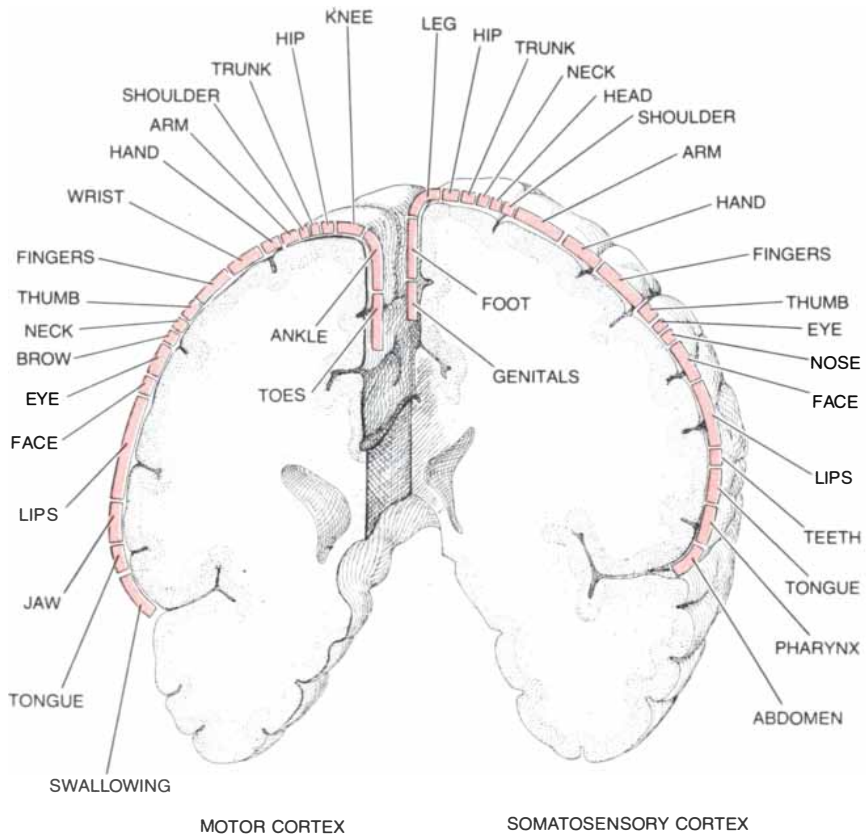
The performance of these simple sensory tests requires certain memory functions: the sensory inputs preceding the input arriving at any given moment must be retained, and the cumulative input must be compared with previous experience. A hypothesis of what the perceived entity means is then formed, and identification is completed by an active search for characteristic features. This process involves associations, in which memory plays a key role. In our experiments we noted that each type of sensory stimulus activated both the primary sensory cortex and the adjacent association area for that specific sensory modality. These areas were the only ones that were consistently activated by sensory input, suggesting that modality-specific forms of memory are localized in the association cortex specific for that modality.

It should be emphasized that we have not studied memory functions other than those directly associated with sensory perception. Short-term memory (which operates, for example, in the immediate recall of a telephone number or a person's name) is generally considered to be localized in the region called the hippocampus in the deeper parts of the temporal lobe. Like the primary visual cortex, the hippocampus gets its blood from the vertebral artery and hence is not represented in our carotid-artery-injection pictures.

Voluntary movements of the hand have been studied by Jes Olesen in Copenhagen in collaboration with one of us (Lassen). In 1970 it was observed that when the fist on the side of the body opposite the cerebral hemisphere being examined was rhythmically clenched, there was an increase in blood flow in the hand area of the primary motor cortex in the central part of the brain. Hand movements also caused an increase of flow in an adjacent area of the primary somatosensory cortex, which receives feedback signals from the skin, tendons and muscles of the hand while the hand is moving. As one would expect, however, when the hand being clenched was



ARRAY OF DETECTORS is located at the front of the instrument. Each detector scans about a square centimeter of cortex. Thus blood flow in an entire hemisphere is measured all at once.



MOTOR AND SOMATOSENSORY AREAS of the cortex are projections of the motor and somatosensory (skin sensation) areas of the body. The areas representing the face, the tongue and the fingers are disproportionately large because the amount of cortical surface devoted to a given part of the body reflects the motor and somatosensory requirements of that body part.

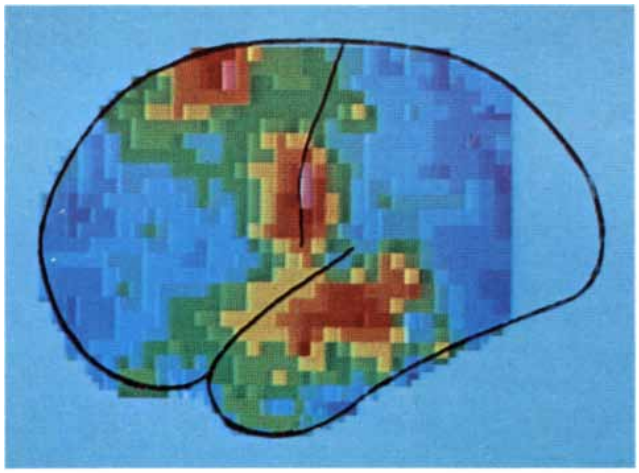
on the same side of the body as the hemisphere being scanned, there was no change in the flow pattern.

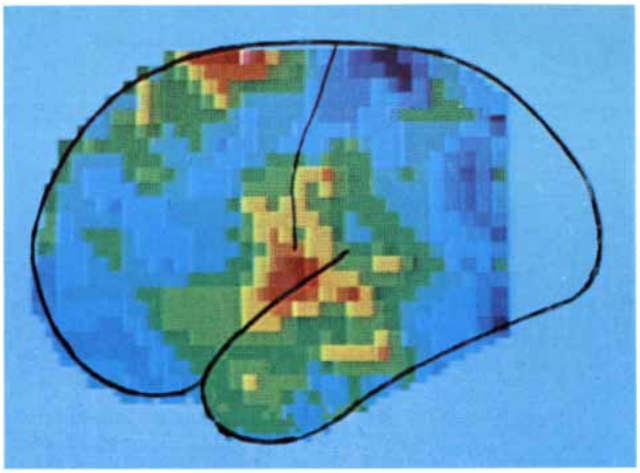
Recently Marcus E. Raichle and his colleagues at the Mallinckrodt Institute of Radiology in St. Louis studied the control of hand movements by injecting a radioactive isotope of oxygen into the brain arteries in order to directly follow regional oxygen consumption by the brain tissue. They found that hand movements increased the oxygen uptake in the same regions of the cortex where we had observed an increase in regional blood flow. This finding provides direct support for the basic assumption on which our interpretation of the blood-flow data rests: that local changes in blood flow reflect local variations in the intensity of nerve-cell metabolism.

Voluntary movements of the mouth in speech cause a well-defined activation of the cortical area that controls the movements of the mouth, the tongue and the larynx; voluntary movements of the foot activate the part of the motor cortex in the opposite hemisphere above the part activated by movements of the hand. These findings and others confirm that the primary somatosensory and motor areas are organized as two adjacent narrow bands extending from ear to ear across the top of the cortex. The maplike relation between the parts of the body and the somatosensory and motor areas of the cortex has been known in detail since Penfield and his colleagues plotted these areas by electrically stimulating the cortex. The map resembles a distorted homunculus with an enlarged head pointing toward the temporal lobe, an enlarged hand and thumb in the middle and a reduced foot at the top, reaching the inner side of the hemisphere.

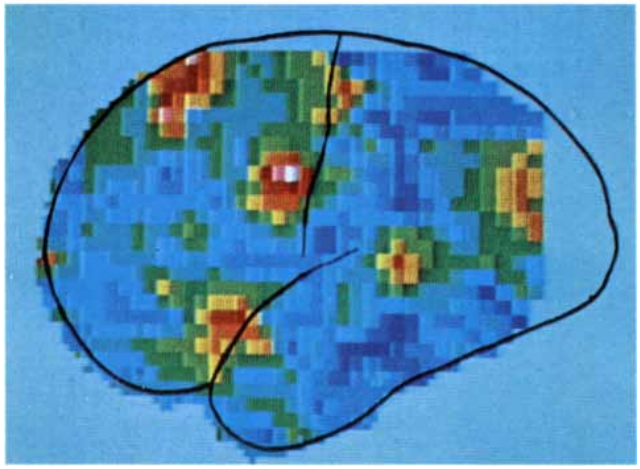
Contractions of voluntary muscle also activate the premotor cortex in the upper part of the frontal lobe. Such activation always involves both hemispheres and as far as we can tell is located in the same area regardless of whether the mouth, the eyes, a hand or a foot is moved. When the detectors of our apparatus are placed above the subject's head, the most marked change in regional cerebral blood flow occurs close to the midline and involves a region of the premotor cortex on the inner part of each hemisphere called the supplementary motor area. This area is known to play a role in complex motor tasks of all kinds, including speech.

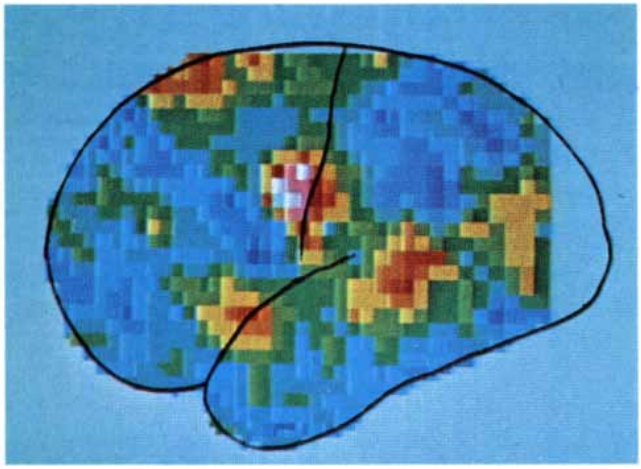
Nevertheless, to see the supplementary motor area and the surrounding premotor cortex so consistently and massively activated during voluntary movements somewhat surprised us. We found that activation of the supplementary motor areas was more marked during dynamic muscle movements, such as





SPEAKING activates three centers in each hemisphere: the mouth-tongue-larynx area of the somatosensory and motor cortex, the supplementary motor area and the auditory cortex. Differences in activity between the two hemispheres can be seen in these averaged images from nine different subjects: in the right hemisphere (*right*) the mouth-tongue-larynx area is less distinct and coalesces with auditory cortex.





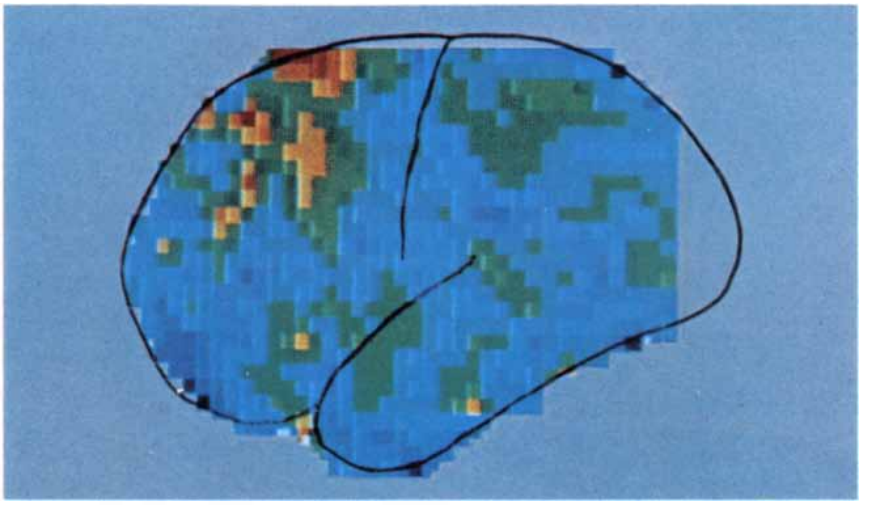
READING SILENTLY AND READING ALOUD involve different patterns of activity in the cortex. Reading silently (*left*) activates four areas: the visual association area, the frontal eye field, the supplementary motor area and Broca's speech center in the lower part of the frontal lobe. Reading aloud (*right*) activates two more centers: the mouth area and the auditory cortex. The left hemisphere is shown in both cases, but similar results have been obtained from the right hemisphere. Adding the primary visual cortex, which is not reached by the radioactive isotope, the act of reading aloud calls for simultaneous activity in seven discrete cortical centers in each hemisphere.

operating a typewriter, than it was during steady muscular contractions. For this reason, and because of supporting evidence in the scientific literature, we have concluded that the upper premotor cortex, including the supplementary motor area, is involved in the planning of sequential motor tasks.

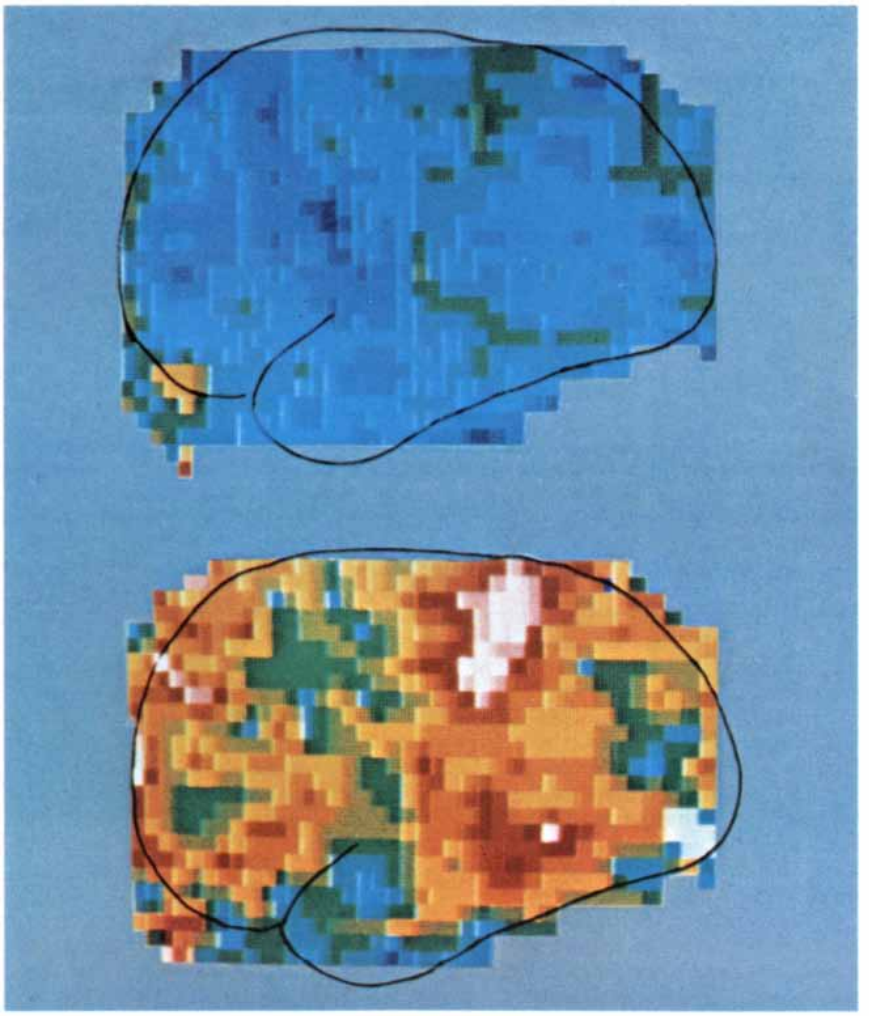
Here it is relevant to mention a recent experiment on the nature of voluntary movement. In both Copenhagen and Lund we have studied the difference between the pattern of regional cerebral blood flow that appeared when a simple sequence of finger movements was being performed and the pattern that appeared when the subject was merely thinking about performing the sequence. With suitable instructions the subject could perform the movement mentally in the correct temporal sequence while keeping the hand perfectly still; the imagined movement activated the supplementary motor area. When the sequence of movements was actually performed, the hand-finger area of the primary motor cortex and the related areas of the somatosensory cortex also became active. These findings suggest that the supplementary motor area is a programmer of dynamic movement, whereas the primary sensory cortex is the controller and the primary motor cortex is the executor.

We have investigated speech processes in detail. Here we were impressed to find that both the right and the left hemispheres become active in much the same manner. As we have mentioned, listening to simple words activates the auditory cortex in both hemispheres. Speaking aloud activates three more areas, namely the face, tongue and mouth areas of the somatosensory and motor cortexes, the upper premotor cortex in both hemispheres (which includes the supplementary motor area) and Broca's area in the lower rear part of the left frontal lobe and the corresponding part of the right frontal lobe. Reading aloud adds activation of the visual association cortex and the frontal eye fields as well as the primary visual cortex (although the last is only inferred, since it is not made visible in our technique). Thus seven discrete cortical regions are simultaneously active, forming a *Z*-like figure on the surface of each hemisphere. It was interesting to note the difference between reading aloud and merely reading: reading in itself does not activate the mouth areas of the somatosensory cortex or the motor cortex or the auditory areas, although the five other areas are active.

Studies of the effects of brain damage



"INTERNAL SPEECH" in the form of counting repeatedly in one's head from 1 to 20 activates the frontal regions, particularly the supplementary motor area. This imagined kind of speech does not measurably activate the areas normally involved in speech such as Broca's area and Wernicke's area. Image therefore represents the localization of a pure mental event.



GLOBAL ACTIVATION of the cerebral cortex is seen when the subject is engaging intensely or emotionally in a task. At the top is an image of the left hemisphere of an elderly man; the global mean flow rate of 33 milliliters per 100 grams of brain tissue per minute is low. During the making of the bottom image the subject was urged on verbal command to make rhythmical gripping motions with his right hand. The global mean flow rate increased to 48 milliliters per 100 grams per minute, and there are local increases in the hand area and in the auditory cortex.

on speech have revealed that destruction of Broca's area in the left hemisphere results in motor aphasia, that is, the loss of the ability to speak more than simple words but not the loss of the ability to understand spoken and written language. Destruction of the corresponding area in the right hemisphere, however, has no discernible effect on speech. We were therefore surprised to observe that this part of the right hemisphere was active during verbalization, suggesting that it makes some contribution (albeit a nonessential one) to the final synthesis and mobilization of speech. In Copenhagen, Borge Larsen, working with one of us (Lassen), analyzed his observations further to see if some slight differences in the blood-flow response of the two hemispheres during speech could be discerned. Although for ethical reasons he could not measure the flow in the right and left hemispheres of the same subject, Larsen's results suggest the following differences: in the left hemisphere an increase in flow is usually seen in the mouth area and the auditory cortex separately, whereas in the right hemisphere the two often form one confluent active region. Moreover, the supplementary motor area in the left hemisphere is usually more active during speech than the one in the right hemisphere.

The analysis of cortical activation during reading illustrates that a complex task is carried out by several circumscribed cortical regions brought into action in a specific pattern. This system is analogous to a computer program in which different subroutines are brought into play depending on the problem to be solved. In general our results confirm a conclusion reached by the late A. R. Luria of Moscow State University on the basis of his neuropsychological analyses of patients with brain damage: "Complex behavioral processes are in fact not localized but are distributed in the brain, and the contribution of each cortical zone to the entire functional system is very specific."

Early in our studies of various forms of brain activation we recognized that many of our patients in the conscious waking state showed not only local increases in the blood flow of specific regions of the cortex but also an increase in the blood flow of the cerebrum as a whole. Jarl Risberg and one of us (Ingvar) found that psychological testing with simple routines of recall and reasoning causes in addition to localized changes a significant overall increase in the cerebral blood flow of about 10 percent. This general increase in blood flow appears to be distinctly related to the subject's effort in performing the task, because it is absent when simple tasks are performed but is evident when the subject shows signs

of struggling with a difficult problem.

This finding supports a distinction made by neurophysiologists between the specific and the nonspecific pathways of the brain. The specific sensory and motor pathways arrive and depart from well-defined areas of the cortex that become active during the reception and interpretation of specific sensory messages or the execution of a specific motor task. At the same time demanding tasks activate larger cortical areas over diffuse pathways that fan out from the reticular formation of the brain stem and the thalamus of the midbrain. Animal studies have shown that in the absence of an activation of the diffuse nonspecific pathways the specific pathways by themselves do not appreciably alter the activity of the brain outside the regions of the brain to which the specific pathways project. Hence it appears that for the brain to "understand" the surrounding world, to perceive its meaning and to take action in difficult tasks the cerebral cortex must be activated not only locally but also totally.

A correspondence between the general activation of the cortex and the level of consciousness during the performance of various tasks has been strongly supported by studies of anxiety and pain. A threat to one's body or psychological well-being elicited by a pain stimulus or by strong anxiety provokes a dramatic increase in one's awareness of self and the environment and also causes a generalized increase in cerebral metabolism and blood flow. Stress activates pathways in the brain and also triggers the secretion of the hormone epinephrine (adrenalin) from the adrenal glands, which has a general arousing effect on the body. Bo Siesjö and his coworkers at the University Hospital in Lund recently studied rats waking up from anesthesia after they had been paralyzed with a muscle-relaxant drug of the curare type. The stress of the animals' waking in a state of paralysis gave rise to an enormous increase in the rate of their cerebral oxygen uptake and blood flow; the increase could be diminished, however, by the removal of the adrenals and could be completely abolished with drugs that block epinephrine receptors.

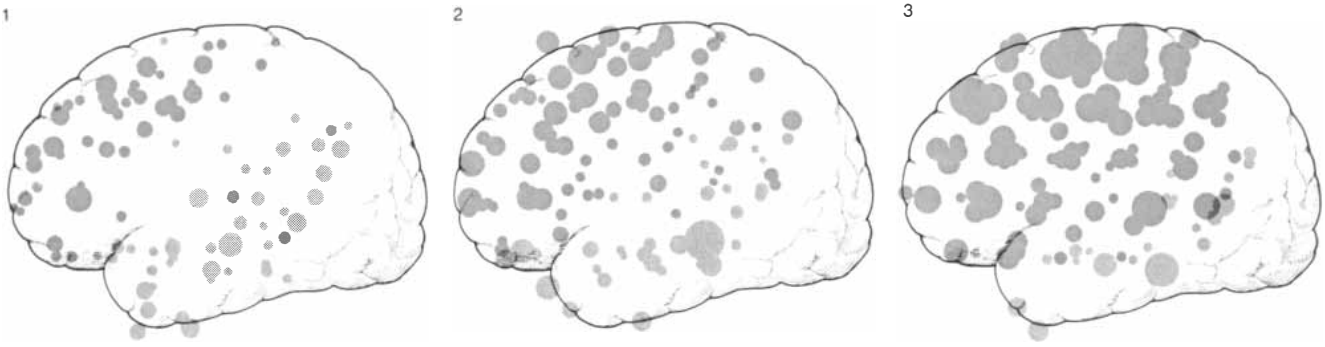
In Lund we recently studied the effects on the pattern of human cerebral blood flow of a pain stimulus: an electric shock applied to the skin. (All such experiments were of course performed with the patients' full informed consent and as a basis for clinical diagnostic tests.) When the intensity of the stimulus was low, just above the threshold, the shock was experienced much as a simple touch; when the intensity was high, the shock was experienced as a moderately painful sensation. As one would expect, the threshold stimulus did not measurably alter the mean hemispheric blood flow or oxygen uptake, although there was a small increase in regional blood flow in the front and upper parts of the frontal lobe. Moderate pain stimulation, on the other hand, gave rise to a general increase of 20 percent in the mean hemispheric blood flow and oxygen uptake, and there were localized increases above the mean in the frontal lobes. Thus touch and moderate pain appear to make the brain more aware, or more conscious.

These observations support the hypothesis that the general activation of the brain is accompanied not only by an arousal of electroencephalographic activity but also by an increase in cerebral blood flow and oxygen uptake, and that this reaction is related to an increased level of awareness. The global activation of the brain is probably also related to the emotional components of experience, although we have not yet made any systematic observations of this kind.

What will cortical mapping be like in the future? The radioactive-xenon technique (and a noninvasive variant of the technique in which the radioactive isotope is inhaled rather than injected) is a somewhat crude one. The results mainly reflect events in the superficial layers of the cortex and leave out deeper structures; moreover, the time resolution is low (minutes at the most). These limitations, together with recent technical developments, have inspired refinements of our technique. Complex multidetector instruments are now being developed for measuring the distribution of the radioactive isotope inside the head in three dimensions, so that activity in deeper parts of the brain can be analyzed.

In addition the application of radioactive isotopes to investigations of brain function has opened up the new field of regional metabolic studies. Louis Sokoloff and Martin Reivich at the National Institute of Mental Health in the U.S. have studied cerebral metabolism on a microscopic scale by injecting a radioactive analogue of glucose into the brain; the rate at which the substance is taken up by nerve cells reflects their functional activity. Such experiments have revealed that the metabolic rate within very small regions of the brain changes in consistent patterns during various activities. For example, the illumination of one eye in monkeys alters the consumption of glucose in the visual cortex in columns of nerve cells less than a millimeter apart; these functional columnar units correspond to those demonstrated with neurophysiological techniques by David H. Hubel and Torsten N. Wiesel of the Harvard Medical School. The Sokoloff-Reivich technique is now being modified for clinical purposes.

The coming generation of powerful integrative techniques and tools will set the stage for a new type of clinical neurophysiology: an era in which the regional circulatory and biochemical accompaniments to the functions of the human brain can be both precisely localized and measured quantitatively. Such methods will bring us closer to perceiving the intricate patterns of activity that underlie the functioning of the most complex of all biological systems, the human brain.



REST, TOUCH AND MODERATE PAIN appear to constitute three levels of increasing awareness. Eight subjects were studied (*1*) at rest, (*2*) during threshold electrical stimulation of the thumb and (*3*) during stimulation at 2.5 times threshold intensity, causing a moderate sensation of pain. During this sequence the mean levels of cerebral blood flow and of oxygen uptake rose progressively. The dots in color indicate flow rates above the mean; the gray dots, rates below the mean. The size of the dots indicates the magnitude of the changes.

The Upsilon Particle

Its unexpected discovery as the heaviest particle has prompted physicists to introduce a massive new quark, raising the number of these unobserved elementary subparticles from four to five

by Leon M. Lederman

The search for the ultimate, indivisible constituents of matter that began with the pre-Socratic, atomistic natural philosophers continues unabated after 2,400 years. In the past few decades the number of identified subatomic particles has risen to more than 100, as powerful machines were developed for smashing bits of matter together and studying the scattered by-products. At first physicists believed these particles could not be broken down into smaller entities. Then they found that only the four leptons (the electron, the muon and two kinds of neutrino) seemed to be truly elementary in the sense of having no measurable size and no constituent parts. The rest of the particles, the hadrons (including the proton, the neutron and the pion), turned out to be complex objects that showed signs of an inner structure. In 1964 the quark hypothesis, which has been a cornerstone of particle physics ever since, was introduced as a description of that structure. It held that the hadrons were all ensembles of only three elementary entities named quarks. An additional quark was soon postulated, for both theoretical and experimental reasons. Although none of the four quarks has ever been observed, in spite of many attempts to isolate one, there are good grounds for believing they exist.

Last year a group of investigators (of whom I was one) from Columbia University, the State University of New York at Stony Brook and the Fermi National Accelerator Laboratory (Fermilab) discovered a new particle with a mass whose energy equivalent is 9.4 GeV (billion electron volts), a mass more than three times greater than that of any subatomic entity previously identified. Designated upsilon (Y), the new particle points to the existence of a fifth quark, one more massive than any of the others. Since the original four quarks could account for all the known properties of hadrons, a fifth subparticle seems superfluous. Its existence appears to be a mixed blessing for the quark hypothesis. On the one hand it should help physicists to determine the nature of the hitherto inscrutable quark forces. On the other the very proliferation of quarks could topple the central hypothesis that they are the most fundamental constituents of matter. After all, quarks were first introduced to account for the ever increasing number of hadrons. Now it is the quarks that are growing in number, and there seems to be no theoretical reason that would block the discovery of even more massive ones.

The research that led to the discovery of the upsilon began in 1967 at the Brookhaven National Laboratory. With the 30-GeV Brookhaven synchrotron we fired energetic protons (p) at uranium nuclei consisting of neutrons and protons, collectively known as nucleons (N). We wanted to study what happened when a pair of oppositely charged leptons (l^- and l^+) emerged, a reaction that can be written $p + \mathrm{N} \rightarrow l^- + l^+ +$ anything. "Anything" means we had no interest in the other particles produced. Before I describe our experiments let me provide somewhat more background on leptons so that the reader will better understand why we worked so intensively with them for 10 years.

Leptons are distinguished from other subatomic particles in that they are not subject to the "strong" force that binds protons and neutrons together to form atomic nuclei. As a result energetic leptons have great power to penetrate matter. The neutrino (ν), for one, has no electric charge and could pass through millions of miles of lead without colliding with anything. The muon (μ), which weighs 200 times more than the electron (e^-) but otherwise exhibits identical properties, is slowed when it moves through matter by the burden of having to drag its electric charge through other electric charges. Nevertheless, because such electromagnetic forces are 100 times weaker than the strong force, the muon could penetrate many meters of iron. With a charge identical with the muon's, the electron is stopped more easily because of its smaller mass; it cannot plow its way through iron as the heavier leptons can.

The lepton pair ($l^- + l^+$) created in the reaction at Brookhaven had the same quantum properties as the quantum of electromagnetic energy: the photon (γ). This was apparent from the ease with which a photon changes into either a muon pair ($\mu^- + \mu^+$) or an electron-positron pair ($e^- + e^+$), illustrated by the reactions $\gamma \rightarrow \mu^- + \mu^+$ and $\gamma \rightarrow e^- + e^+$.

A major difference between photons and lepton pairs is mass. Whereas the lepton pair has a positive rest mass when it is regarded as a single particle moving with a velocity equal to the vector sum of the motions of its two components, a photon always has zero rest mass. This difference can be glossed over, however, by treating the lepton pair as the offspring of the decay of a short-lived photonlike parent called a virtual photon. The concept of the virtual photon also appears in other reactions where the electric and magnetic properties of matter are being examined. The laws of the conservation of energy and of momentum enabled us to routinely compute the mass, energy and momentum of the virtual parent, in spite of its evanescent nature. To determine its mass (M) we had only to measure the energy of the l^- and l^+ particles emerging from the collision. The formula $M^2 = 4E^-E^+(\sin^2\theta)$ told us that we were dealing with a massive parent whenever both the angle (θ) between the leptons and the prod-

EDITOR'S NOTE

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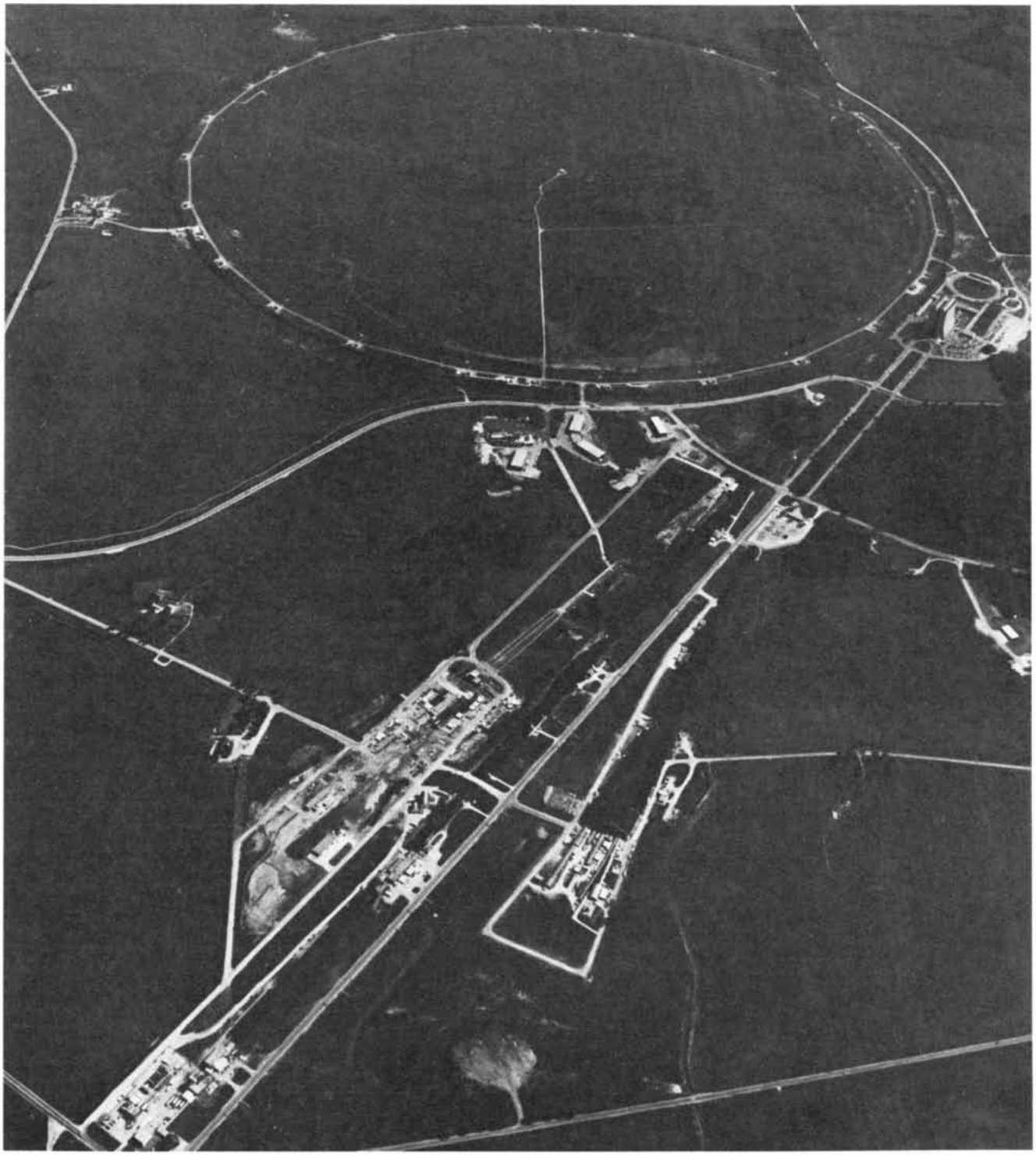
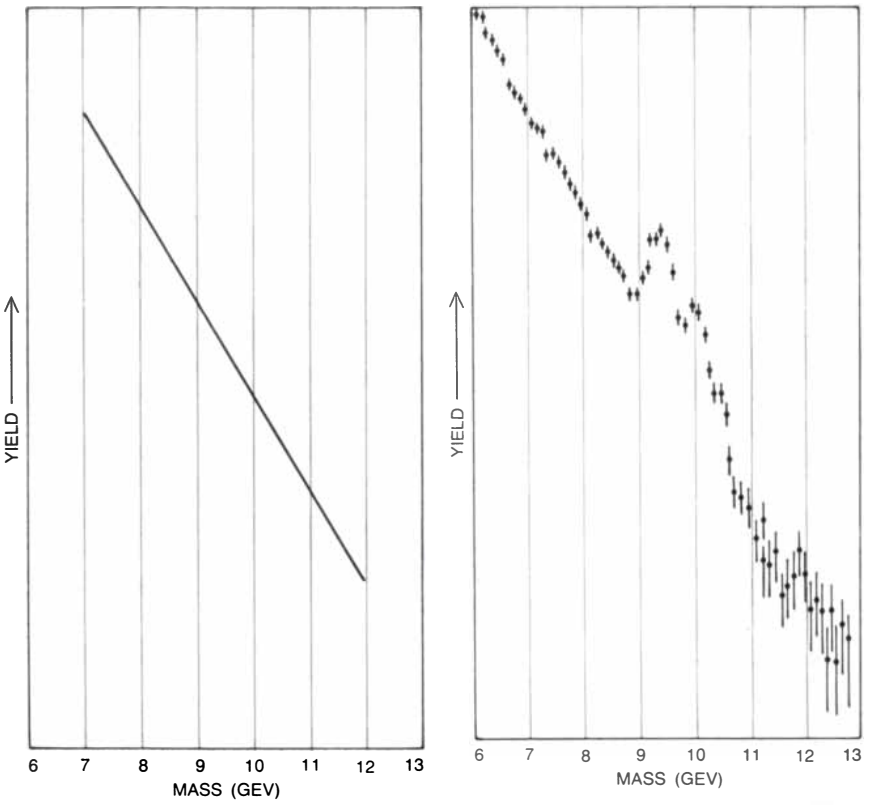
uct of their respective energies ($E^- E^+$) were large.

As long ago as 1967 we recognized in a vague and intuitive way that the emission of virtual photons could be indicative of unexplored domains inside the colliding nuclear particles. We reasoned that when an extremely energetic proton collided with a target nucleon, a highly excited and complex state would be generated. Most of the time this state would lose energy with the emission of such strongly interacting particles as pions and kaons. Occasionally, however, deexcitation would result in part from the emanation of virtual photons that would decay immediately into lepton pairs.

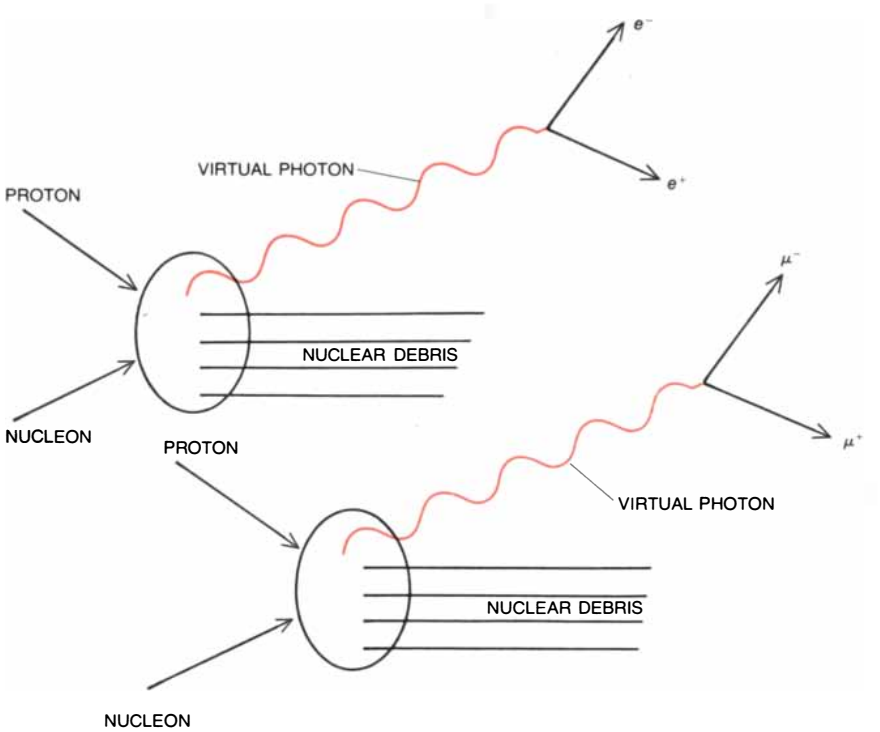
We had expected the masses of the virtual particles, as computed from measurements made on the leptons, to



PROTON SYNCHROTRON at Fermi National Accelerator Laboratory (Fermilab) was used to generate muon pairs in experiments that led to the discovery of the upsilon particle. Here the 400-GeV (billion-electron-volt) machine appears as the large circle, which has a circumference of four miles. Tangent to the circle are long tunnels that carry particles to experimental stations. The upsilon work was done in the proton laboratory, which is in the large area at the lower left that looks as if it is under construction. Fermilab stands on a four-by-five-mile tract 30 miles southwest of Chicago in Batavia, Ill. Built by the Atomic Energy Commission under contract with a consortium of 53 universities, the laboratory facilities are used by groups from all over the world. Under the direction of Robert R. Wilson the accelerator, which went into full operation at 200 GeV in 1972, was upgraded to 300 GeV in 1973 and to 400 GeV in 1974.



MASSES OF VIRTUAL PHOTONS that decayed into muon pairs were expected to be distributed continuously (*left*). This turned out to be the case, although in addition there was an unexpected cluster at about 9.4 GeV (*right*). Such a cluster, called a resonance, marked the presence of the upsilon. Vertical error bars through each data point represent the uncertainty as to where it should be plotted. The smaller the number of events, the larger the uncertainty.



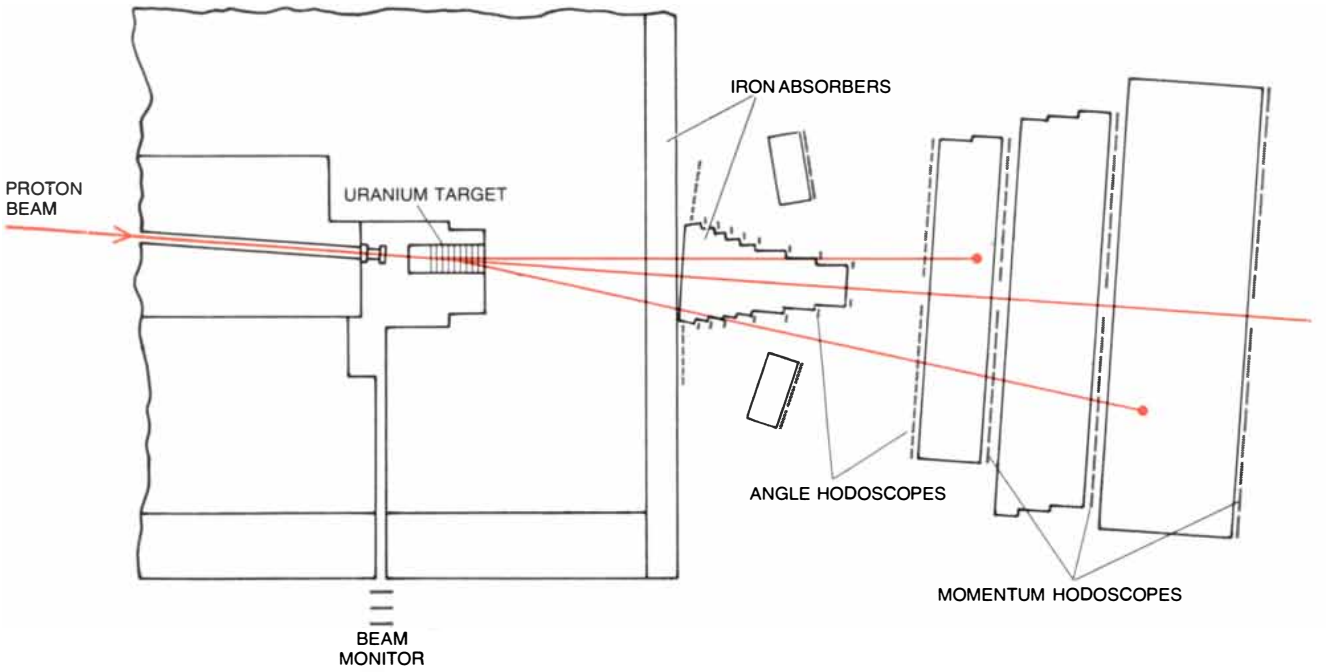
COLLISIONS BETWEEN PROTONS AND NUCLEONS (either protons or neutrons) sometimes generate virtual photons that decay immediately into electron-positron pairs (e^-e^+) or into pairs of oppositely charged muons ($\mu^-\mu^+$). The bottom reaction will require much more energy than the top reaction because the muon is 200 times more massive than the electron. The additional mass of the muon, however, will enable it to penetrate much deeper into matter. The nuclear debris from these particular reactions will have very little penetrating power.

be distributed continuously [*see top illustration at left*]. Because we had recognized that smaller masses would be easier to create than larger ones, we thought that the yield of virtual photons would fall steeply as their mass increased. Although we did not expect the mass calculations to cluster around any particular value, we hoped this would happen. Such a cluster is called a resonance. If a resonance did manifest itself, it would indicate that the lepton pairs emanated not from some virtual entity but from some real particle. On the basis of Werner Heisenberg's uncertainty principle we could then estimate the size of whatever material within the colliding nucleons had served as the source of the new particle. Heisenberg's principle suggests that the greater the particle's mass, the smaller the size of its source. This meant that if we discovered sufficiently massive resonances, we would in fact be detecting extremely small structures within the target nucleons.

Our search for such lumps within the target nucleons was undertaken in 1967 in spite of the widespread view that matter in highly excited states was smooth and homogeneous. Moreover, even if such small but massive entities did exist, our equipment might not be sensitive enough to detect them. Other experimenters had already discovered that low-mass resonances were extremely rare; in the Brookhaven accelerator a lepton pair with a mass close to that of a proton would be created only once in a million collisions. Larger masses would be produced even less frequently, and for every one produced millions of strongly interacting particles would also be produced. Our detector would have to be capable of sorting out the rare lepton pairs from the abundant background hadrons.

After much discussion we realized we could build a detection system based on the fundamental fact that leptons can penetrate matter and hadrons cannot. Since muons can travel deeper into matter than electrons, we decided to concentrate on them and to ignore any electron-positron pairs also created. That led us to put 10 or more feet of iron between the uranium target and the lepton-pair detector. The iron would absorb the strongly interacting particles but allow the muons to pass through and trip a series of scintillation counters.

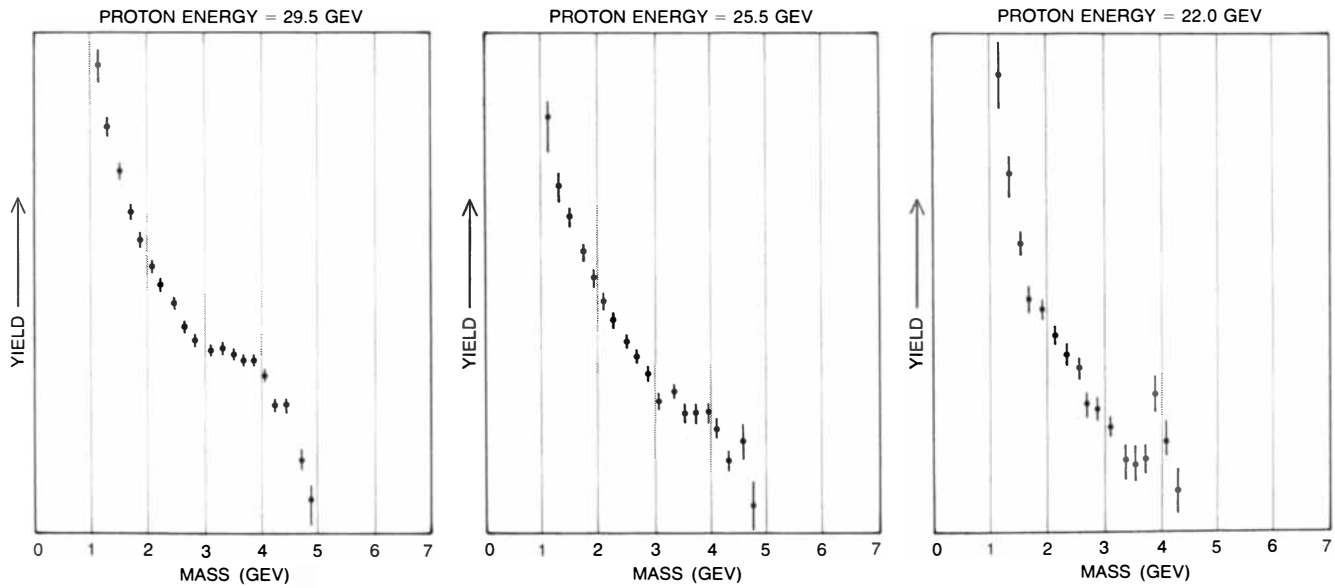
The drawback of this detection system was that it would alter the trajectories of the muon pairs. The atoms of the iron not only would decelerate the muons, causing them to lose energy, but also would push and pull on their electric charge, deflecting them from their original paths. We were therefore in a predicament. If we measured the energy and the angle of separation of the muons after they emerged from the iron absorber and used these values to calcu-



APPARATUS AT 30-GEV ACCELERATOR of Brookhaven National Laboratory generated muon pairs when protons struck uranium. The muons passed through iron that absorbed unwanted nuclear debris. Hodoscopes measured the muons' angles and momentum.

late the mass of their virtual parent, we would get an inaccurate answer. Yet we could not make a more accurate calculation by looking at the muons before they entered the absorber because at that point the enormous flux of hadrons would interfere with the counters. At this early stage in our work we were not too concerned about having to settle for an imprecise calculation. The goal was to detect heretofore unseen resonances at high masses, and we believed our apparatus would do this even though it would also distort the characteristics of such resonances. That would be a small price to pay if we could discover a new particle.

We began collecting data in the fall of 1968. A digital computer processed the information and drew a graph of the yield of muon pairs observed at each mass. Since we were studying an unexplored reaction, we had no idea what the distribution would look like. Nevertheless, we were startled by the drop that began at about 1.5 GeV, flattened out just above 3 GeV and then plunged precipitously at the upper limit of our detection system, where we were not able to collect much data [*see illustration below*]. This "shoulder" excited us. We wondered if it could represent a sharp resonance that was smeared by our crude apparatus but marked the presence of some new particle. When we lowered the energy of the bombarding protons, the shoulder would not go away. That was a good sign. It meant that the curious distribution was probably not the spurious result of some undetected quirk in the equipment. The



UNEXPECTED "SHOULDER" in the masses of the virtual photons generated at Brookhaven would not go away when the energy of the bombarding protons was lowered from 29.5 GeV (*left*) to 25.5 GeV (*middle*) and then to 22.0 GeV (*right*). This result suggested that the shoulder was real, perhaps the poorly resolved resonance of a new particle and not the counterfeit product of apparatus malfunction.

burden of proof, however, was still on us. We could not completely dismiss the possibility that the distortion effects of the apparatus might be so overwhelming that they had spuriously warped the low-energy distribution as well. Moreover, we had to consider the possibility that the shoulder might be a peculiar characteristic of the smooth distribution of virtual photons rather than the smeared resonance of a new particle.

Tentative as our uninterpreted results were, theoreticians took an immediate interest in them because they seemed to relate to the quark hypothesis. The original hypothesis of 1964 suggested that all known hadrons were composed of three quarks, labeled *u*, *d* and *s* (for "up," "down" and "strange"), and three corresponding antiquarks, $\bar{u}$, $\bar{d}$ and $\bar{s}$. Although the original quark model beautifully and simply accounted for the static properties of the more than 100 hadrons, it did not describe their dynamical properties. By 1968, however, pioneering workers had used the quark model to explain scattering data and collisional processes. The main difficulty with their explanation was its lack of uniqueness: reasonable alternative hypotheses that did not incorporate quarks could account for the dynamical characteristics just as well.

Our lepton-pair data turned out to provide a considerable boost to the quark explanation of hadron dynamics. In 1970 two Stanford University physicists, Sidney D. Drell and Tung-Mow Yan, tried to use a quark model to generate our lepton-pair results theoretically. Their predictions matched our data fairly well near 2 GeV but fell below them near 3 GeV. Encouraged by this partial correlation, by the intriguing possibility of clustering and by the tremendous interest of theorists in our results, we decided to run an improved version of our experiment on the more powerful accelerator at Fermilab. The accelerator's tremendous energy, which was at that time 300 GeV, would increase the probability of pair emission at 3 GeV, and we hoped this would finally enable us to identify the significance of the mysterious shoulder.

Then in 1974, before we began taking data, the three-quark model was overthrown by what was called "the November revolution." The discovery of a new particle was independently announced by Samuel C. C. Ting of Brookhaven and the Massachusetts Institute of Technology and by Burton D. Richter of Stanford. At Brookhaven the new particle, which was named by Ting *J* and by Richter ψ (psi), showed up as a spectacular enhancement in the masses of virtual photons that had decayed into electron-positron pairs [*see illustration on page 78*].

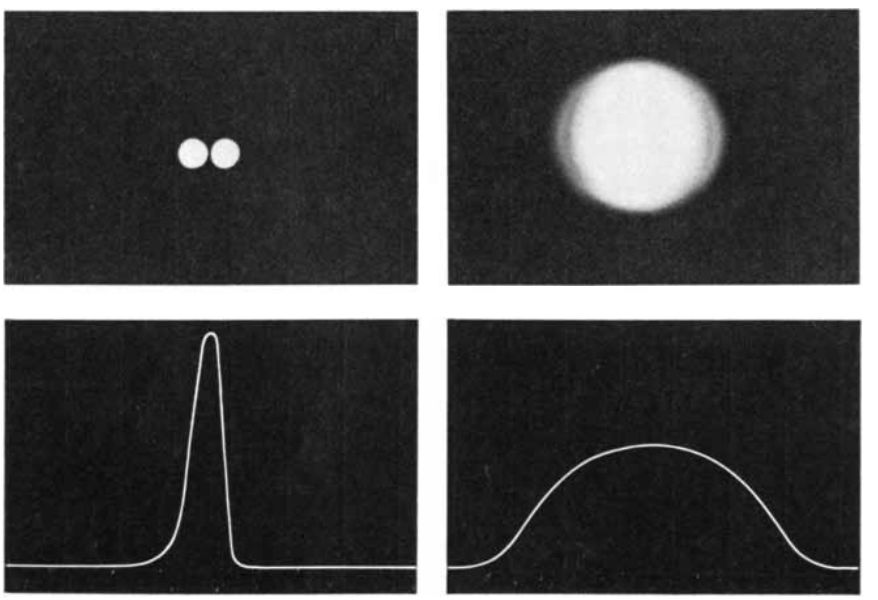
The discovery of the J/ψ resolved several significant problems in particle physics. It explained our lepton-pair data, and it suggested the existence of a fourth quark, designated *c* (for "charm," the new quantum-mechanical property it implied). The shoulder we had seen in 1968 was now interpreted as being a badly smeared version of the J/ψ's narrow enhancement at 3.1 GeV. The revolutionary aspects of the J/ψ lay in this very narrowness. According to Heisenberg's uncertainty principle, a narrow, or well-defined, mass implies a lifetime that is long compared with that of most other subatomic particles. And a long life span meant that the J/ψ was inhibited from decaying into such particles as pions and kaons. The existence of a fourth quark could explain why this was so. Since quarks are truly fundamental, one kind of quark cannot easily turn into another. If the J/ψ's were made up of only the charmed quarks, they could not easily decay into pions and kaons, which are made up of only the other three quarks. Subsequent investigations supported the interpretation of the J/ψ as a bound state of a fourth quark and its antiquark. The concept of a fourth, charmed quark was further confirmed when particles were discovered that seemed to consist of various combinations of all four quarks.

A comparison of our shoulder distribution of 1968 and the J/ψ data of 1974 bore out our conviction that what we had gained in sensitivity we had lost in resolution. We had detected more than 10,000 muon pairs with our highly sensitive apparatus, but we could not interpret the smeared distribution. The discoverers of the J/ψ at Brookhaven, on the other hand, used a new generation of particle detectors to find only 242 pairs, but because their apparatus could locate the positions of the pairs on the mass scale with greater accuracy they saw a highly resolved, narrow peak.

Now that the mystery of the shoulder had been solved, we decided to use the new Fermilab accelerator to look for resonances in the unexplored mass range above 5 GeV. In 1975 and 1976 we observed hundreds of events in three lepton-pair runs. The energy of the Fermilab accelerator had been boosted to 400 GeV, an increase that would turn out to be crucial for our work. This time we could monitor the distorting effects of our apparatus by examining how it altered the J/ψ resonance, which we could not have done in 1968. We also had years of experience with muon pairs and of progress in detector development that we could put to good use.

In February of last year our group began to assemble a new version of the lepton-pair experiment utilizing what we had learned over the preceding two years. We realized that in order to draw any conclusions about the rarer, higher masses we would have to observe many more events. At the same time we would have to improve the resolution or we would be confronted with the same kind of uninterpretable data we had collected in 1968.

John Yoh of Columbia had noticed a small number of events near 9.5 GeV in our 1976 results. He put a bottle of Moët champagne, labeled "9.5," in our group's refrigerator. This convinced no one that we were on the track of a new particle. We were nonetheless encouraged in our search by the fact that our data were unique: no one else had ever seen 350 lepton pairs with masses



PROBLEM OF POOR RESOLUTION in high-energy experiments is illustrated by comparing photographs with curves of experimental results. An unfocused camera can make two lights (*top left*) appear to be one (*top right*). The Fermilab apparatus made the J/ψ particle's narrow resonance (*bottom left*) look broad (*bottom right*). A computer helped to clarify the distortion.

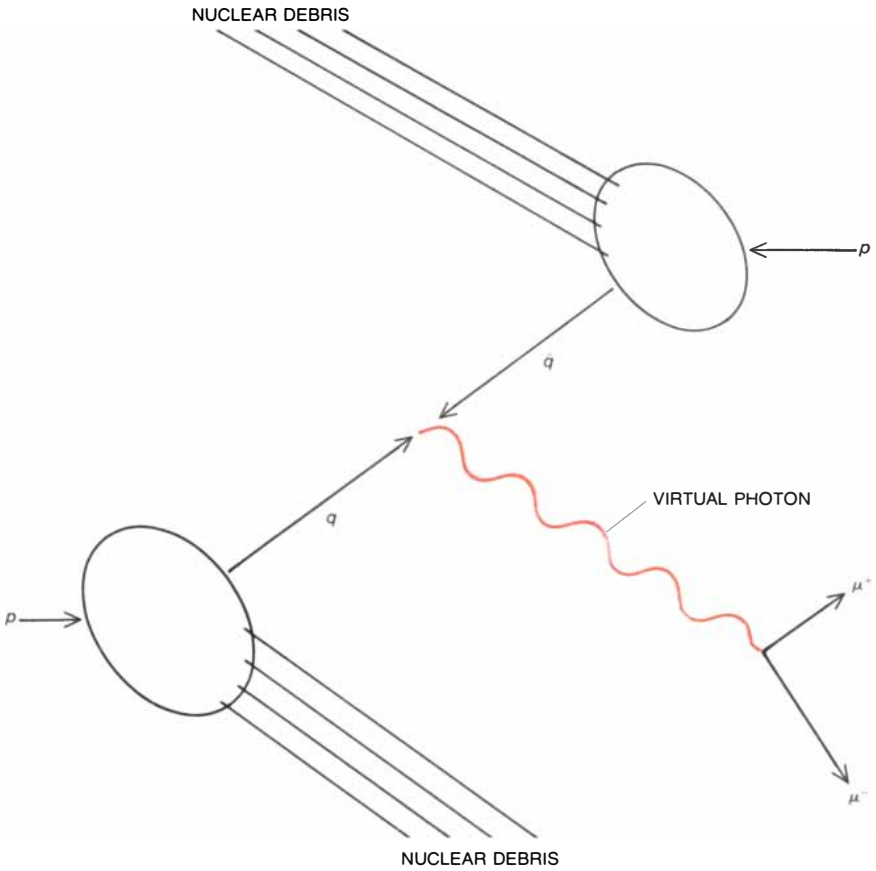
greater than 5 GeV. There might just be something there—somewhere.

Experience showed we could move the detectors closer to the target so that more muon pairs would reach them. Stephen W. Herb of Columbia had predicted correctly that this would not also increase the enormous flux of hadrons interfering with the detection system. In 1968 we had used iron to absorb the unwanted particles, but the iron atoms, with their 26 protons and 26 electrons, exerted an electromagnetic force on the muons that deflected them from their original paths. As a result the masses of the muons could not be accurately calculated. This time we would use the metal beryllium as the principal absorber. With only four protons and four electrons, the beryllium would hardly deflect the muon pairs, although it would still be able to screen out most of the hadrons.

One major obstacle remained. Muons are treacherous particles. As I have mentioned, they can easily penetrate many meters of iron. We needed absolute assurance that our muon pairs were honest: that they had been born in the target and had proceeded undeviated and unscattered through a large deflection magnet and into our counters. To gain this assurance we wanted to put a detector in the middle of the magnet. This proved difficult (it was somewhat like designing a delicate and precise watch to operate inside a blast furnace), but Walter R. Innes of Fermilab came up with a successful design. Still, we were not satisfied with the setup. The events of greatest interest were also the rarest ones. Over a long day with more than 10 billion nuclear collisions per second extremely improbable happenings could conspire to spoof the experiment. To guard against this possibility Charles N. Brown of Fermilab designed a simple magnetic system that would remeasure each muon's energy after it emerged from the main detector.

On May 1 of last year we gathered our first data. We were elated to find that our improved apparatus registered 90 times more muon pairs than it had the year before. The upgraded accelerator had functioned superbly, supplying unlimited quantities of protons with needle-sharp precision. In the first week we observed 3,000 muon pairs with energies higher than 5 GeV, more than 10 times the rest of the world's data and of much better quality. We graphed the results, and they seemed remarkably free of the interfering effects of hadrons. The J/ψ resonance showed up clearly, which meant we had succeeded in increasing the resolving power of our apparatus. Our excitement rose to a high pitch when we saw that the steady decrease in the yield of muon pairs, as they became more massive, was interrupted near 10 GeV by an intriguing bump.

The following week we doubled our data and still the bump remained. Although we could no longer dismiss it as a misleading happenstance, we wondered if it could be the wayward product of some undetected idiosyncrasy of our apparatus. Perhaps the deflecting magnets or the counters had malfunctioned. Fortunately we had mechanisms for checking that out. We looked separately at each square centimeter of the detector's surface to see how the muons that struck each area were distributed. Everywhere we found smooth distributions, indicating that the apparatus had not generated the resonance. Moreover, when we artificially mixed Monday's μ^+'s with Tuesday's μ^-'s to form fake $\mu^+\mu^-$ pairs, we got a perfectly smooth distribution that conformed to all our expectations about how the equipment worked. As the apparatus passed other tests and as we accumulated more data we became convinced that the resonance represented something real: a new particle with a mass of 10 GeV. Although we wanted to keep our results secret until we could fully interpret them, rumors of our discovery spread rapidly throughout the physics community. Therefore on June 20 we made our data public: 26,000 pairs, almost 100 times the data of all previous experiments combined. We named the particle upsilon.



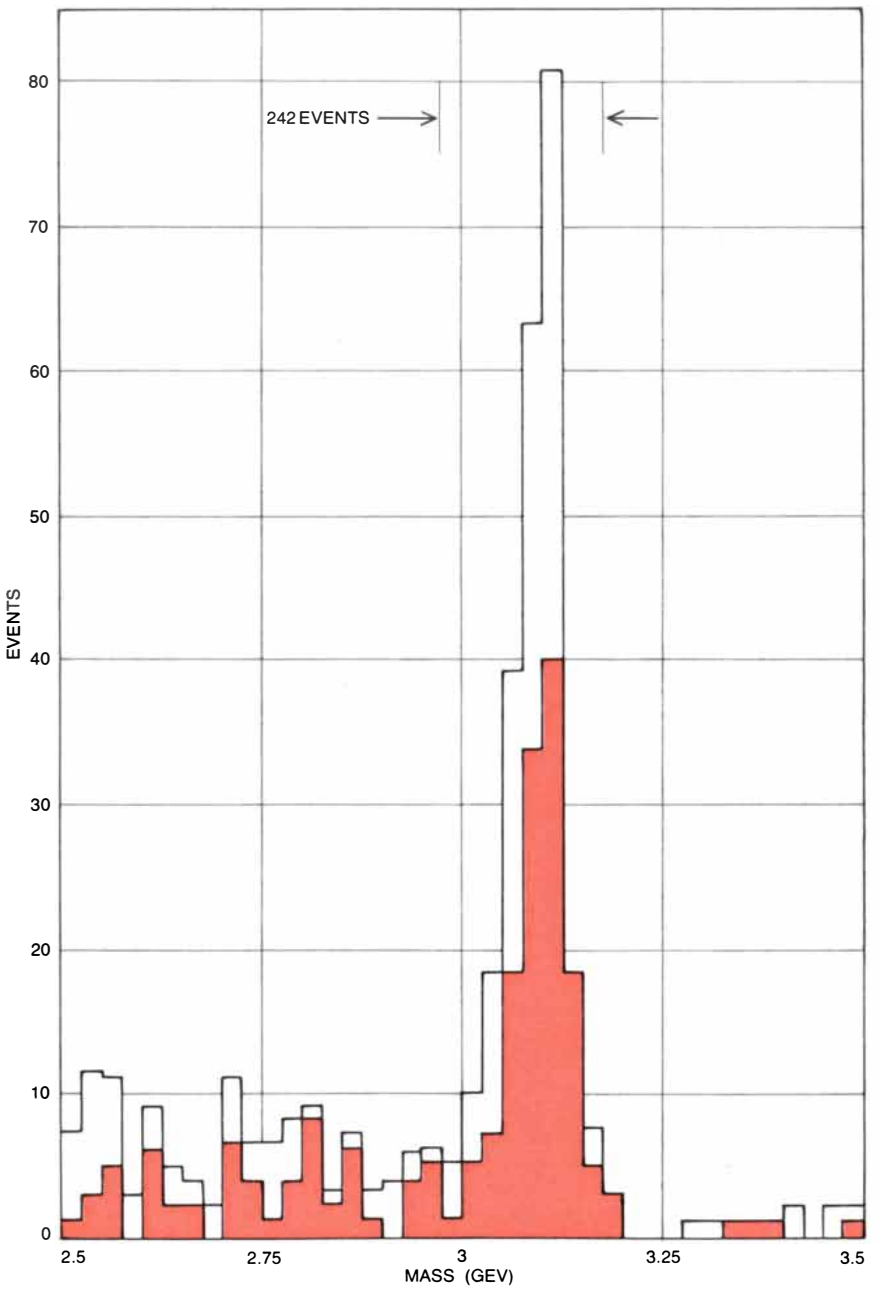
QUARK MODEL, although introduced to explain the static properties of particles, can also account for such dynamical processes as the creation of muon pairs. Sidney D. Drell and Tung-Mow Yan of Stanford University proposed that a virtual photon that decays into a muon pair is formed when a quark (q) from the bombarding proton and an antiquark ($\bar{q}$) from a quark "sea" associated with the target nucleon annihilate each other. Drell and Yan tried to predict the Brookhaven data, succeeding fairly well at masses near 2 GeV but not with those near 3 GeV.

We next set out to determine the width of the resonance, using the same method by which the span of the J/ψ resonance had been calculated. In effect the width is the uncertainty in the mass of the resonance, and Heisenberg's principle associates a narrow peak (a small uncertainty) with a long lifetime, and a broad peak (a large uncertainty) with a short life span. After we had gathered more data we found that the resonance consisted of two closely spaced peaks (with a suggestion of a third) 600 MeV (million electron volts) apart and each peak 500 MeV wide. This indicated that the upsilon could exist in two and perhaps three states of slightly different energies. Before we concluded from these width values that the resonance of the upsilon was intrinsically narrow we needed to take into account the distortion effects of the inevitably imperfect apparatus. Apparatus with a low resolving power will make nature's peaks look broad, much as a camera lens of poor quality will blur the fine details in a photograph. In our Brookhaven experiment of 1968 poor resolu-

tion had distorted the data to the point where they were uninterpretable.

To determine how the Fermilab apparatus had deformed the shape of the resonance we relied on a game-theory approach in which a computer simulated our entire experiment. Such simulations, called the Monte Carlo method, are ubiquitous in high-energy physics. In our case the computer, programmed to know the location and function of each piece of our apparatus, selected a configuration of two muons and traced their trajectories to the final detector. If the computer program called for the muons to encounter an absorber consisting of, say, beryllium, the program would call for the muons to be scattered just as if the muons and the beryllium were real. The computer we used was a powerful one, so that the simulation could trace tens of thousands of muon pairs through the apparatus.

We then graphed the mass distribution of the Monte Carlo events and discovered that the simulated upsilon resonance was much narrower than the measured one. This suggested that the measured width was produced mainly by the apparatus. Complex computer programs do, however, have bugs. Had we caught them all? Perhaps the simulation was wrong and the resonance was actually as broad as the one we had measured. Fortunately we had ways of eliminating that possibility. Since we already knew how our apparatus had distorted configurations such as the J/ψ resonance, we could test the Monte Carlo program to see whether it correctly revealed such distortions. Indeed it did, and we confidently concluded that the width of the upsilon resonance was less than 100 MeV. This extremely narrow width indicated that our new particle had a very long lifetime.



J/ψ PARTICLE was discovered in 1974 as a narrow resonance in the masses of virtual photons that decayed into electron-positron pairs. The colored distribution represents the yield of masses obtained when the detection spectrometer was run with the bombarding particles at a normal intensity; the white distribution, the yield when the intensity was cut by 10 percent. The resonance at 3.1 GeV, which showed up clearly in both runs, was interpreted as a highly resolved version of the shoulder found at Brookhaven in 1968. The J/ψ particle pointed to the existence of a fourth quark, labeled *c* for "charm," and a corresponding antiquark, labeled $\bar{c}$.

One would normally expect that a particle with a mass as great as 10 times the mass of the proton should have an enormous number of lower mass states into which it could decay, each state contributing to a shorter lifetime. But contrary to expectations the upsilon, the heaviest particle ever discovered, has a long lifetime. This means that it does not decay into the less massive hadrons, all of which are composed of *u, d, s* and *c* quarks. At the time of our discovery last year, however, the known laws of physics could not explain why this was so. The conclusion was clear and exciting: some new law of physics forbids (or, more precisely, inhibits) the upsilon from decaying into ordinary hadrons.

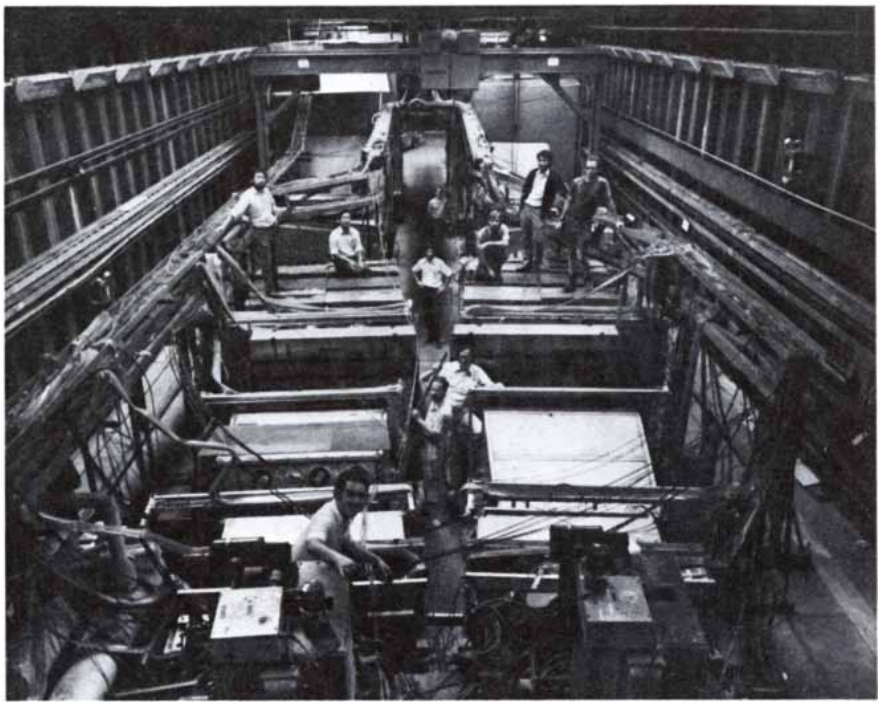
In search of this new law we looked to see if any work in theoretical physics had anticipated our discovery of the upsilon. Over the years many theorists have suggested the existence of new particles to account for puzzling data, and we wondered if the upsilon could be one of those that had been proposed.

The only reasonable candidate was a new, massive quark bound to its antiquark in atomlike configurations that would show up as a closely spaced set of masses having many features of the upsilon. The theoretical papers that raised the possibility of such a quark were speculative discussions appealing to aesthetic prejudices. One group of papers hoped the existence of a new quark would be able to account for some curious results of certain neutrino-scattering experiments. Our best calculations, made early this year, indicate that the upsilon has resonances at 9.4, 10.0 and 10.4 GeV [*see top illustration on page 80*]. A particle made up of a fifth quark and its antiquark might exist in a ground state, or lowest state, at 9.4 GeV and in excited states at 10.0 and 10.4 GeV. Moreover, the existence of a fifth subparticle would neatly account for the long lifetime of the upsilon, just as the fourth quark had accounted for the long life span of the J/ψ. If the upsilon consisted only of the fifth kind of quark, it could not decay into ordinary hadrons, which consist of various combinations

of only the other four quarks. Such compelling considerations convinced most particle physicists that the upsilon is indeed an atomlike composite of a fifth kind of quark bound to its antiquark.

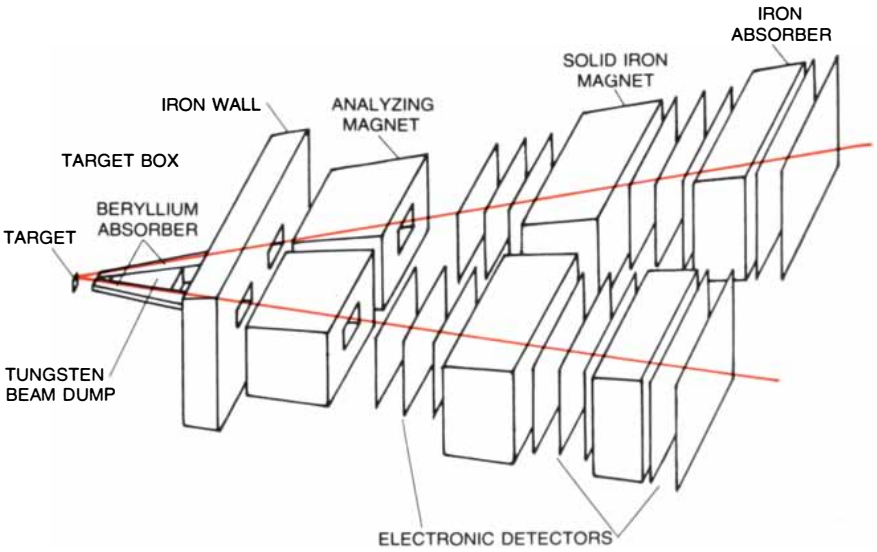
An amusing thing about the hypothesis of a fifth quark is that the reasons for which some theoretical papers introduced it turned out later to be specious. The new subparticle was supposed to explain puzzling data from scattering experiments, which on closer examination proved not to be puzzling at all. Where the fourth quark had accounted for all kinds of enigmatic phenomena, the fifth quark explained only the results of our experiment. The misinterpreted scattering data had nonetheless served a valuable heuristic purpose in stimulating speculation about the properties of particles composed of heavier quarks, properties the upsilon turned out to have. The fact that the four identified quarks were paired off as "up" and "down" and as "strange" and "charm" had led theorists to predict that if there were a fifth quark, there would also be a sixth. The eccentric names "top" and "bottom" or "truth" and "beauty" had been reserved for the two new quarks in the event they were discovered.

The upsilon resonances present physics with an embarrassment of riches: an unexpected family of new particles composed of an unexpected fifth quark. The impact of the upsilon has already been far-reaching. It has prompted searches for other heavy particles in hitherto unexplored ranges of mass, and it has shed light on the inscrutable strong force. This force, which binds quarks together into hadrons and hadrons together into atomic nuclei, is too powerful to investigate by conventional scattering and collision techniques. Yet any proposed model of the strong force, being a description of the force between a quark and an antiquark, should correctly predict the energy (or mass) levels of the upsilon family. With the upsilon, as opposed to the hadrons of lower mass, it is easier to evaluate these predictions because the velocities of massive quarks are comparatively low. This means that complicated relativistic considerations never enter the calculations. The predictions of several such theoretical models have failed, which removes them from consideration. The successful models all suggest that the new fifth quark has a charge of $-1/3$ (the charge of the electron being -1) and that the force between quarks increases with the distance between them. Such a force had been proposed to account for the failure of particle physicists to observe quarks in the free state: so much energy is needed to increase their separation that when energy is supplied, it goes into creating new quark pairs rather than into splitting old ones. The current thinking is that quarks may be permanently confined to composite structures.

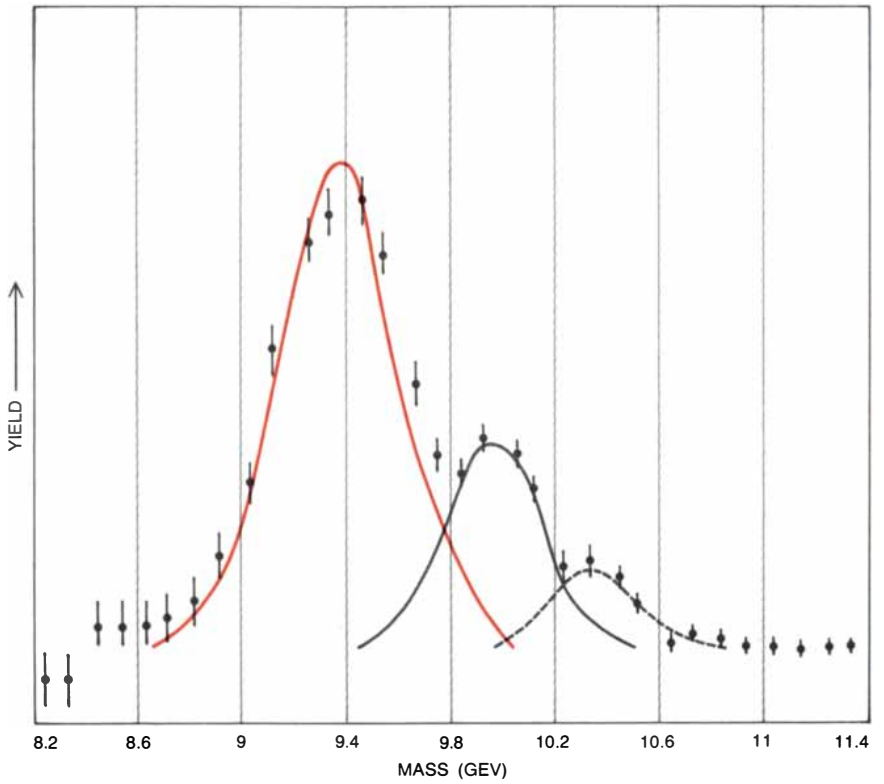


FERMILAB APPARATUS detected the upsilon. The bombarding protons and the target nucleons collided at a point just out of sight in the foreground. The electromagnets, located at the left and the right in front of the man in the foreground, deflected the muon pairs so that their energies and separation angles could be measured. The two components of each muon pair traveled through different arms of the detectors. Six feet wide, six feet high and 100 feet long, the two arms extend from the electromagnets to where the man in the rear is standing.

The confirmation of this suggestion and a better understanding of the strong force may not come, however, from the study of upsilons created in proton accelerators, such as the ones with which we worked at Brookhaven and Fermilab. The production process is too complex. For example, the initial collision at Fermilab involves three quarks in the proton projectile smashing into three quarks in the target nucleon. The next step in the demystification of quark forces will come when physicists are able to intensively study upsilons that have been produced in storage-ring machines in which electrons and positrons circulate in opposite directions and collide with one another. These machines will provide cleaner and more highly resolved data. Indeed, they already have.



BERYLLIUM ABSORBER was used to screen out nuclear debris in the Fermilab experiment because beryllium affects the trajectories of muons much less than iron does. The tungsten beam dump collected bombarding protons that missed the target nucleons. This schematic diagram is a side view of the apparatus seen head on in the photograph at the top of the page.



THREE CLOSELY SPACED RESONANCES characterize the upsilon. With a lowest state at 9.4 GeV and excited states at 10.0 and 10.4 GeV, the particle was interpreted as consisting of a massive fifth quark bound to its antiquark. The upsilon's spectroscopy will be clarified by experiments with storage-ring accelerators, and the search for a sixth quark has already begun.

In April a group of workers at the DESY (for Deutsches Elektronen Synchrotron) laboratory in Hamburg modified their electron-positron storage ring to look for the upsilon. They found it at 9.46 GeV and were able to place an upper bound of 7 MeV on the width of its resonance. (This is a substantial improvement on our value of 100 MeV.) Their data also suggest a $-1/3$ charge. The spectroscopy of the upsilon system will surely be worked out in detail over the next few years when powerful new storage rings are completed at Hamburg, Stanford and Cornell University. Physicists will be looking for the sixth quark, the expected mate of the fifth, and they will be searching for particles made up of combinations of the six quarks.

PARTICLE	SYMBOL	MASS (GEV)
PHOTON	γ	0
NEUTRINO	ν	0
ELECTRON	e	.0005
MUON	μ	.105
PI MESONS	π^0	.135
	$\pi^{\pm}$	.140
K MESONS	$K^{\pm}$	.494
PROTON	p	.938
NEUTRON	n	.940
PHI	ϕ	1.020
LAMBDA	Λ	1.116
CHARMED MESONS	D^0	1.863
	D^+	1.868
CHARMED LAMBDA	Λ_c	2.260
J OR PSI FAMILY	J/ψ	3.098
	ψ'	3.684
UPSILON FAMILY	Υ	9.4
	Υ'	10.0
	Υ''	10.4

PARTICLE MASSES are listed in ascending order. The upsilon, with a ground-state mass equivalent to an energy of 9.4 GeV, is the heaviest particle yet discovered. It is three times heavier than the J/ψ, which is the second most massive particle, and 19,000 times heavier than the electron. Particles incorporating quarks of a sixth kind would weigh more than the upsilon.

As accelerator techniques advance, physicists will undoubtedly continue to discover new subatomic entities. The proliferation will raise deep, unsettling questions. Are the kinds of quark limited in number? If there are six, why not 12? If there are 12, why not 24? And if the number of kinds of quark is large, does it make sense to call the quarks elementary? The history of science suggests that the proliferation of physical entities is a sign the entities are not elementary. The chemists of the 19th century reduced the apparently infinite variety of chemical substances to some 36 elements, which escalated over the years to more than 100. As indivisible, ultimate constituents of matter the chemical elements simply proved to be too many. In the 1930's it was discovered that all the elements were made up of electrons, protons and neutrons. After World War II these particles were joined by dozens of others: pions, kaons, lambda particles and so on. Again there were too many. Then it seemed that all of these could be reduced to three quarks. Now experiments indicate that a fourth and a fifth quark exist. Are they also too many? Will simpler structures from which quarks are made soon be proposed? Is it possible that there are no elementary particles at all, that every entity in nature has constituent parts? Or will the ultimate simplicity that most physicists believe in be lodged in the mathematical groups that order the particles rather than in truly elementary objects?

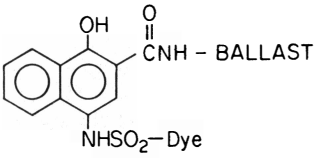
Putting aside these last highly speculative ideas, most physicists despair of addressing such questions because of the difficulty, if not impossibility, of examining a quark in isolation. Yet the experience with the upsilon particle indicates that in spite of this difficulty detailed knowledge of the motions and forces of quarks can be acquired. The apparent inseparability of these entities should not in itself block the path of inquiry. Consider the lesson physicists should have learned from the electron. The development of the theory of the electron would probably have been slowed but not otherwise hampered if electrons had only been observed bound in atoms and never in the free state. This is an experimentalist's response to the prophets of gloom who view the confinement of quarks as an ultimate limitation on knowledge: a wall erected by nature to hide its last secrets forever. And who is to say that physicists will never build an ultrapowerful accelerator that could overcome the confining force and liberate the quark?

Hammett's sigma values helped

Now that well over a million Kodak instant cameras are out working, word of the color performance of Kodak instant print film PR-10 is getting around. Organic chemistry students doing academic exercises based on the Hammett equation and wondering where it all leads may be heartened by the kind of talk that went on in the Kodak Research Laboratories when the three image dyes for this film were being designed.

Just like the teams who worked on each of the many other segments of the project, the folks who had to come up with the image dyes considered *theirs* the most crucial and toughest.

The concept called for a set of dye releasers—compounds to be oxidized by an electron transfer agent—no longer called a developer because it recycles—donating electrons to neutralize Ag^+ and regenerating itself by taking electrons from the dye releaser,



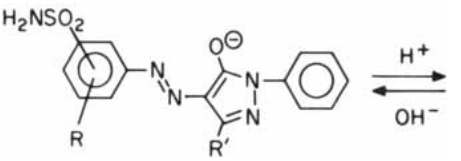
The oxidation in a highly alkaline environment releases the ionic entity $\bar{N}HSO_2$-Dye. This entity must survive unchanged through a pH range of 14 to 4, diffuse quickly through several gelatin-based layers, make its way past a gaggle of other chemical species that are there for various jobs, and attach itself firmly by ionic bonds and van der Waal's forces to a polymeric cationic mordant in the receiving layer. The negative charge that spreads over the combination as a whole of the sulfamoyl group and the π-electron cloud of the chromophore it has in tow is the key both to the mobility and to the final immobility.

A seminal paper by L. P. Hammett appeared in 1935 in *Chemical Reviews* 17:125. It did much to make the phenomena of organic chemistry quantitatively predictable, bringing order to masses of empirical data about the effect on reaction rates and equilibria of a given substituent in the meta- and para-positions on an aromatic nucleus. The relationship that pulls things together rather well is

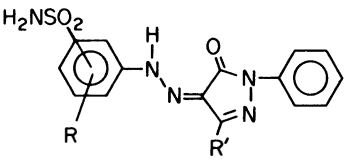
$$\log \frac{K}{K_0} = \rho\sigma$$

where, for specified reaction conditions, K is the equilibrium constant for an aromatic reactant, K_0 the constant for benzoic acid so substituted, ρ a constant that characterizes the reaction, and σ one that characterizes the behavior of that substituent in the meta- or para-position as the case may be. The σ-value then turns out to be interpretable as the tendency of the substituent to push electrons toward the reaction site or draw them away, according to whether σ is negative or positive respectively. That being the case, one might expect σ-values to help predict not only ease of ionization but also shifts in absorption maxima. Both, of course, were vital to our endeavor.

Cross-purposes between hue considerations and ionization ease came to a head in selecting R and R′ for our yellow dye:

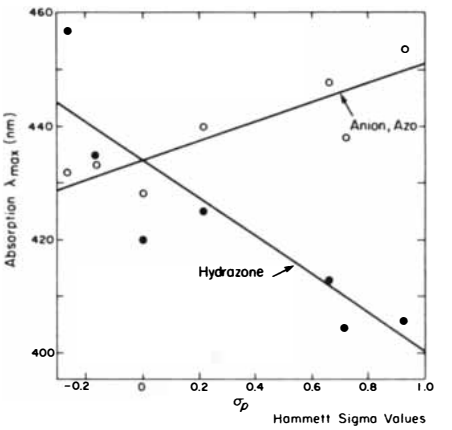


azo anion



hydrazone

Plots like the following showed us that loss of the ionic state could shift hue badly:



As any organic major struggling with a Hammett question on an exam can plainly see, such plots also show that choosing the substituents for σ-values near the intersection of the two lines would avoid such troubles.

Nice, but to show the colors we have to know where the electrons are.

The man who simplified housing bought a Honda Civic.

You can imagine our feeling of satisfaction when we discovered that R. Buckminster Fuller had walked into Darling's Honda in Bangor, Maine, and bought a Honda Civic® CVCC® Hatchback.

Buckminster Fuller is, after all, one of history's most original and prolific thinkers. As an architectural engineer, philosopher, mathematician, and educator, he has spent over half a century finding simple, economical ways to improve our lives.

What's more, he knows a good deal about automobiles, having owned 43 different cars over the years.

Of course, you may know Bucky Fuller best for his masterpiece of simplicity, the geodesic dome. This ingenious structure is one of the strongest and most efficient means of enclosing space yet devised by man. More than 150,000 geodesic domes have been built, ranging in size from small dwellings to a railroad roundhouse big enough to cover a football field.

Which brings us back to the subject of automobiles. In 1933 Bucky Fuller designed and built the Dymaxion Car. It rode on three wheels and steered by a single wheel in the rear. This design made it highly maneuverable and easy to park. It even had front-wheel drive. Sound familiar?

Here's what he told us about his Honda Civic CVCC: "Its handling feels better to me than any other car I've ever owned—except my Dymaxion."

There. Isn't that nice? And isn't it wonderful when someone like Buckminster Fuller appreciates what we've done.

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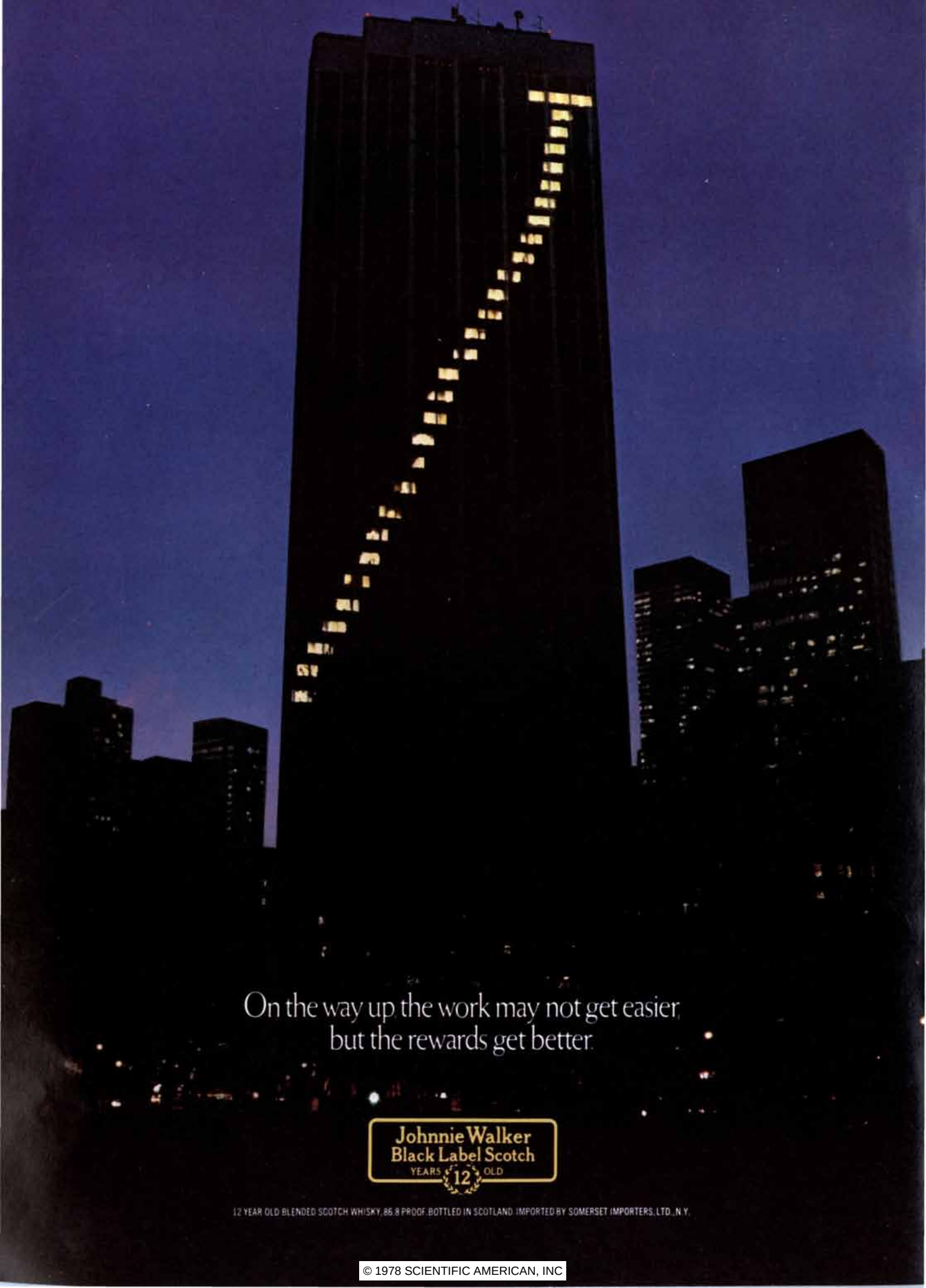

SCIENCE AND THE CITIZEN

Expenditures and Transfers

A recent study by the U.S. Arms Control and Disarmament Agency, *World Military Expenditures and Arms Transfers 1967–1976,* documents what almost everyone knows: the nations of the world steadily spend more money on arms and the international traffic in arms grows even more rapidly. The new report, the tenth in a series, for the first time introduces social indicators that make it possible to compare military outlays with, for example, expenditures for education or for public health. The report also makes it possible to compare, per 1,000 population for each country, the number of people in uniform with the number of teachers or physicians. Among some of the indicators there are hopeful signs.

For the world as a whole military expenditures, in constant dollars, increased 19 percent from $319 billion in 1967 to $380 billion in 1976, a growth rate that almost exactly paralleled the growth in world population, which increased 18.4 percent. The gross product of all the nations, however, increased more than twice as rapidly, so that the fraction of the gross product spent on arms actually declined from 7.1 percent to 5.8. Nevertheless, among the developing countries the increase in arms outlays virtually kept pace with the increase in the gross product: both rose 78 percent. The fraction of the gross product spent on arms therefore remained constant at 6.3 percent.

In the 10-year period ending in 1976 the nations of the North Atlantic Treaty Organization (NATO) decreased their annual military spending by 14.5 percent from $171 billion to $147 billion, representing a drop from 7.1 to 4.6 percent in the fraction of a sharply rising gross product spent on arms. In the same period the nations of the Warsaw Pact increased their annual military spending by 51 percent from $92 billion to $139 billion, representing a rise from 10.7 percent to 11 percent of the gross product spent on arms. Over the 10-year period, however, the NATO nations outspent the Warsaw Pact nations by a total of $412 billion.

The 1976 world military outlays of $380 billion were 11 percent higher than the $343 billion spent on public education and nearly 2.5 times higher than the $157 billion spent on public health. Over the 10-year period, however, expenditures for education and public health grew respectively by 70 and 88 percent, or roughly at four times the world rate of arms expenditures. In the developing nations annual expenditures for both public education and public health doubled over the 10-year period, slightly exceeding the growth rate in arms budgets. Over the same period the developing nations showed a sharp rise in the number of teachers per 1,000 population from 2.8 to 3.8, and a slight increase in the number of physicians per 1,000 from .17 to .19. In the developed nations the 10-year increases per 1,000 were from 9.9 to 11.4 in the number of teachers and from 1.56 to 1.68 in the number of physicians. For purposes of comparison in 1976 the number of people in military uniform per 1,000 was 10.1 in the developed nations, down 15 percent in 10 years, and 4.97 in the developing nations, up about 6 percent.

Not surprisingly much of the world's growth in military expenditures for the decade 1967 through 1976 was made possible by an even more spectacular growth in the value of arms exports (and corresponding imports). That value increased 60 percent from $8 billion in 1967 to $12.8 billion in 1976. By and large the developed nations were the exporters and the developing nations were the importers. Five nations—the U.S., the U.S.S.R., France, West Germany and Britain—provided about four-fifths of the world's arms exports. Although the U.S. (with 1976 shipments of $5 billion) and the U.S.S.R. (with 1976 shipments of $3.6 billion) are by far the largest exporters, the fastest growth over the 10-year period was registered by Italy, West Germany, France and Britain.

In a foreword to the report, Paul C. Warnke, head of the Arms Control and Disarmament Agency, wrote: "We hope that this publication will help to focus attention on the serious need for timely, reliable data about worldwide national expenditures. But its primary purpose is to stimulate informed attention to the growing global trade in destructive weaponry, to the increasing diversion of scarce resources to military purposes, and to the opportunities for arms control that these circumstances suggest."

Enhanced Ecological Effects

Much has been written in recent months about what effects enhanced-radiation weapons ("the neutron bomb") might have on troops in the field. Now Arthur H. Westing of Hampshire College has calculated some of the effects such weapons might have on the natural environment. Writing in the Royal Swedish Academy of Sciences environmental journal *Ambio,* Westing compares the environmental effects of a one-kiloton conventional nuclear weapon (which maximizes blast and heat) and those of a one-kiloton enhanced-radiation weapon (which minimizes blast and heat and maximizes penetrating radiation such as neutrons), both weapons being exploded at a height of some 1,000 feet.

The blast effect of the enhanced-radiation weapon, Westing writes, would be only a fifth that of the conventional nuclear bomb. As a result the radius within which virtually every living thing would be killed would be less than 200 yards, or about 25 acres, compared with the 125 acres that would be destroyed by the conventional weapon. On the other hand, the areas that would be affected to varying degrees by the penetrating radiation would be very much larger. The lethal radius for plant microorganisms would be about 400 yards, affecting approximately 100 acres; for insect life it would be more than 600 yards, or 250 acres, and for trees and shrubs it would be an average of nearly 900 yards, or some 500 acres (and for a conifer forest 750 acres). The area of radiation intense enough to ensure the eventual death of 50 percent of the animal population has a radius of more than 1,300 yards, or some 1,200 acres.

Westing notes that these effects would be the result of radiation emitted by the enhanced-radiation weapon instantaneously. In addition neutrons would be absorbed by the nuclei of elements in the soil, some of which would thereby be made radioactive. The radioactivity, however, would not be long-lived. Some silicon, the most abundant element in soil (some 30 percent by weight), would be transmuted into silicon 31, a radioactive isotope with a half-life of 2.6 hours. Sodium, a tenth as abundant in soil as silicon, would be transmuted into a somewhat longer-lived artificially radioactive isotope: sodium 24, which has a half-life of 15 hours.

Insulin by Bacterium

Millions of diabetics depend for their survival on daily injections of the hormone insulin, which is too complex a molecule to synthesize industrially and must be extracted from the pancreatic glands of slaughtered pigs and cattle. Because the number of diabetics is estimated to be increasing at an annual rate of 6 percent the demand for animal insulin may soon exceed the available supply. The outlook has now been improved by an application of recombinant-DNA technology. Writing in *Proceedings of the National Academy of Sciences,* Walter Gilbert and his colleagues at Harvard University (Lydia Villa-Komaroff, Argiris Efstratiadis, Stephanie Broome, Peter Lomedico, Richard Tizard, Stephen P. Naber and William L. Chick) report that they have induced the bacterium *Escherichia coli* to manufacture and secrete rat proinsulin, an immediate precursor of rat insulin that incor-

porates the insulin itself. Their effort is an important step toward the goal of developing bacterium-based industrial systems that will replace animal and human tissues as the source of medically useful proteins such as insulin, growth hormone and clotting factor.

The first attempts to manufacture rat proinsulin in bacteria were made last year by Howard M. Goodman and his colleagues at the University of California Medical School at San Francisco. They obtained messenger RNA bearing the genetic code for proinsulin from the insulin-secreting islet cells in the pancreas of the rat and used the RNA as a copying template for the synthesis of DNA. (The copying was achieved with the aid of the viral enzyme reverse transcriptase.) The copied DNA, representing the gene for proinsulin, was then inserted into a bacterial plasmid, a small ring of DNA that can pass from one bacterium to another. The bacteria did not, however, manufacture proinsulin, because (1) the gene for proinsulin was not inserted into the plasmid in such a way that it would be recognized by the bacterium as one of its own genes, and (2) even if the proinsulin had been manufactured, it would have been recognized as being foreign and would have been degraded by bacterial enzymes.

In order to induce the manufacture of proinsulin and circumvent its degradation Gilbert and his co-workers took a slightly different approach: they inserted the proinsulin DNA into a plasmid-carried gene for a bacterial protein that is normally secreted into the periplasmic space, the space between the outer wall of the bacterium and the plasma membrane inside it. The protein they chose was penicillinase, an enzyme that inactivates penicillin and thereby renders the bacterium resistant to the drug. The investigators reasoned that if the proinsulin gene were inserted into the middle of the penicillinase gene, the combined DNA would give rise to a hybrid protein that would be reasonably stable. The rat proinsulin would then "hitchhike" with the bacterial penicillinase into the periplasmic space, from which it could be extracted and then assayed with an antibody technique.

The Harvard group utilized a specific restriction enzyme (designated *Pst*) to cut the plasmid at a unique site in the middle of the penicillinase gene. The proinsulin gene was spliced into this site, and the ring of DNA was resealed with a ligating enzyme. Several clones of bacteria containing the spliced genes were then prepared by softening the outer wall of the bacteria so that the plasmid could enter the bacterial cells and be maintained there. In accordance with the guidelines for recombinant-DNA research laid down in 1976 by the National Institutes of Health, the experiments were done in a biological safety cabinet in the *P*3 (moderate isolation)

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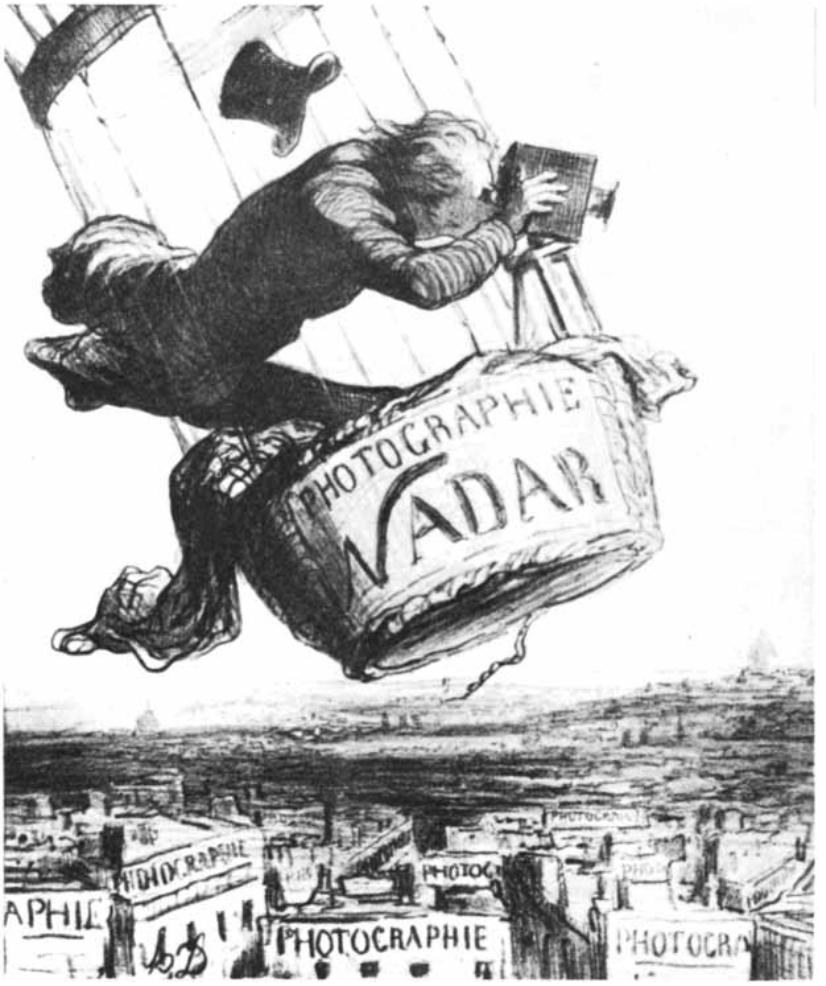
THE SECOND EMPIRE

Art in France under Napoleon III, 1852-1870

Art, Science, and Manufacture in an Age of Experiment



NADAR, in his friend Daumier's cartoon, rises above the boulevards of newly transformed Paris to take the first photographs from the air.

Having shown by his portraits that science could assist art, Nadar took his camera into the catacombs to emerge with the first photographs made by artificial light.

His balloons carried printing presses aloft to publicize projects for heavier-than-air flight, and the second voyage of the "Giant," the largest balloon ever made, resulted, thanks to a strong gale, in the first international passenger flight.

Undaunted by a crash near Hanover, Nadar's restless imagination conceived the idea of the balloon airmail which broke the siege of Paris in 1870 by flying above the reach of Prussian guns.

The Philadelphia Museum of Art presents, from October 1 to November 26, 1978, an exhibition of more than 300 Second Empire objects, including painting, sculpture, outstanding decorative arts of the period, architectural drawings, and photographs.

The exhibition will also be shown at The Detroit Institute of Arts from January 18 to March 18, 1979, and at the Grand Palais, Paris, from April 24 to July 2, 1979.

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laboratory at the Massachusetts Institute of Technology. In addition the investigators used as the bacterial host a "crippled" strain of *E. coli,* designated χ1776, which can survive only in a complex synthetic medium and hence cannot infect man or other organisms.

Gilbert and his co-workers got 48 clones of *E. coli* that contained plasmids with the inserted proinsulin gene. About two-thirds of the clones were resistant to penicillin, indicating that active penicillinase was being manufactured. The degree of resistance varied, suggesting that different segments of the two genes were being expressed to yield hybrid proteins of different sizes and stabilities. Only one clone secreted a hybrid protein that incorporated nearly all the proinsulin molecule in addition to about two-thirds of the penicillinase molecule. This hybrid protein reacted with antibodies specific to proinsulin and penicillinase, indicating that it contained regions whose three-dimensional structure resembled the native conformation of the two molecules. Determining the sequence of nucleotides in the plasmid DNA for the hybrid protein revealed that the proinsulin gene had by chance been inserted into the penicillinase gene in the correct orientation and "reading frame" for it to be successfully expressed.

The Harvard group has obtained biologically active rat insulin from the hybrid protein by digesting it with a protein-cleaving enzyme, but the yield of the product is extremely low: about 100 molecules per cell. One problem is that small proteins such as insulin are very sensitive to degradation by enzymes that are normally present in *E. coli.* The group is now attempting to increase the amount of proinsulin that is manufactured and secreted by the bacterium.

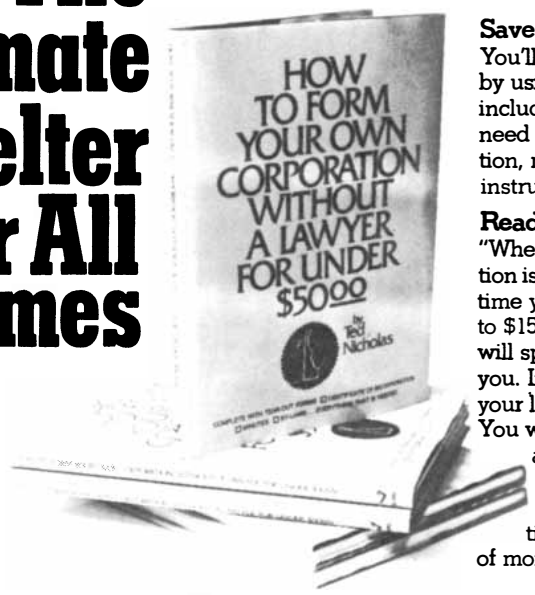
Rat insulin cannot be utilized by human diabetics, but Gilbert and his colleagues believe much the same approach can be taken in preparing human insulin in *E. coli.* Indeed, the bacterial manufacture of human insulin may eventually prove to be cheaper and more efficient than the purification of the hormone from pigs and cattle, and it would be particularly valuable to diabetics who are allergic to animal insulin.

Cost-Effective

Preventive medicine is the best example of the adage "An ounce of prevention is worth a pound of cure," and the economic equation implied by the adage can take some interesting forms. A case in point is presented by Brandon S. Centerwall and Michael H. Criqui of the School of Medicine (at La Jolla) of the University of California at San Diego, who have analyzed a simple preventive measure: fortifying alcoholic beverages with thiamine (vitamin B-1) in order to forestall the Wernicke-Korsakoff

The Ultimate Tax Shelter For All Incomes

Tax experts are calling a small, privately-owned corporation "the ultimate tax shelter."



Because government has recognized the important role of small business in our country, there are numerous laws favoring corporation owners. With the help of my book, anyone—from any income bracket can take advantage of this readily available tax shelter.

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Startling Facts Revealed

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syndrome, a thiamine-deficiency disorder occurring primarily among alcoholics. They have concluded that the adoption of the measure in the U.S. would be worth at least $53 million per year. Writing in *The New England Journal of Medicine,* they report that the annual cost of the long-term institutionalization of sufferers from the Wernicke-Korsakoff syndrome is $70 million and that "the cost of adequately fortifying alcoholic beverages is estimated to range from $3 million per year if allithiamines are used to as much as $17 million per year if thiamine hydrochloride proves necessary." (The allithiamines are analogues of thiamine that appear to have the same pharmacological effects and are absorbed from the intestinal tract essentially without limit; thiamine hydrochloride, the standard form, is absorbed poorly by alcoholics.)

The Wernicke-Korsakoff syndrome is a neurological disorder that begins with an acute phase characterized by palsy and poor muscular coordination; with treatment the acute phase gives way to a chronic phase, Korsakoff's psychosis, characterized by severe amnesia. The patients usually do not respond to treatment and must be institutionalized. Thiamine deficiency, brought on by the typical alcoholic's poor nutritional habits, has been well documented as the cause of the disease. Since alcoholic beverages already contain a small fraction of the recommended daily allowance of thiamine, which is from one milligram to 1.5 milligrams, Centerwall and Criqui renew a proposal that others have made previously: add thiamine to alcoholic beverages, as vitamins are added to milk. They buttress their proposal with an array of economic data, including the cost of institutionalizing victims of Korsakoff's psychosis, the U.S. consumption of alcoholic beverages in 1977 (21.5 billion liters, or 5.7 billion gallons, consisting of 1.5 billion liters of wine, 1.5 billion liters of liquor and 18.5 billion liters of beer) and the cost of adding two milligrams of allithiamine to every half liter (pint) of liquor, two liters (two quarts) of wine and four liters (one gallon) of beer.

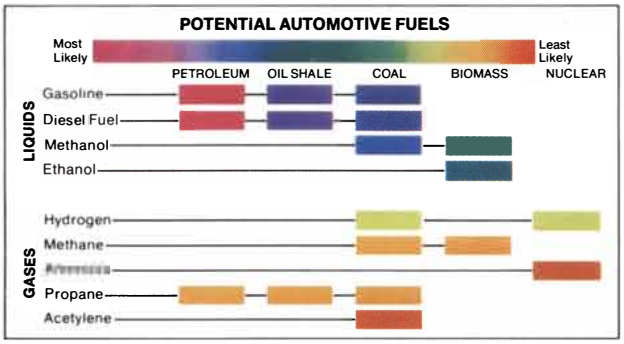
"Some may believe," they write, "that alcohol is not a legitimate 'food' and that adding vitamins would give it an undeserved aura of legitimacy. Unfortunately, alcohol is the chief source of calories for millions of Americans. Similarly, some may think drinking should not be made safer because it will only encourage the practice. We can only suggest that the presence or absence of thiamine in alcoholic beverages is unlikely to influence rates of alcoholism."

Past and Future Shocks

Predicting earthquakes can be a shaky business, but two geologists have been able to make some interesting pre-

By the end of this century, when the world's demand for petroleum will exceed what it can produce, alternative fuels will have already begun phasing into the energy picture.

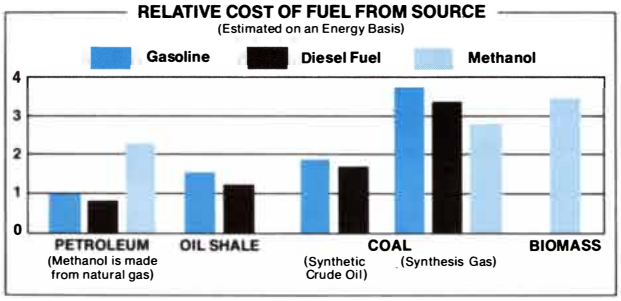
What will these new fuels be? Scientists here at the General Motors Research Laboratories long ago started exploring the possibilities. They've conducted engine studies with hydrogen, methane, ammonia, propane, acetylene, methanol, ethanol, and with liquid hydrocarbons from coal and oil shale.



Although the principal aim was to understand the combustion process, the overall system — from resources in the ground to power at the wheels — was also considered.

So what have we learned? Hydrogen, for example, behaves well enough in an engine. However, storage and control problems in a car severely limit its prospects.

Methanol, on the other hand, is more manageable. And we have modified production vehicles to run on this fuel. But methanol poses a serious starting difficulty below 5° C. Moreover, it would be costly.



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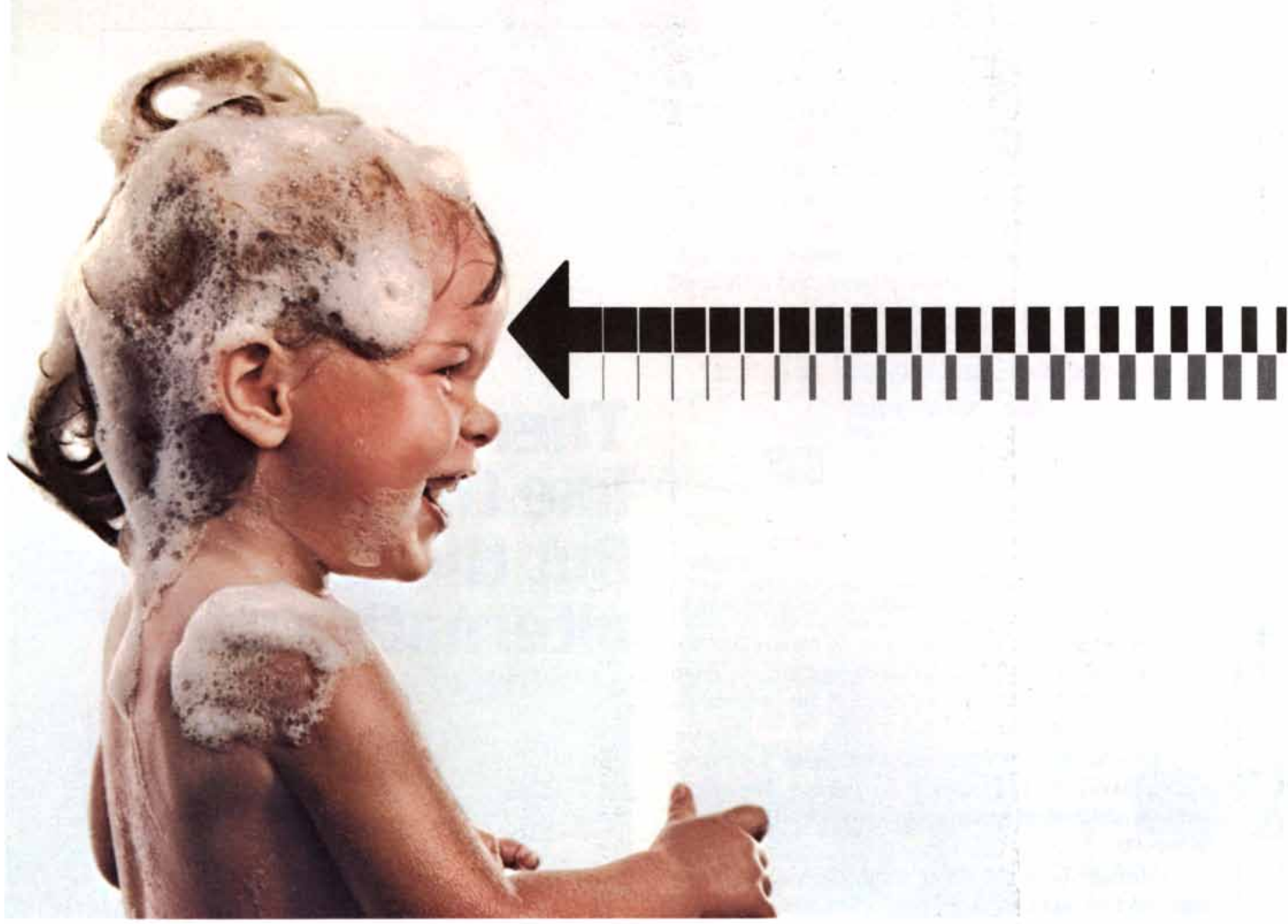

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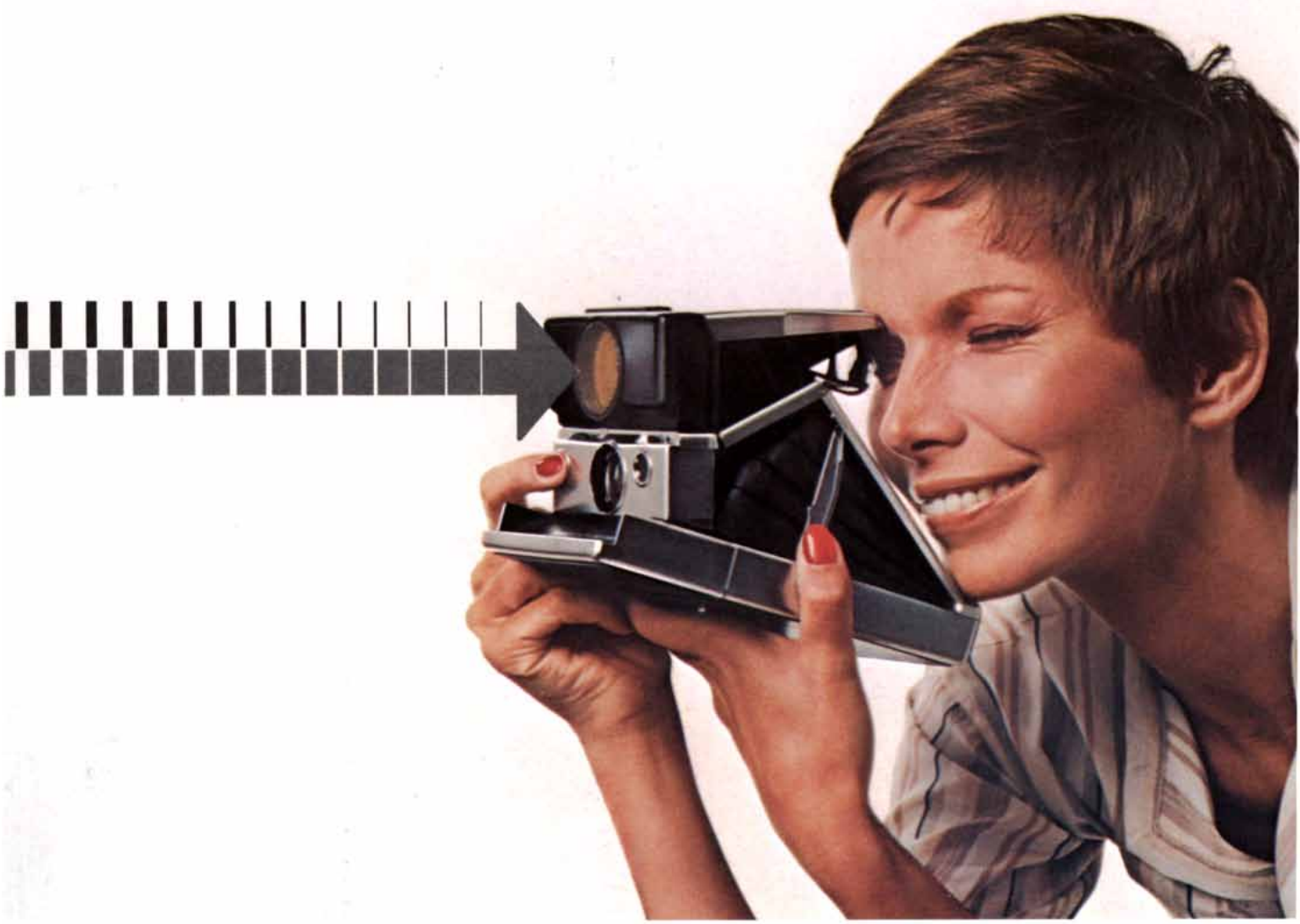

the camera. In a split second, the lens automatically rotates to the precise focus.

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Polaroid's new Sonar OneStep Land camera is available in two models. The SX-70 Sonar OneStep and the Pronto Sonar OneStep, from $99.95.

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dictions about the earthquakes in California's future by looking into the past. Kerry Sieh of the California Institute of Technology and Duncan Carr Agnew of the Scripps Institution of Oceanography have used historical accounts—newspaper stories, letters, diaries and so on—to reconstruct the events of the great earthquake of 1857, the last major quake to strike southern California. Their findings about the causes of the quake have enabled them to draw some interesting conclusions about the form and impact of any future earthquakes that might strike in the area.

The great earthquake occurred on January 9, 1857. It was caused by a rupture of a fault in the San Andreas fault system extending from near Parkfield in central California south to near San Bernardino, with slippage along the fault amounting to as much as 9.5 meters. The quake is estimated to have had a magnitude of approximately 8¼ on the Richter scale, about the same as the famous San Francisco earthquake of 1906. (The 1857 quake did far less damage than the 1906 one because it occurred in a much less populated area.)

Sieh and Agnew used the historical accounts of the 1857 earthquake to rate its intensity at various points throughout central and southern California. They found that the intensity of the earthquake in the area that is now metropolitan Los Angeles was not notably high. In fact, although heavy shaking in the vicinity of the fault caused damage even to well-designed structures, the damage to houses and other small structures in the present metropolitan area was slight. Sieh and Agnew conclude that if the 1857 quake were to occur today, "there would not be extensive damage to low-rise construction in the metropolitan area," although there would probably be substantial damage to low-rise structures close to the earthquake fault. Their evidence also suggests that the 1857 quake was characterized by substantial long-period, or low-frequency, waves. Such slow undulating movements would have their greatest impact on modern high-rise structures.

The analysis of the accounts of the 1857 earthquake also revealed that there were numerous foreshocks—smaller quakes with an estimated magnitude of 4 or 5 on the Richter scale—in the hours preceding the main earthquake. Sieh has located the epicenters of those shocks in central California, about halfway between San Franciso and Los Angeles, at the northwest end of the fault rupture that caused the main earthquake. It is possible that the foreshocks triggered the main quake. To the northwest of the epicenters there is a creeping, or constantly slipping, segment of the fault and to the southeast there is a locked segment of the fault. Sieh believes that although slippage in the creeping section relieves much of the

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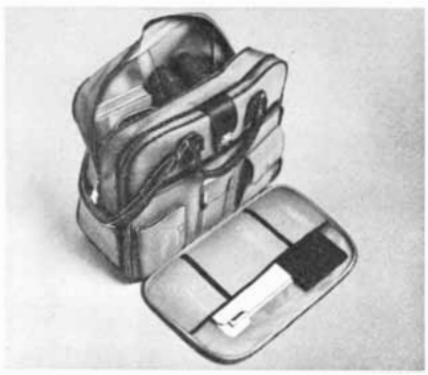

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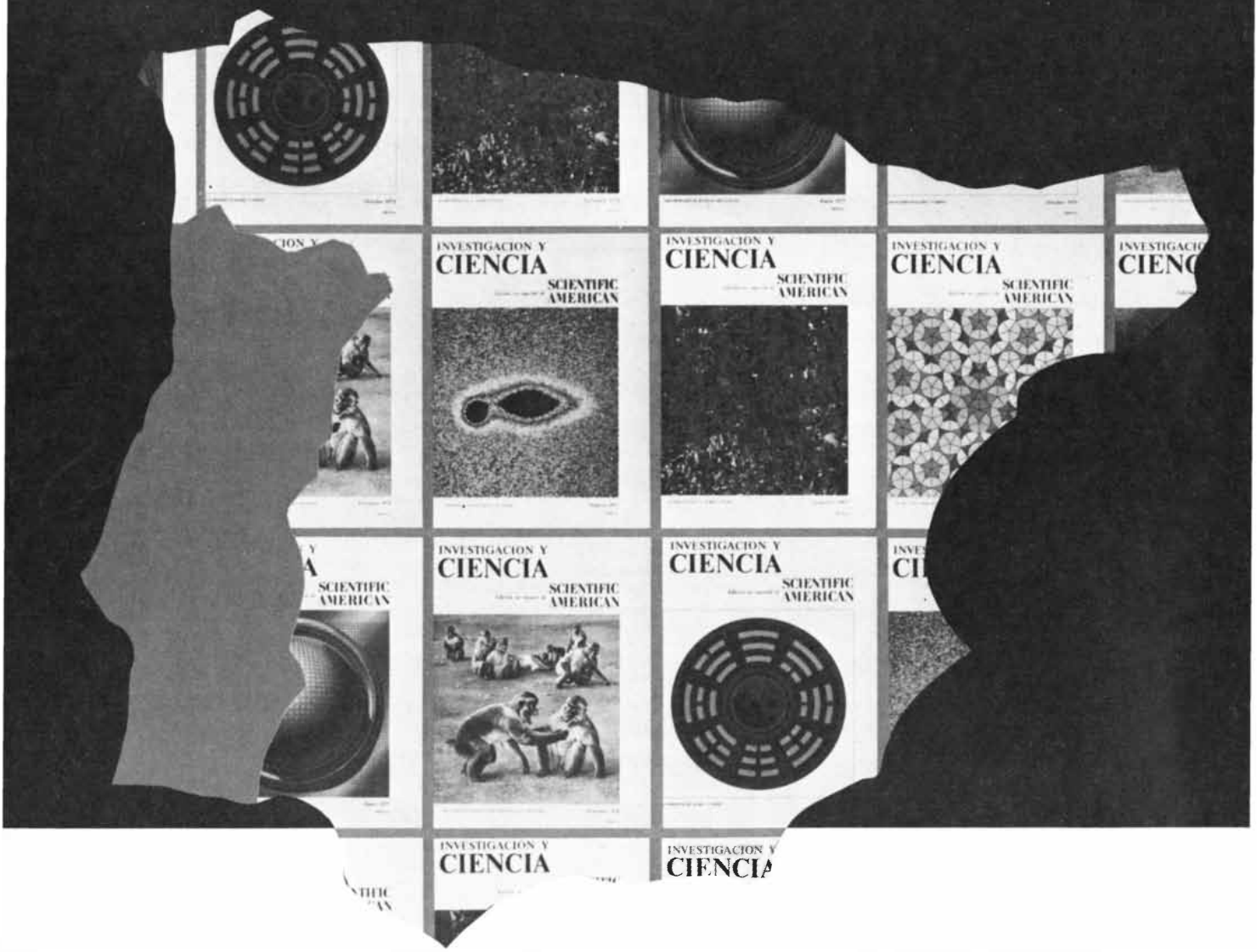

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LAS MATEMATICAS DEL "I CHING"

strain there, pressures build up in the locked section until finally, every few hundred years, a foreshock-size quake in the creeping section triggers a major quake. (Small foreshock-size earthquakes are not unusual in the creeping section: four have been recorded in the past 80 years.) Sieh's findings imply that the earthquake of 1857 began at the northwest end of the fault rupture and propagated southeast from the creeping section of the fault through the locked section. If he is right, studies of the creeping section could be valuable in predicting the next major earthquake in southern California.

A Star Is Reborn

On July 4, 1054, a supernova flared up in the sky of the Northern Hemisphere, giving rise to what is now observed as the Crab Nebula. It was so bright that it could be seen in broad daylight for 23 days, and it was visible at night for six months. All of this and more was recorded by observers in China and Japan. Comparable records from Europe and the Near East, however, have been mysteriously lacking. The gap has now been filled by the discovery of a medieval Arabic text that provides an eyewitness account of the celestial event.

The discovery is described in a recent issue of *Nature* by Kenneth Brecher, Elinor Lieber and Alfred E. Lieber. The medieval text is a biographical encyclopedia of physicians that was assembled in about 1242. Among the physicians listed in the work is 'Ibn Buṭlān, a Christian who lived in Constantinople at the time of the supernova, and contained in his entry is his unmistakable personal observation of the event. In the tradition of Hippocrates and Galen, 'Ibn Buṭlān believed there was a connection between celestial phenomena and human disease. He thought the supernova of 1054 was responsible for a devastating epidemic that had swept the Near East that year.

Before the discovery of 'Ibn Buṭlān's account numerous speculations had been put forward to explain why no one in Europe or the Near East had noticed the supernova. Some historians had blamed the failure of monastic chronicles to describe the event on the Aristotelian concept of a perfect, changeless celestial vault, in which there would be no place for such an evanescent and explosive phenomenon as a supernova. The noted historian of science George Sarton wrote: "The failure of medieval Europeans and Arabs to recognize such phenomena was due not to any difficulty in seeing them but to prejudice and spiritual inertia connected with the groundless belief in celestial perfection." This explanation is not convincing, write Brecher and his colleagues, because in 1006, 48 years earlier, both Europeans and Arabs had written detailed descriptions of another supernova. And late in the 11th century Halley's comet, another fleeting and imperfect object from the Aristotelian point of view, was included in the Bayeux tapestry depicting the Norman conquest of England. Other historians had suggested that for the entire six months of the supernova Europe and the Near East had been covered with clouds. Such cloud cover is not only improbable; it is not indicated by any evidence.

Although 'Ibn Buṭlān's account is evidence that people outside the Orient did observe the supernova, it leaves unexplained why so few of them wrote about it. It suggests, however, that since historians seeking evidence of medieval astronomical observations have concentrated on astrological and monastic works, the real significance of the find made by Brecher and his colleagues is that such historians might well turn their attention more toward neglected medical writings, which, in their astrological speculations, might reveal much about medieval astronomy.

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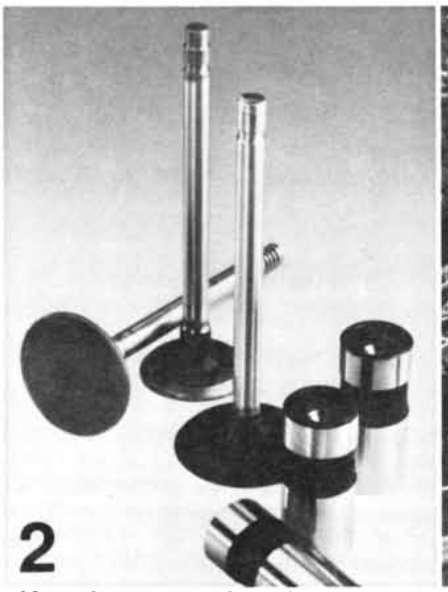

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EATON

Fermat's Last Theorem

For 300 years mathematicians have tried without success to prove a theorem Pierre de Fermat asserted he could prove: No nth power can be the sum of two other nth powers, where n is greater than 2

by Harold M. Edwards

The 17th-century French mathematician Pierre de Fermat was the father of modern number theory, the branch of mathematics that deals with the properties of whole numbers. Like many other scholars of his time he studied the classics of antiquity. In number theory he drew inspiration from Diophantus, the Greek mathematician whose *Arithmetica* had been rediscovered by Europeans in the mid-16th century. Fermat made extensive marginal notes in his copy of the book, and after his death in 1665 his son published a new edition of *Arithmetica* including Fermat's notes. One of the notes has become one of the most famous statements in the history of mathematics.

Next to a problem on finding squares that are sums of two other squares (for example, 25 equals 9 plus 16), Fermat wrote (to translate from the Latin): "On the other hand, it is impossible for a cube to be the sum of two cubes, a fourth power to be the sum of two fourth powers or in general for any number that is a power greater than the second to be the sum of two like powers. I have discovered a truly marvelous demonstration of this proposition that this margin is too narrow to contain." The proposition has come to be called Fermat's last theorem, and although the keenest mathematicians of the past three centuries have tried to prove it, no such demonstration has been found. Fermat's last theorem remains one of the great unsolved problems of modern mathematics.

Did Fermat really have a "marvelous proof" of the theorem? He was certainly a prodigious mathematician, helping to establish the disciplines of analytic geometry (with Descartes), infinitesimal calculus (with Leibniz and Newton) and probability theory (with Pascal). He was not a mathematician by profession but a jurist at Toulouse in the south of France. His extensive participation in the intellectual life of his time was conducted entirely through his private correspondence with other scholars in the major European centers of learning.

It is charming to think of a provincial 17th-century jurist outsmarting the best mathematical minds of three centuries with his theorem, but the facts suggest that he did not have a proof. Except for the famous note in the margin of Diophantus' book there is no mention of a proof of the theorem in any of Fermat's writings that have survived. He did state elsewhere that he could show it was impossible to find solutions to the equations $x^3 + y^3 = z^3$ and $x^4 + y^4 = z^4$. If he discovered a valid proof of the full theorem (that $x^n + y^n = z^n$ is impossible for positive whole numbers x, y, z and n, where n is greater than 2), it is surprising that he did not mention it too. It seems most likely that at the time he wrote the note Fermat had an idea for a proof he later realized was faulty. His notes were almost certainly not intended for publication, and there may have been no occasion for him to go back and delete or amend the note.

It is of course more exciting to believe Fermat did have a rigorous proof of the theorem, and it is just possible that he did. In either case the theorem has played an important role in the development of number theory. Some of the greatest creations of mathematical thought have been prompted by the study of the theorem, and the techniques that have been developed in the effort to prove it have contributed to the solution of many other problems.

Finally, the history of Fermat's last theorem provides an excellent illustration of the real nature of mathematical inquiry. Mathematicians are often asked: "How is it possible to do research in mathematics?" I doubt that physicists or astronomers or biologists are ever asked such a question, but to many people mathematics seems to be such a cut-and-dried subject that work in it should amount to nothing more than an orderly recording of the facts. Of course, nothing could be further from the truth. In mathematics, as in any other field, unanswered questions are everywhere, and the difficulty mathematicians face is finding questions they can answer, not ones they cannot. It is difficult, however, to illustrate the point for a nonmathematician, because the formulation of interesting mathematical questions usually calls for specialized terminology and background. Fermat's last theorem is a rare exception to this rule.

Proof by Infinite Descent

Part of the fascination of Fermat's last theorem is due to the fact that the theorem is unusually simple to state and understand: It is impossible to find positive whole numbers x, y, z and n for which n is greater than 2 and the equation $x^n + y^n = z^n$ holds. Nonmathematicians usually approach the theorem in what seems to be a very reasonable way: by "trying it out." Consider the case where n is equal to 3, that is, the case that consists in proving that $x^3 + y^3 = z^3$ has no solution. The cubes of the first 10 positive integers are 1, 8, 27, 64, 125, 216, 343, 512, 729 and 1,000. It is not difficult to see that none of these num-

PIERRE DE FERMAT is called the father of number theory, the branch of mathematics that deals with the properties of the whole numbers. Born in 1601 near Toulouse, Fermat spent all his life in the south of France, far from the great European centers of learning. He worked as a jurist, not as a professional mathematician, and none of his mathematical works was published until after his death. His extensive participation in the mathematics of his time was conducted entirely through his private correspondence with other scholars. Fermat formulated many challenging and perceptive theorems that were not proved until long after his death. By 1840 only one of these theorems remained to be proved. It has come to be called Fermat's last theorem: There are no solutions in whole numbers to the equation $x^n + y^n = z^n$, where n is greater than 2. Fermat's last theorem is one of the most famous unsolved problems of modern mathematics. This painting of Fermat is in the collection of the Académie des Sciences, Inscriptions et Belles Lettres de Toulouse; it is reproduced here with the kind permission of Robert Gillis.

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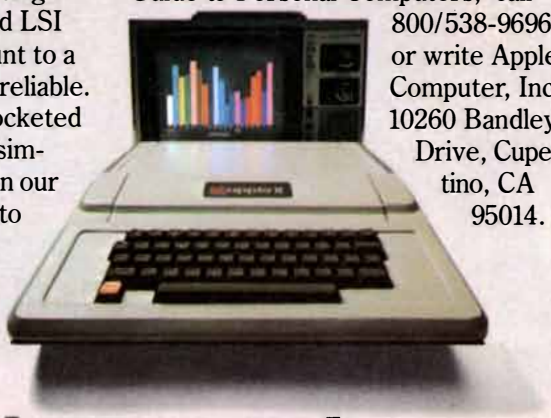

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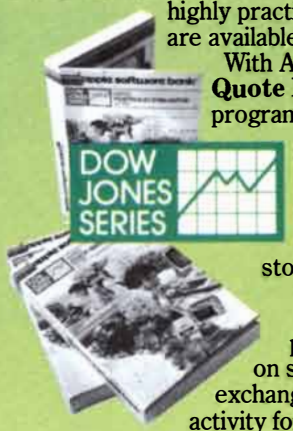

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A BABYLONIAN CLAY CUNEIFORM TABLET dating from about 1500 B.C. is one of the oldest-known documents dealing with number theory. The tablet lists (in slightly disguised form) several sets of Pythagorean triples, or distinct, positive whole numbers x, y and z, for which $x^2 + y^2 = z^2$, for example 4,961, 6,480 and 8,161. Fermat formulated his last theorem while he was considering a problem concerning Pythagorean triples (*see illustration on next page*). Any triple provides an immediate proof that the theorem is not true when the exponent n is equal to 2. Pythagorean triples are named for their relation to the Pythagorean theorem, which states that in a right triangle the square of the hypotenuse is equal to the sum of the squares of the other two sides. It is not easy to find triples by trial and error, particularly those that involve large numbers, and so the Babylonians probably had a method for finding them. It seems most likely that their interest stemmed from the geometric applications of the sets of numbers and that therefore they knew of the Pythagorean theorem 1,000 years before Pythagoras. The tablet is part of the Plimpton Collection in the Butler Library at Columbia University.

bers can be expressed as the sum of two other cubes. For example, if 512 were equal to the sum of two other cubes, the cubes would be smaller than 512 and would precede it on the list of cubes. The cubes 216 and 343 are good candidates, but their sum is 559, which is too large. The next smaller sum, 216 plus 216, equals 432 and not 512. Hence 512 is not equal to the sum of any two cubes.

It is easy to verify by this procedure that any particular cube is not the sum of two other cubes. The required calculations could be carried out at high speed on a computer, and it could be shown very quickly that no cube with fewer than, say, 10 digits is the sum of two other cubes. There are, however, an infinite number of cubes to be tested, so that with this procedure even the largest computer could never resolve the question of whether any cube can be the sum of two other cubes.

Once nonmathematicians have seen that the impossibility of $x^3 + y^3 = z^3$ cannot be proved simply by "trying it," they may swing to the opposite extreme and ask how such a statement can ever be proved. The answer is that it can be proved by the method of reasoning to a contradiction: One assumes that there is a solution to the equation, and one deduces from this assumption a statement known to be false. Arriving at a false statement, or contradiction, shows that the original assumption was false and therefore that there can be no solution.

More specifically, in the case of statements, such as Fermat's last theorem, that are concerned with positive whole numbers a proof by contradiction often takes the form of a proof by infinite descent. Fermat maintained he had invented this method, which he said was the basis of all his proofs in the field of number theory. In a proof by infinite descent one shows that if a solution in positive whole numbers to the equation in question is given, it can be used to produce a smaller solution, also in positive whole numbers. The same argument then shows that the smaller solution can be used to produce a still smaller one, and the process can be repeated indefinitely. Since the solutions are all positive whole numbers, however, it is obviously impossible to find increasingly small solutions ad infinitum. Hence there can be no solution at all.

Early Findings

In all Fermat's writings on number theory that have been preserved there is only one proof, found in another of the marginal notes in Diophantus' *Arithmetica*. It concerns Pythagorean triangles, or right triangles with sides of integer length. (They derive their name from

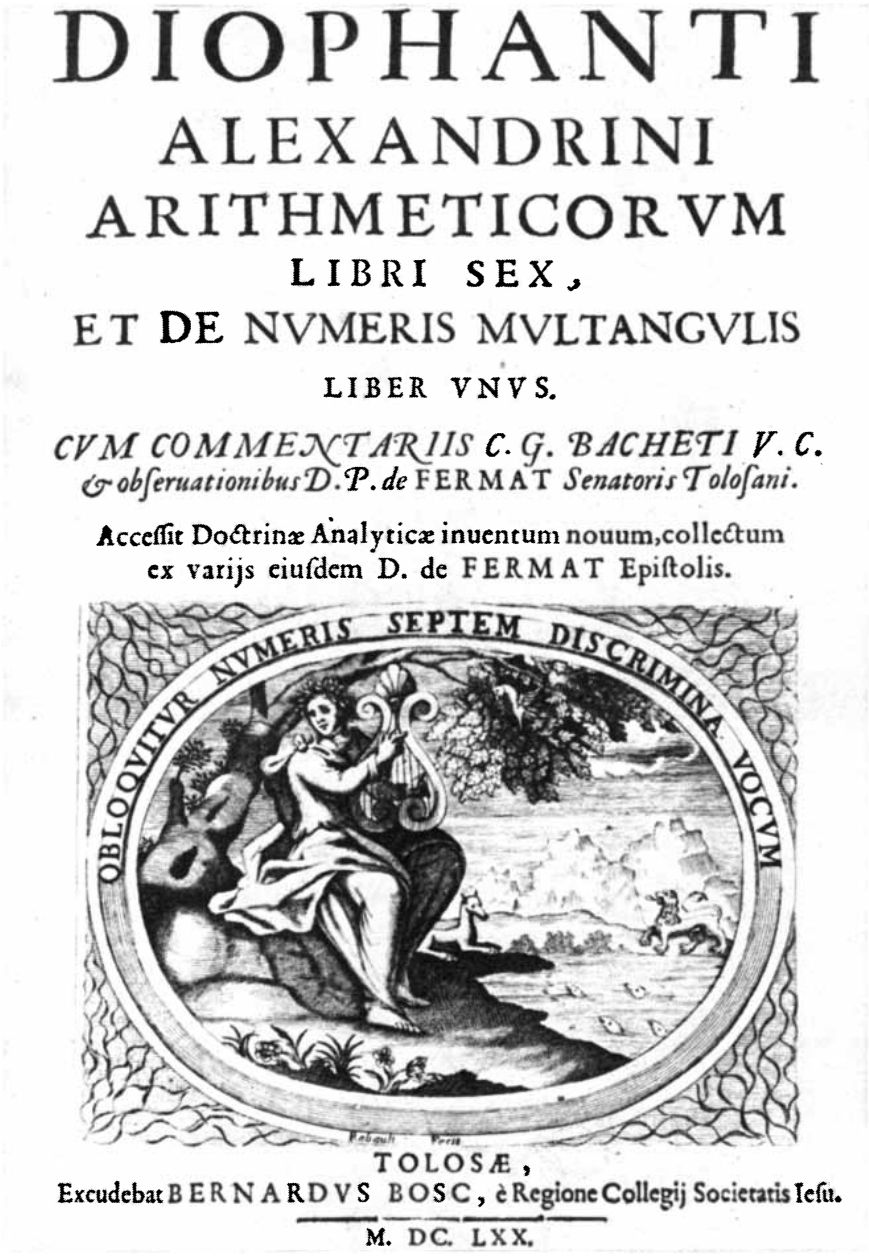
their relation to the Pythagorean theorem, which states that the sides x and y and the hypotenuse z of a right triangle are related by the equation $x^2 + y^2 = z^2$.) Fermat proved that the area of such a triangle cannot be a square: If x, y and z are positive integers and $x^2 + y^2 = z^2$, then $(1/2)xy$ is not the square of an integer. It is easy to show that either x or y must be even and therefore that $(1/2)xy$ must be a whole number.

Fermat used the method of infinite descent in the proof. Specifically, he gave an explicit method by which, given positive whole numbers x, y, z and u that satisfy the equations $x^2 + y^2 = z^2$ and $(1/2)xy = u^2$, it is possible to derive another set of positive whole numbers X, Y, Z and U such that $X^2 + Y^2 = Z^2$ and $(1/2)XY = U^2$, and such that the triangle with sides X, Y and Z is smaller than the triangle with sides x, y and z in the sense that the hypotenuse Z is less than the hypotenuse z. Fermat's method for deriving X, Y, Z and U is subtle and would call for a long explanation. The fact that such a method exists, however, shows that it is impossible to find any positive whole-number solutions to the equations $x^2 + y^2 = z^2$ and $(1/2)xy = u^2$, because one solution x, y, z and u would lead to a smaller solution X, Y, Z and U, which in turn would lead to a still smaller solution X', Y', Z' and U', and so on. That would imply the existence of infinitely decreasing sequences of positive whole numbers $z > Z > Z' > \ldots$, which is impossible. (The sign ">" stands for "greater than.")

It is interesting and probably not coincidental that the fact that the area of a Pythagorean triangle cannot be a square immediately implies that $x^4 + y^4 = z^4$ has no solution, or that Fermat's last theorem is true for the case where n equals 4. A simple but ingenious trick suffices to connect the two propositions: assume that $x^4 + y^4 = z^4$ for some positive integers x, y and z, and set a equal to y^4, b equal to $2x^2z^2$, c equal to $z^4 + x^4$ and d equal to y^2xz. Then the simple algebraic identity $(r+s)^2 = r^2 + 2rs + s^2$ implies that $a^2 + b^2$ equals $(z^4 - x^4)^2 + 4x^4z^4$, or $z^8 - 2x^4z^4 + x^8 + 4x^4z^4$, or $(z^4 + x^4)^2$, which is equal to c^2. Furthermore, $(1/2)ab$ is equal to $(1/2)y^4 2x^2z^2$, or $(y^2xz)^2$, which is equal to d^2. Thus $a^2 + b^2 = c^2$ and $(1/2)ab = d^2$, which Fermat proved was impossible. Hence the original assumption, that $x^4 + y^4 = z^4$ has a solution, must be incorrect, and Fermat's last theorem is established for the case n equals 4. In essence, then, Fermat himself proved his last theorem for the case of fourth powers.

This proof also establishes that Fermat's last theorem is true whenever n is a multiple of 4, because if n is equal to $4k$ for some positive integer k, then $x^n + y^n = z^n$ implies that $(x^k)^4 + (y^k)^4 = (z^k)^4$, which is impossible because a fourth power cannot be the sum of two other fourth powers. In exactly the same way, if the theorem can be proved for any given exponent m, then it is true for all multiples of m. Therefore, since every whole number n greater than 2 is divisible either by an odd prime (a prime number other than 2) or by 4, it suffices to prove Fermat's last theorem in all cases where the exponent is an odd prime number.

Fermat maintained he could prove the theorem in the case n equals 3, but no published proof of the impossibility of finding a solution for $x^3 + y^3 = z^3$ appeared until about 100 years later. The proof, which was the work of the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M. DC. LXX.

FERMAT'S LAST THEOREM was first set down in the margin of *Arithmetica*, a work on number theory by the ancient Greek mathematician Diophantus. Fermat had studied the book closely, making many marginal notes in his copy of it, a translation into Latin by C. G. Bachet. After Fermat's death in 1665 his son published a new edition of Bachet's translation of *Arithmetica* that included Fermat's marginal notes in an appendix. The title page of the book is shown in this illustration. Translated from the Latin, it announces *Six Books of Arithmetica and One Book on Polygonal Numbers by Diophantus of Alexandria*, "with notes by the distinguished gentleman C. G. Bachet and observations by Doctor P. de Fermat, Senator of Toulouse," and "a new discovery of analytical doctrine collected from the various letters of the aforementioned Doctor de Fermat." Fermat's historic note referred to a problem concerning Pythagorean triples. He wrote: "On the other hand, it is impossible... for any number that is a power greater than the second to be the sum of two like powers. I have discovered a truly marvelous demonstration of this proposition that this margin is too narrow to contain." To this day it is not known whether Fermat really had a rigorous proof of the theorem. In any case no other mathematician has been able to prove the theorem or to find a counterexample to it.

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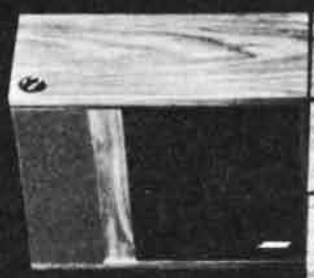

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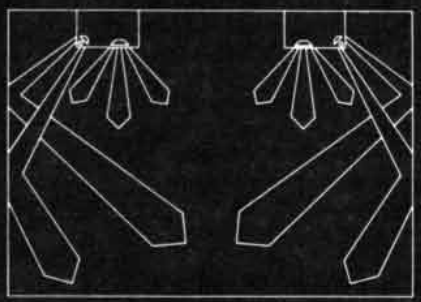

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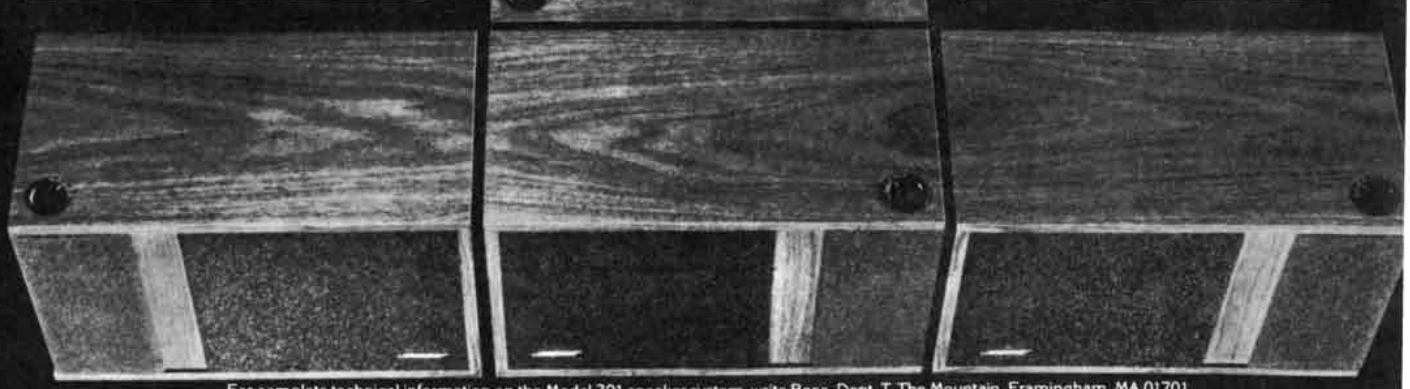

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Swiss mathematician Leonhard Euler, did, however, have a serious flaw.

Euler's Proof

Euler proved the case n equals 3 by infinite descent, setting forth a method by which it is possible to derive from any given solution x, y and z for the equation $x^3 + y^3 = z^3$ a new solution X, Y and Z such that Z is less than z. The method is too long to explain in detail here, but in outline, by making calculations concerning various characteristics of x, y and z, Euler reduced the problem of deriving a smaller solution to one of proving the following proposition: If p and q are relatively prime integers (if they have no common factor, or divisor, greater than 1) and $p^2 + 3q^2$ is a cube, then there must be integers a and b such that p equals $a^3 - 9ab^2$ and q equals $3a^2b - 3b^2$. The proposition is quite correct and can be proved by applying simple variations of methods found elsewhere in Euler's published work. In this instance, however, Euler chose to employ a novel type of argument that involved introducing numbers of the form $a + b\sqrt{-3}$, where a and b are integers.

To understand why Euler found the numbers $a + b\sqrt{-3}$ useful, expand the expression $(a + b\sqrt{-3})^3$. It is equal to $a^3 + 3a^2b\sqrt{-3} - 9ab^2 - 3b^3\sqrt{-3}$, or $(a^3 - 9ab^2) + (3a^2b - 3b^3)\sqrt{-3}$, or $p + q\sqrt{-3}$, where p and q are defined as they are in the conclusion of the proposition. In other words, the conclusion of the proposition states that $(a + b\sqrt{-3})^3 = p + q\sqrt{-3}$. Now, the proposition assumes that $p^2 + 3q^2$ is a cube. If $p^2 + 3q^2$ is rewritten as $(p + q\sqrt{-3})(p - q\sqrt{-3})$, then the proposition can be restated: If $(p + q\sqrt{-3})$ $(p - q\sqrt{-3})$ is a cube, then $p + q\sqrt{-3}$ must be a cube, that is, must have the form $(a + b\sqrt{-3})^3$ for some integers a and b. Thus the introduction of the numbers $a + b\sqrt{-3}$ makes it possible to write the proposition much more simply and naturally.

The numbers $a + b\sqrt{-3}$ form a number system much like that of the integers. In either case adding, subtracting or multiplying any two numbers in the system gives another number in the system, whereas dividing two numbers usually does not. For example, 4 does not divide 5 in the system of integers (that is, no integer can be multiplied by 4 to give 5), and given two numbers of the form $a + b\sqrt{-3}$ it is not usually possible to find a third number of that form that is their quotient. The similarities of the two systems led Euler to take an innovative and incorrect step in his proof. He applied an established property of the integers to the numbers $a + b\sqrt{-3}$.

The property of the integers that Euler needed for his proof is derived from the unique factorization of integers into primes. A positive integer can be written as a product of prime factors in just one way. For example, 124 is equal to $2 \times 2 \times 31$, and no prime number other than 2 or 31 divides 124 evenly. Unique factorization implies the following property of the integers: A product of relatively prime positive integers can be a cube only if each of the integers is a cube. For example, assume that c and d are relatively prime and that cd is equal to 1,000, or 10^3. Expressed as a product of prime factors, 1,000 equals $2^3 \times 5^3$. The factorizations of 1,000 are obtained by splitting the factors into two subsets, for example $(2 \times 2 \times 5)(2 \times 5 \times 5)$, or 20×50. If the splitting must be done in such a way that the two subsets are relatively prime, then all the 2's must go in one subset and all the 5's must go in the other. Hence the only possible values of the factors c and d are $2^3 \times 5^3$, 2^3, 5^3 and 1, all of which are cubes. Similarly, the product of two relatively prime positive integers can be an nth power only if each of the integers is an nth power.

Euler assumed that this property of the integers was also a property of the numbers $a + b\sqrt{-3}$, and he proved the proposition by the following line of argument. The proposition states that if p and q are relatively prime and $(p + q\sqrt{-3})(p - q\sqrt{-3})$ is a cube, then $p + q\sqrt{-3}$ is a cube. Euler first showed that if p and q are relatively prime, then $p + q\sqrt{-3}$ and $p - q\sqrt{-3}$ are also relatively prime. By extension of the property of the integers, the product of relatively prime numbers of the form $a + b\sqrt{-3}$ can be a cube only if the numbers themselves are cubes. Hence the assumption that $(p + q\sqrt{-3})$ $(p - q\sqrt{-3})$ is a cube implies that $p + q\sqrt{-3}$ is a cube, and the proposition is proved.

The argument certainly gets Euler to his desired conclusion. The problem is

LEONHARD EULER proved Fermat's last theorem for the case of the first odd prime exponent, n equals 3. This painting, made in about 1745, shows the Swiss mathematician during his lifetime. Before Euler's proof Fermat's last theorem had been established (by a direct application of Fermat's own work) in only one case: n equals 4. It is easy to show that if the theorem is true when n equals some integer r, then it is true when n equals any multiple of r. Since every integer is divisible either by 4 or by an odd prime, it remained only to prove the theorem in the cases where n is an odd prime. The first successful effort in this direction was Euler's, but although his proof was ingenious, it had a serious flaw. The flaw was easily corrected in the proof of the case n equals 3, but it turned out to be a central issue in many later attacks on theorem.

that reasoning by analogy to the arithmetic of the integers does not constitute a valid proof. Arguments by analogy are extremely suggestive and, as the history of mathematics demonstrates, can yield useful ideas, but they cannot be taken as proof of anything. It is particularly surprising that Euler was not more circumspect in his use of analogy, because although the numbers $a + b\sqrt{-3}$ do have many properties in common with the integers, there are also many properties in which the two number systems differ. For example, the integers have a natural ordering, $\ldots -2, -1, 0, 1, 2, \ldots$, but the numbers $a + b\sqrt{-3}$ do not. There is only one way to be sure the numbers $a + b\sqrt{-3}$ share with the integers the property that the product of two relatively prime numbers is a cube only if each of the numbers is a cube, and that is to prove they do.

The Flaw in Euler's Work

Even the best mathematicians, however, succumb to the temptation of proof by analogy from time to time, often failing to be sufficiently critical of an argument because they know the conclusion it reaches is correct. The temptation is particularly strong when the argument has the appealing simplicity of Euler's. It is quite possible that Euler neglected to be more rigorous because he knew from other considerations that the final conclusion $p + q\sqrt{-3} = (a + b\sqrt{-3})^3$ was correct. Long before he published his proof of the case n equals 3 of Fermat's last theorem Euler worked on other unproved assertions of Fermat's concerning the representation of numbers in the form $x^2 + 3y^2$. In particular he proved Fermat's assertion that every prime number p that is one more than a multiple of 3 (p equals $3n + 1$) has a unique representation as a square plus three times a square (p equals $x^2 + 3y^2$); for example, 7 equals $2 \times 3 + 1$ and $2^2 + 3 \times 1^2$. The techniques Euler developed in the proof of this theorem are easily applied to prove the proposition in the case n equals 3 of Fermat's last theorem. It is possible Euler realized he could prove the proposition with the established techniques and therefore did not subject his more unusual proof to sufficiently careful scrutiny.

In the earlier proof Euler was extremely cautious about employing questionable arguments. For example, an intermediate step in the proof requires a proof that if a and b are relatively prime integers, then every odd prime factor of $a^2 + 3b^2$ can be written in the form $c^2 + 3d^2$. In this instance Euler did not have the dangerous assurance that the statement to be proved was correct, and his demonstration is a model of clarity and rigor. It is curious, however, that his experience with this proof did not alert him to the unreliability of his later argu-

ment. The argument by analogy can be used to prove that every odd prime factor of $a^2 + 3b^2$ is of the form $c^2 + 3d^2$, but it can also be used to prove that every odd prime factor of $a^2 + 5b^2$ is of the form $c^2 + 5d^2$, which is false. (Note that $4^2 + 5 \times 1^2$ equals 21 and that neither of the factors of 21, 3 and 7, can be written as the sum of a square and five times a square.) Such considerations may have prompted the rigor that characterizes Euler's earlier proof. He had evidently forgotten them when he returned to the subject many years later.

Euler's lapse in rigor is closely related to his great strengths, namely his extraordinary imagination and inventiveness. His ability to see new connections and formulate problems in original and perceptive ways made his work a great source of inspiration for generations of mathematicians. His factoring of the numbers $a + b\sqrt{-3}$ into primes by analogy to the factorization of the integers certainly showed great ingenuity. In fact, although his application of the idea in his proof of the case n equals 3 of Fermat's last theorem was premature, later events would prove the idea to be an inspired one. Indeed, the flaw in Euler's argument—the fact that a property derived from the unique factorization of the integers does not necessarily hold for number systems resembling the integers in other ways—would turn out to be a central issue in more sophisticated investigations of the theorem.

Two More Cases

Euler's proof needed some patching, but it essentially established Fermat's last theorem for the case where n equals the first odd prime 3. In the 1820's Gustav Lejeune Dirichlet and Adrien-Marie Legendre proved the theorem for the case where n equals the next prime 5. Their method of proof was basically an extension of the one Euler had used in the proof of the case n equals 3, and the analogue of the crucial equation $p + q\sqrt{-3} = (a + b\sqrt{-3})^3$ was the equation $p + q\sqrt{5} = (a + b\sqrt{5})^5$. (As n increases, the equations encountered in this type of proof become much more complex and the method fails to work.) For the case n equals 5 in order to prove that $p + q\sqrt{5}$ is a fifth power it must be assumed not only that $p^2 - 5q^2$ is a fifth power and p and q are relatively prime, as in the case n equals 3, but also that they have opposite parity (that one is odd and the other is even) and that q is divisible by 5. Dirichlet's proof of this fact was based on a completely rigorous study of the numbers of the form $x^2 - 5y^2$. The proof, modeled on other works of Euler's, including his rigorous study of numbers of the form $x^2 + 3y^2$, and on works by Joseph-Louis Lagrange and Carl Friedrich Gauss, did not rely in any way on analogy to the factorization of the integers.

Some 15 years passed before Gabriel Lamé proved Fermat's last theorem for the case of the next prime: 7. The proof was a great accomplishment, but it did not bode well for future proofs because it was long, difficult and closely bound to the number 7. There was little hope that the proof could be applied to the next case, n equals 11, or to any other cases of the theorem. It seemed, then, that substantial progress would not be made in the study of Fermat's last theorem until a new approach to the problem was discovered.

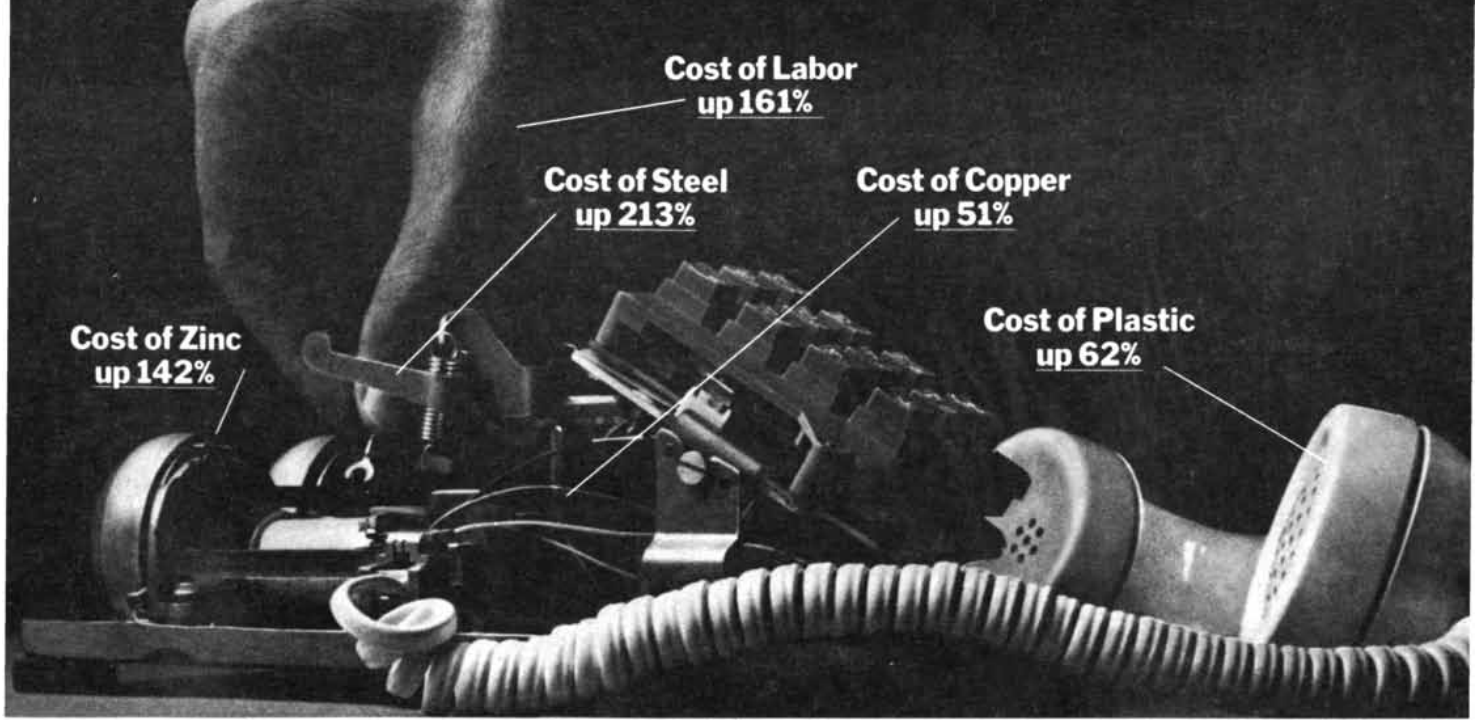
Lamé himself proposed such an approach in 1847. He tried to prove the general theorem, introducing a complex nth root of unity: a complex number α for which α^n equals 1, but α^k does not equal 1 for any positive integer k less than n. The idea was not new. In the preceding century Lagrange had pointed out that introducing α into the study of Fermat's last theorem makes it possible to split $x^n + y^n = z^n$ into n factors, each one containing x and y to the first power. (It is usually easier to deal with lower powers of variables.)

To obtain the factorization note that $1, \alpha, \alpha^2, \ldots, \alpha^{n-1}$ are the roots, or solutions, of the equation $X^n - 1$, and so by the fundamental theorem of algebra $X^n - 1 = (X - 1)(X - \alpha)(X - \alpha^2)\ldots(X - \alpha^{n-1})$. Now set X equal to $-x/y$ and multiply both sides of the equation by y^n. Since only the cases where n is odd are under consideration, the resulting equation is $x^n + y^n = (x + y)(x + \alpha y)(x + \alpha^2 y)\ldots(x + \alpha^{n-1} y)$.

The Cyclotomic Integers

Each of the factors of $x^n + y^n$ is a number of the form $a_0 + a_1\alpha + a_2\alpha^2 + \ldots + a_{n-1}\alpha^{n-1}$, where $a_0, \ldots, a_{n-1}$ are integers. Today the numbers of this type—the numbers in the system made up of the integers and powers of α—are called the cyclotomic integers, because the nth root of unity α is closely related to the problem of dividing a circle into n equal parts. (The complex number α can be interpreted as a point on a circle of unit radius whose center is at the origin of the complex plane; the arc of the circle that lies between 1 and α is $1/n$th of the entire circle.) Like the numbers $a + b\sqrt{-3}$, the cyclotomic integers form a number system resembling the integers in that adding, subtracting or multiplying two cyclotomic integers results in a cyclotomic integer but dividing usually does not.

Lamé's treatment of the arithmetic of the cyclotomic integers resembles Euler's treatment of the numbers $a + b\sqrt{-3}$, although it may have been an independent invention. Given the factorization of $x^n + y^n$ into cyclotomic integers, Lamé proposed applying the "fact" that the product of relatively prime numbers (here by numbers he



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meant cyclotomic integers) can be an nth power only if each of the numbers is an nth power. From this point Lamé saw a fairly direct route to completing the proof that $x^n + y^n = z^n$ is impossible. The problem is that a property derived from the unique factorization of the integers is no more automatically applicable to the cyclotomic integers than it is to the numbers $a + b\sqrt{-3}$. In fact, although the application is valid for the numbers $a + b\sqrt{-3}$ (for a reason that is not obvious), it is usually not valid for the cyclotomic integers, that is, it is

ERNST EDUARD KUMMER made the greatest advance that has ever been made on Fermat's last theorem. In 1847 the German number theorist, working on a system of numbers called the cyclotomic integers, discovered a sufficient condition for a prime number p to be an exponent for which Fermat's last theorem is true, that is, if a prime p satisfies Kummer's condition, then $x^p + y^p = z^p$ is impossible. Today prime numbers that satisfy the condition are said to be regular. When regular primes were discovered, Fermat's last theorem had been established only for the cases where n equals 3, 4, 5 and 7, but Kummer was able to prove the theorem true for all but three of the primes (37, 59 and 67) smaller than 100. More recently sufficient conditions that are far more inclusive than Kummer's have been discovered. All primes within the range of computation, even on the largest computers, have been proved to be exponents for which Fermat's last theorem holds. The theorem has still not been proved, however. In fact, it has not even been shown to be true for an infinite number of prime exponents.

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valid for only a few values of n, where n is an odd prime and α is an nth root of unity.

The unfortunate Lamé was so carried away by his own optimism that he announced to a meeting of the French Academy of Sciences that he had proved Fermat's last theorem by this method. As soon as he had presented a sketch of his proof, however, Joseph Liouville rose to object to Lamé's application of the properties of the ordinary integers to the arithmetic of the cyclotomic integers. It is not clear whether Liouville knew of Euler's similar error. In any case it is remarkable that he was able to instantly spot the weakest point in Lamé's argument. There were other weak points, however. Lamé's enthusiasm was so extreme that he overlooked several other serious difficulties. In fact, his method turned out to be unworkable, even for the exceptional values of n for which his main assumption holds: n equals 3, 5, 7, 11, 13, 17 and 19.

Naturally Lamé was embarrassed by the foolishness of his errors and by having them published in the proceedings of the French Academy for the entire mathematical world to see. "If only you had been in Paris or I had been in Berlin," he wrote to his friend Dirichlet in Berlin, "all of this would not have happened." Actually it would have been enough for Lamé to have read the proceedings of the Berlin Academy of Sciences, where a few months earlier there had appeared the first announcement of a new and important theory of the arithmetic of cyclotomic integers.

Kummer's Contribution

The author of the new theory was Ernst Eduard Kummer. Several years earlier Kummer had realized that for problems in number theory such as Fermat's last theorem the important property of ordinary integers is their unique factorization into primes, and so he had attempted to prove that the property applied to the cyclotomic integers as well. What he proved, however, was that unique factorization usually does not hold for those numbers. (He had published the finding in 1844, but in a rather obscure place.) As Kummer continued to work on the cyclotomic integers, however, it became clear to him that the full power of unique factorization, which could not be obtained in the cyclotomic integers, was not really necessary. His theory of 1847 showed that there was a way to modify the concept of unique factorization so that the modified version could be applied to prove some subtle and useful properties of the cyclotomic integers.

The basis of Kummer's theory was the introduction of what he called ideal prime factors into the arithmetic of cyclotomic integers, in a manner somewhat analogous to the introduction of the imaginary number i, or $\sqrt{-1}$, into the arithmetic of ordinary integers. I shall not discuss the character of Kummer's ideal numbers except to say they restored some of the most important properties derived from unique factorization to the cyclotomic integers and to other number systems, such as the numbers $a + b\sqrt{-3}$, that arise in proving the various cases of Fermat's last theorem. The theory of ideal factorization was unquestionably one of the major achievements of 19th-century mathematics. Through a rather bizarre evolution of terminology Kummer's ideal prime numbers and certain classes of numbers that are related to them are now called ideals. Today ideal theory is a separate branch of mathematics, which is further testimony to the far-reaching importance of Kummer's ideas. His work illustrates a strange fact about mathematical research, namely that it is impossible to predict in advance which lines of investigation will lead to useful discoveries. His study of extremely pure, or theoretical, questions in the field of number theory led him to formulate concepts of unforeseeable value and versatility for mathematics in general.

Kummer's theory led in particular to the greatest advance that has ever been made in the study of Fermat's last theorem. Only a few years earlier the proofs for the cases n equals 5 and n equals 7 had been considered major accomplishments, but in 1847 Kummer was able to prove the theorem true for all prime exponents smaller than 37, thereby, of course, establishing the theorem for all exponents smaller than 37. Moreover, he came close to proving the theorem for all prime exponents smaller than 100. Only the exponents 37, 59 and 67 eluded his method.

Although many historians of mathematics have stated that Kummer's theory grew out of his work on Fermat's last theorem, a careful study of Kummer's work and correspondence indicates that Fermat's last theorem was rather incidental. Kummer's main aim was to find the solution to another problem in the area of higher arithmetic, or number theory: the problem of the higher reciprocity laws posed by Gauss. (The problem of the higher reciprocity laws consists in generalizing to higher powers the famous quadratic reciprocity law that Gauss proved for second powers. Briefly, the quadratic reciprocity law states that if p and q are odd prime integers, then there is a simple relation between the answers to the questions "Does p differ from the square of an integer by a multiple of q?" and "Does q differ from the square of an integer by a multiple of p?") In 1847 Kummer's work on the higher reciprocity laws was still in its early stages, but by 1859 he had achieved

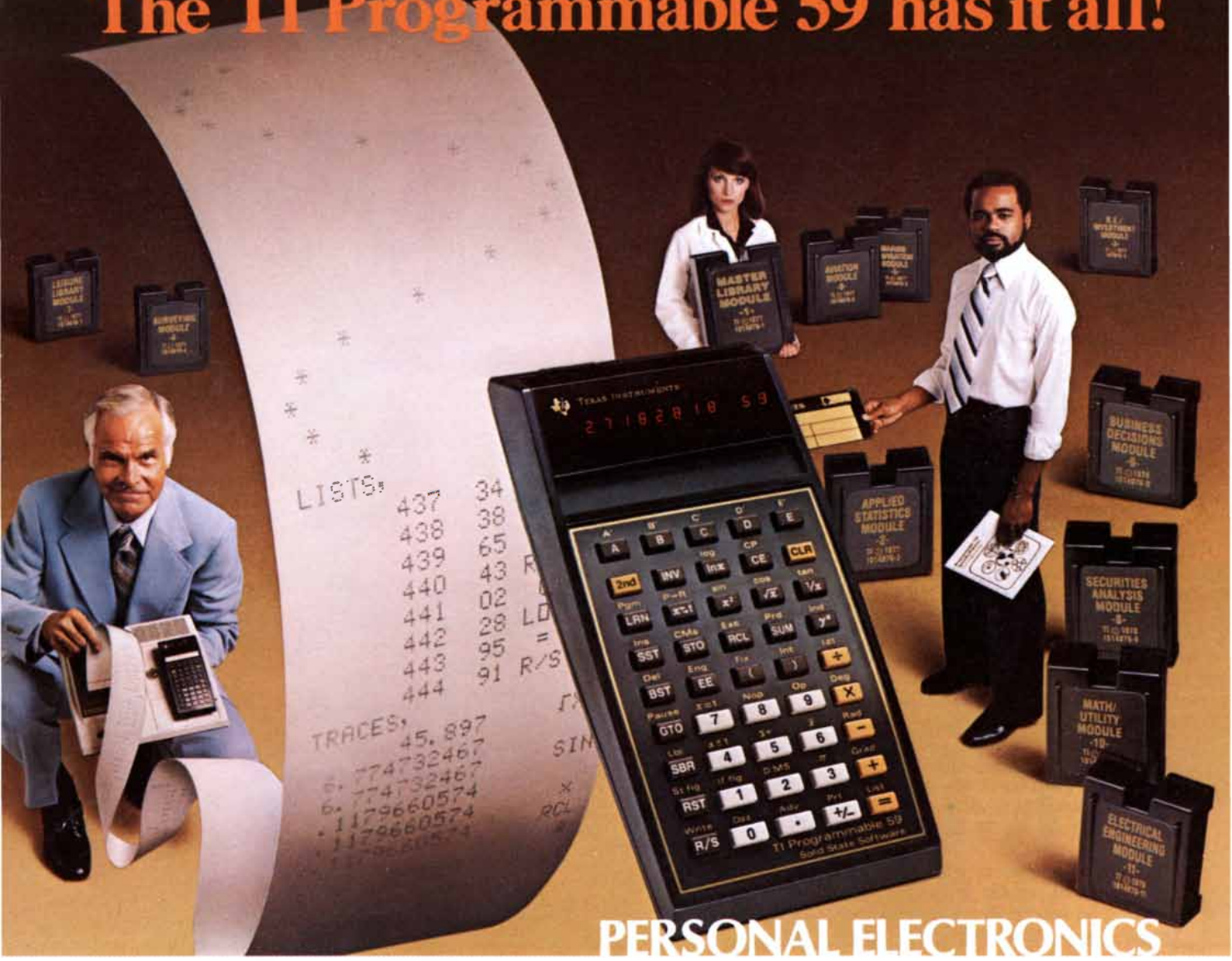
great success, proving a general theorem that was the culmination of his work in number theory. The traditional view that Kummer was motivated by interest in Fermat's last theorem is not entirely false, however, because the theorem is closely related to the problem of the higher reciprocity laws. Gauss himself, although he always denied that he was interested in Fermat's last theorem per se, expressed the hope that from his results concerning the higher reciprocity laws he would one day be able to deduce Fermat's theorem easily.

Regular Primes

Kummer's theory of 1847 was particularly valuable because it provided a sufficient condition for an odd prime p to be an exponent for which Fermat's last theorem is true. In other words, if an odd prime p satisfies Kummer's condition, then $x^p + y^p = z^p$ has no solution. In modern terminology a prime that satisfies the condition is called regular. (Specifically, a prime p is regular if and only if it does not evenly divide the numerator of any of the first $p - 3$ numbers in the series of fractions called the Bernoulli numbers.) Although regularity is a sufficient condition for Fermat's last theorem, it is not a necessary condition. There are primes p that are not regular for which $x^p + y^p = z^p$ has been proved impossible. Of the primes smaller than 100 all but 37, 59 and 67 are regular.

Kummer jumped to the conclusion that the set of regular primes was infinite, but he soon realized he could not prove it to be true. Indeed, no subsequent effort has yielded a proof, although on the basis of intuition and numerical evidence the assertion that there are infinitely many regular primes seems to be as certain as an unproved statement can be. (Oddly enough, it has been proved that there are infinitely many irregular primes. About 60 percent of the primes within the present range of computation are regular, and there are good reasons to believe the majority of all primes are regular. Hence all the prime numbers can be divided into two subsets, the regular primes and the irregular primes, where the set that is expected to be larger cannot be proved infinite but its complement can be proved infinite.)

In later years Kummer established other sufficient conditions for Fermat's last theorem that covered even more prime numbers, including the irregular primes 37, 59 and 67. Since Kummer's time even more inclusive sufficient conditions have been found, some of the most inclusive of them by H. S. Vandiver of the University of Texas. Even the most inclusive conditions, however, have still not been shown to apply to an infinite number of prime exponents. Thus it is still conceivable, no matter



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how unlikely, that Fermat's last theorem is true only for a finite number of prime exponents and consequently that there is some very large number M such that the theorem is false for all prime exponents greater than M.

On the other hand, the sufficient conditions for the theorem are now so inclusive as to cover all the prime numbers that have ever been tested. In other words, all the primes within the range of computation have been proved to be exponents for which Fermat's last theorem is true. The algorithms for checking whether primes satisfy the conditions are quite simple, and over the past 25 years intensive checking has been done on large modern computers, notably by D. H. Lehmer of the University of California at Berkeley, R. G. Selfridge of the University of Florida, Wells Johnson of Bowdoin College and Samuel S. Wagstaff of the University of Illinois. In the early 1970's Johnson's computations established that Fermat's last theorem was true for all prime exponents smaller than 30,000. More recently Wagstaff, working with sophisticated techniques and a large computer at the University of Illinois, has pushed the limit past 125,000.

The Present Situation

These computations also show that a counterexample to Fermat's last theorem, a set of integers x, y, z and p for which $x^p + y^p = z^p$, would consist of numbers so immense that they would be far beyond the range of hand computation or even of computation on the largest existing computers, indeed far beyond the range of any computer that is remotely conceivable. If p is a prime beyond Wagstaff's limit, say p is about 300,000, then it can be shown that $x^p + y^p = z^p$ is impossible unless x, y or z is divisible by p. Therefore z^p must be greater than $300{,}000^{300{,}000}$, a number of at least a million digits. Other results show that a counterexample would involve even more outlandishly large numbers.

Thus in a certain sense Fermat's last theorem is empirically true. If there is a solution for $x^n + y^n = z^n$, then the numbers in it are so inconceivably large that human beings will never be able to deal with them. From a philosophical and mathematical point of view, however, the size of the numbers has no bearing on the validity of Fermat's last theorem. When a mathematician says a statement is true for all numbers, he does not mean that it is true only for all the numbers anyone has ever encountered or ever will encounter. On the contrary, since Fermat's last theorem has not even been proved true for an infinite number of prime exponents, one might say that all the work on the problem has done nothing more than verify the theorem in a

few thousand special cases, and that there is not even any reliable indication of whether the theorem is true.

What, then, is the present status of the work on Fermat's last theorem? It is certainly one of the most famous unsolved problems in mathematics today, but it is not the object of a great deal of mathematical research because no one knows how to attack it. It has withstood Kummer's powerful methods and their many subsequent refinements, and it has still not even been proved for infinitely many prime exponents. If someone were to put forward a concept that promised to bring about some real advances on the problem, it would surely elicit a great deal of interest and activity. At the present time, however, the subject of Fermat's last theorem is more or less dormant.

Interest in the Theorem

In the past 100 years Fermat's last theorem has become a favorite topic of mathematical amateurs, taking a place beside the problems of squaring the circle and trisecting the angle with ruler and compass. Fermat's last theorem differs from circle squaring and angle trisecting in that those tasks are known to be impossible, and so any purported solutions can be rejected out of hand. No such assurance exists for Fermat's last theorem. On the contrary, there is just an outside chance that there is a reasonably elementary proof of the theorem that Fermat did discover. Amateurs rarely succeed, however, in proving even the case n equals 3 of Fermat's last theorem, which was proved by Euler two centuries ago, much less the harder but also well-known cases n equals 5, 7 and 11.

Perhaps the persistence of amateurs—the belief that mathematical results are just "out there" waiting to be noticed—has to do with a general lack of understanding about what it is that mathematicians do. In this article I have attempted to show that mathematics is certainly not cut and dried, that, on the contrary, mathematicians are usually adrift in a sea of unanswered questions. In fact, research in mathematics routinely takes such unexpected turns that the investigator often ends up finding answers to questions quite different from those he set out to answer. Moreover, as the history of Fermat's last theorem shows, even great mathematicians make mistakes. Fermat's last theorem remains in itself an intriguing question, and although its importance is largely a historical accident, it will surely continue to attract the attention of mathematicians until the proof is found. There is every reason to believe that in the future, as in the past, attempts to solve Fermat's last theorem will bring about important advances in mathematics.

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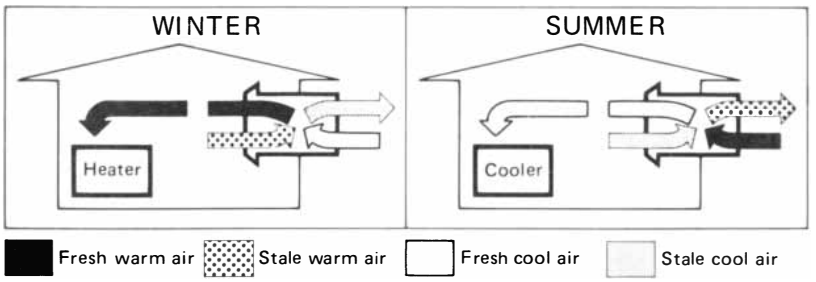

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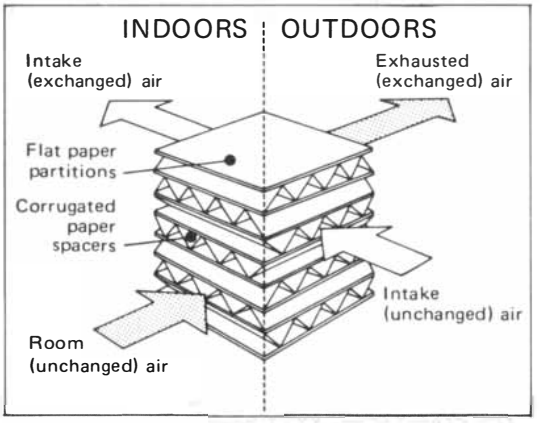

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Did a Supernova Trigger the Formation of the Solar System?

Isotopes found in a few primitive meteorites are probably debris from a massive star that apparently exploded near the developing solar system about a million years before the meteorites formed

by David N. Schramm and Robert N. Clayton

The stellar explosions called supernovas are rare events: among the 100 billion stars of our galaxy there are probably about three supernovas a century. In spite of their rarity, however, supernovas had a seminal role in the origin of the solar system. Much of the material that came together to form the sun and the planets was dust and gas that had been ejected by supernovas over a period of several billion years. Now there is evidence for a more intimate connection with a particular supernova. It appears that a massive star exploded in the vicinity of the developing solar system at about the time the system condensed.

The evidence comes from studies of the chemical elements in meteorites, and in particular from measurements of the abundance of the various isotopes of certain elements. In specimens of material from the most primitive class of meteorites the relative abundances of some isotopes is different from what it is on the earth, in moon rocks and presumably everywhere else in the solar system. The isotope anomalies can be explained by assuming that matter from a supernova was injected into the solar system no more than a few million years before the meteorites solidified. Indeed, there is reason to believe the close association between the supernova and the birth of the solar system was not a coincidence. The collapse of a diffuse cloud of gas and dust into the sun and its planetary system may have been triggered by the concussion from the nearby explosion.

Isotopes are species of atoms that have the same number of protons (and hence represent the same chemical element) but different numbers of neutrons. Oxygen, for example, has three isotopes that are stable to radioactive decay. All of them have eight protons, but they have eight, nine or 10 neutrons. The isotopes are generally identified by the symbol for the element and by the atomic mass number, which is simply the sum of the proton and neutron numbers. Thus the stable isotopes of oxygen are O-16, O-17 and O-18.

It is often said that the isotopes of an element are chemically identical. It is certainly true that chemical processes cannot change one isotope into another, any more than they can change one element into another. For most purposes it is even a reasonable approximation to say that chemical processes do not distinguish between isotopes, so that any one isotope enters into the same reactions as the others. In the formation of minerals, for example, different elements are segregated according to their chemical properties, but all the isotopes of a single element ordinarily remain together. Indeed, isotopes are similar enough in this respect that separating them is a difficult and costly process.

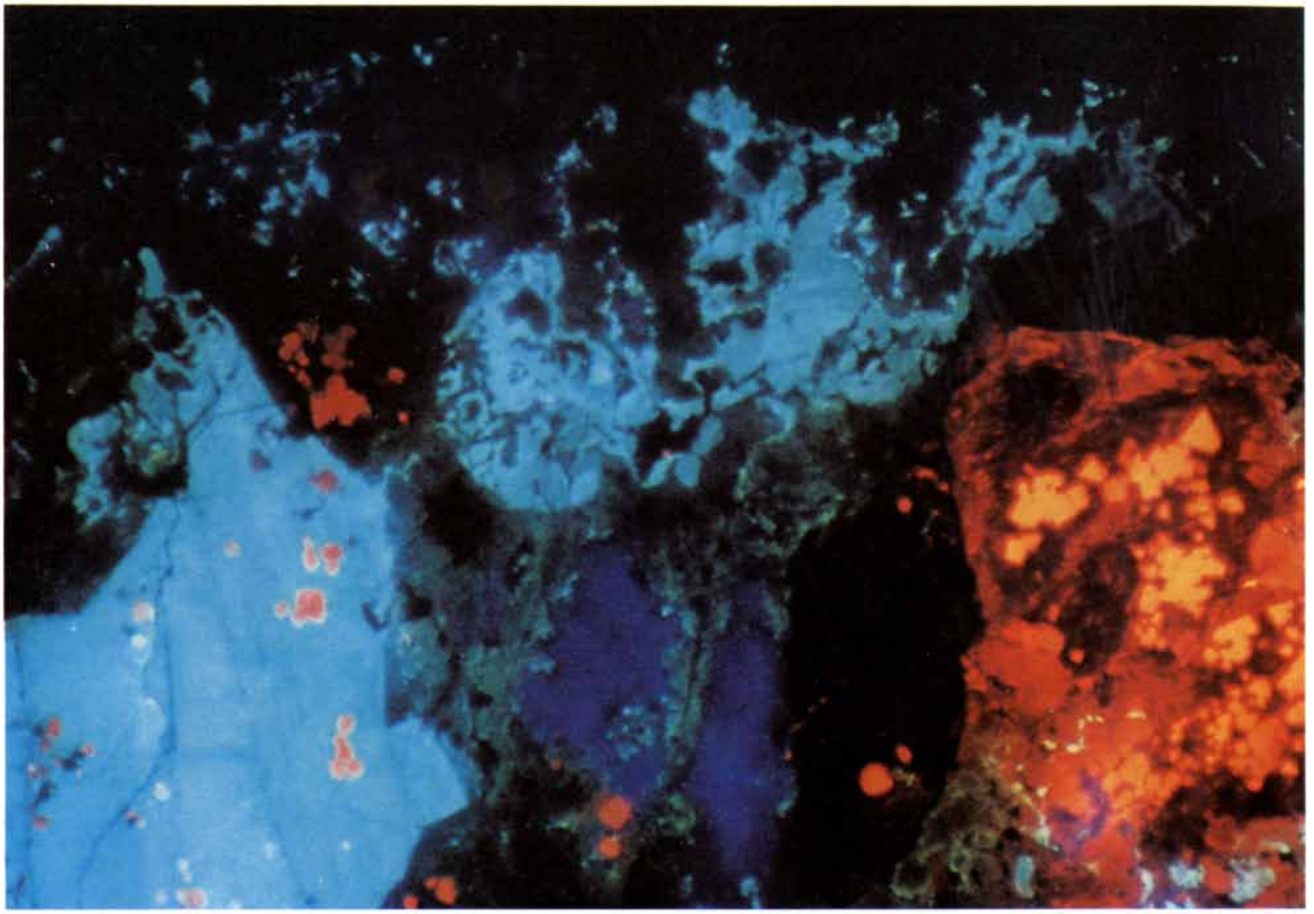
The statement that isotopes are chemically equivalent to one another is nonetheless an approximation: most isotopes do exhibit small differences in their chemical properties. The differences are all determined strictly by atomic mass, which has a slight influence on the rate and the equilibrium point of chemical reactions. The effect is seldom large, but it can be significant. For example, the extent to which the heavier isotopes of oxygen are incorporated into marine sediments is sensitive to temperature, and so the abundance of the isotopes in such sediments can be employed to deduce the temperature of ancient oceans.

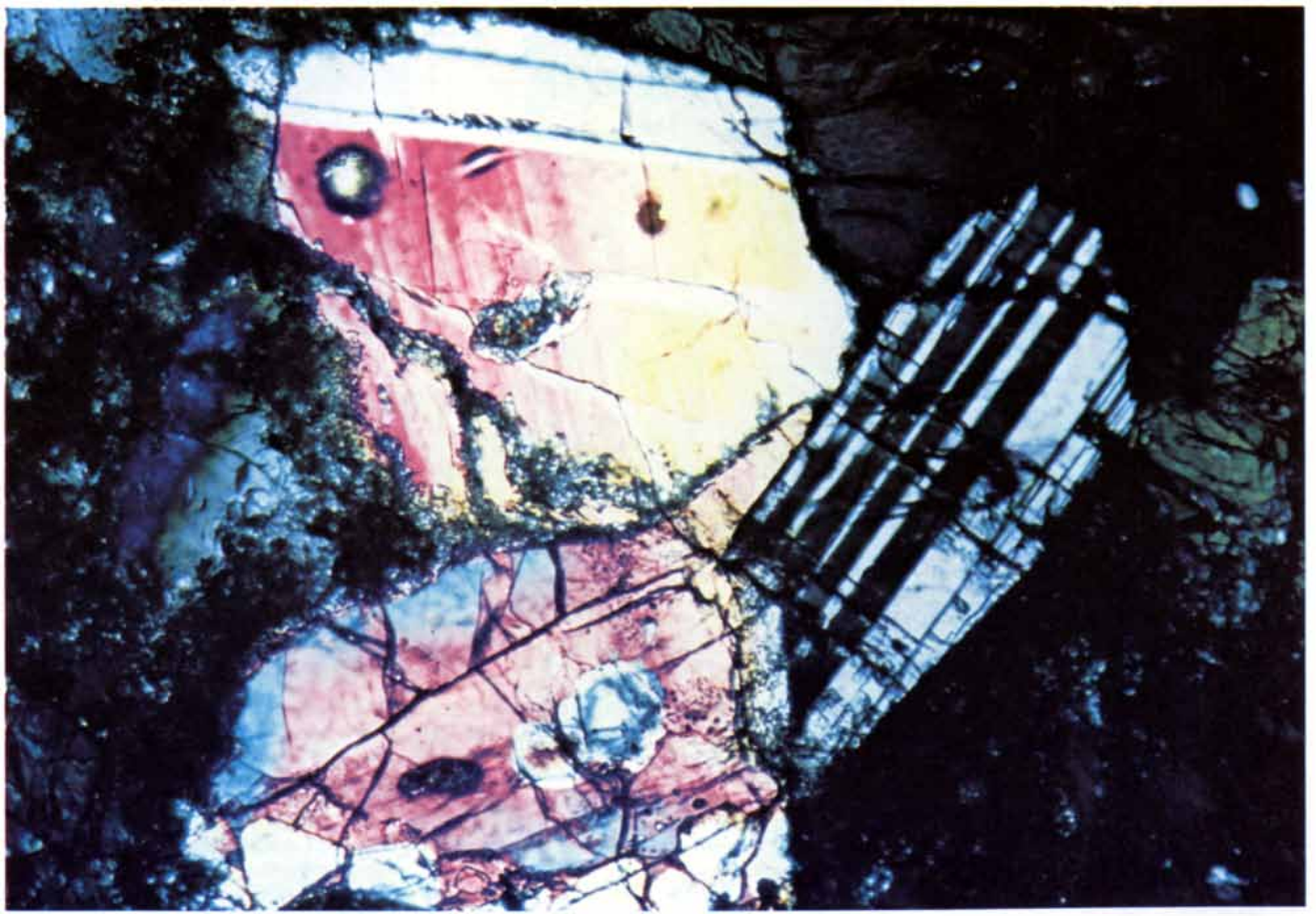
Because the chemical segregation of isotopes is always dependent on atomic mass it follows a simple pattern. If the ratio of O-17 to O-16 is slightly increased by a chemical process, the ratio of O-18 to O-16 must be increased by twice as much since the difference in mass is twice as great. Knowing this relation, it is possible to compensate for the effects of chemical fractionation and retrieve the "true" isotopic abundance.

When these minor chemical effects are taken into account, it is found that the relative abundances of isotopes are constant to high accuracy. Terrestrial oxygen is 99.756 percent O-16, .039 percent O-17 and .205 percent O-18. The same ratios can be observed (after adjustments for chemical effects) in oxygen from the atmosphere, from seawater and from sedimentary or igneous rocks. The amount of oxygen in these substances varies widely, of course, but the oxygen itself seems to be identical in isotopic composition.

Isotope ratios for oxygen and for other elements have been measured in moon rocks and have been found to be essentially the same as they are on the earth. Indeed, the most widely accepted theory describing the origin of the solar system leads one to expect that the same ratios would also be observed if materi-

MINERAL GRAINS from a meteorite include elements whose isotopic composition differs from that of all other known matter in the solar system. The specimens on the opposite page are from the Allende meteorite, which fell in Mexico in 1969. In the micrograph at the top a polished section of rock has been irradiated with electrons so that minerals can be identified by the characteristic color of their luminescence. One mineral of particular interest is anorthite, which is unusually rich in aluminum and poor in magnesium. Grains of anorthite appear light blue; other minerals are melilite (dark blue or purple), pyroxene (red) and spinel (yellow). At the bottom three crystals of anorthite are seen in a photomicrograph made with crossed polarizing filters, which lend their false colors to the crystals. Near the upper left of one crystal is a small crater made by an ion beam employed to extract elements for isotopic analysis. The analysis of this specimen revealed an excess of the magnesium isotope with a mass number of 26, which was created by the radioactive decay of aluminum 26. The aluminum isotope must have been made in a supernova explosion shortly before meteorite condensed. Photographs were made by Ian M. Steele (*top*) and Ian D. Hutcheon (*bottom*) of University of Chicago.

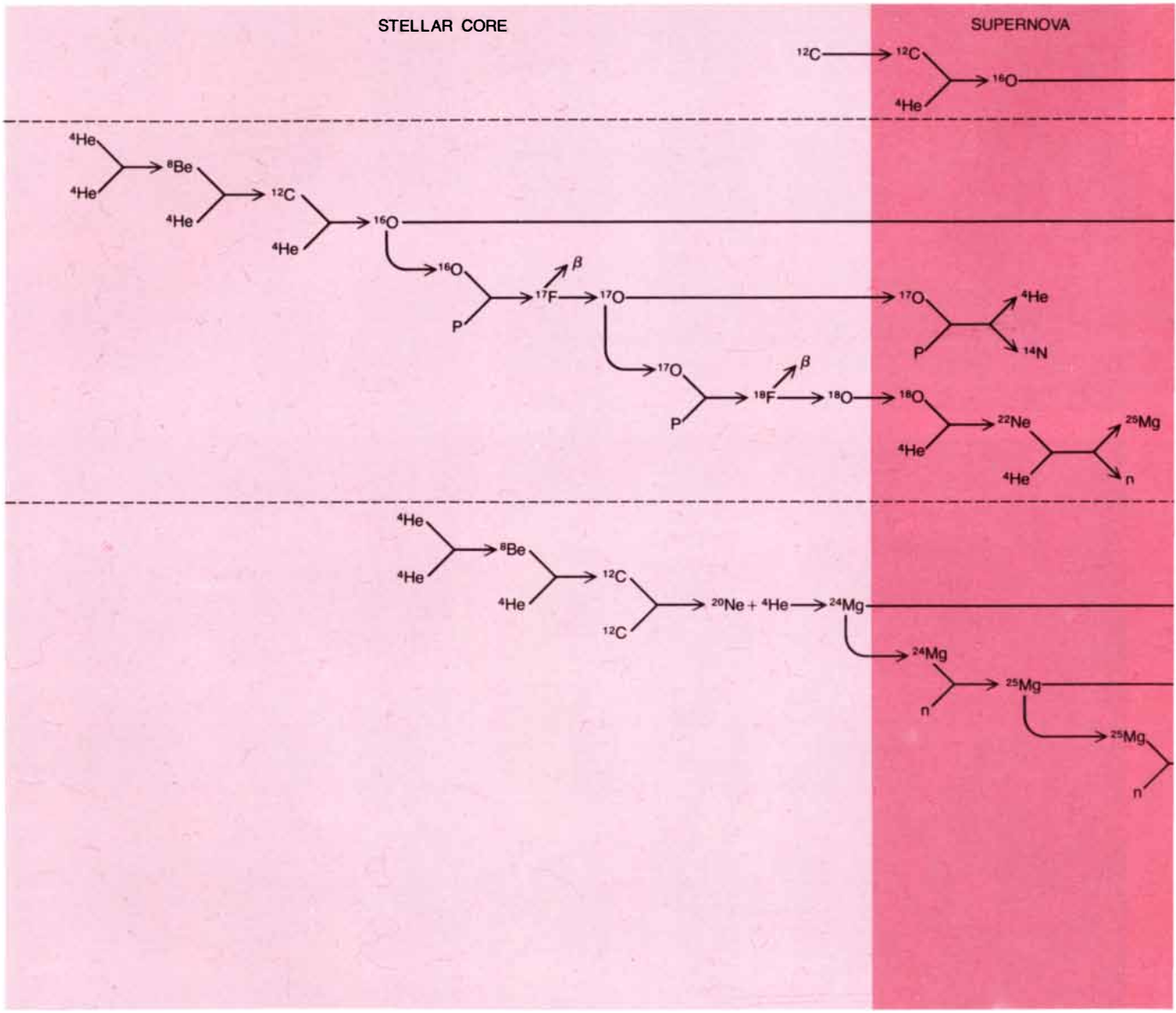




al from any of the other planets could be examined. In this theory the solar system is seen as emerging from the gravitational collapse of a diffuse and swirling cloud of gas and dust. The lightest and most abundant elements in the cloud, hydrogen and helium, were primordial materials, but the heavier elements were mainly the debris from supernovas.

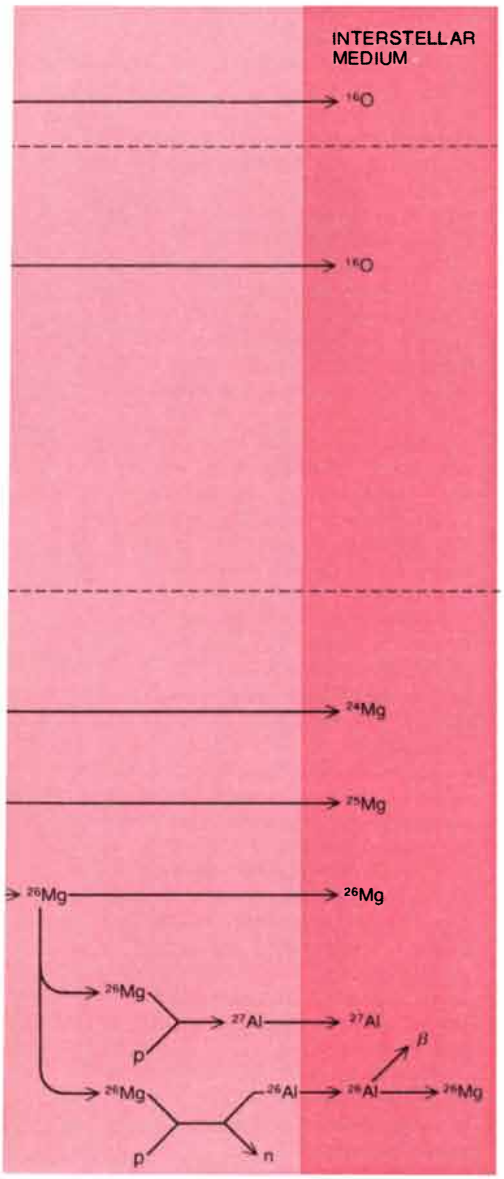
The matter ejected by all the supernovas contributing to the protosolar cloud need not have been identical in isotopic composition or even in elemental composition; in fact, it is likely that each supernova issued a distinctive mix of isotopes and elements. Once these diverse contributions joined the cloud, however, they were thoroughly blended. By the time the solar system condensed from the cloud the isotopic composition was homogeneous and reflected only the average isotopic content of all the supernova debris. The recent discovery of material with an isotopic composition that departs from the solar-system average indicates there was at least one supernova that exploded later than the rest, too late for the matter it ejected to be fully blended with all the earlier contributions.

Although isotope ratios are not substantially altered by chemical reactions, anomalous ratios can be expected to persist today only in material that has been subject to little chemical processing. The reason is that the blending of materials from diverse sources that took place in the protosolar cloud has continued unabated in the chemical systems of the more active planets. Suppose, for example, in the region of the cloud where the earth took form 1 percent of the oxygen had an anomalous isotopic compo-



SYNTHESIS OF THE ELEMENTS in which anomalies in isotopes have been found involves nuclear reactions either in the core of a massive star or in the explosion of a massive star. In either case a supernova is required to eject the material. Unstable nuclei can be further transformed by spontaneous decay after they are ejected. For two of the elements, oxygen and magnesium, a few representative reaction sequences are shown. The most abundant isotopes of both elements, O-16 and Mg-24, occupy important positions in a major nucleosynthetic pathway; in part, that is why they are abundant. The other isotopes are made in more peripheral pathways. Oxygen 17 and 18 are formed in stars during a cycle of reactions whose eventual product is helium 4. O-17 and O-18 nuclei, however, cannot survive the high temperatures that prevail in a supernova. O-17 is a fragile nucleus that can break down in many ways; O-18 readily absorbs a helium nucleus to become neon 22. Some O-17 and O-18 can escape from a star in the stellar wind (*not shown*), but the oxygen cast off by a supernova is essentially pure O-16. Mg-25 and Mg-26 can form during a supernova as a result of neutron capture by the abundant Mg-24. Some of these isotopes can then give rise to Al-27, the only stable isotope of aluminum. Other reactions, such as the simultaneous ab-

sition. It might have been possible to find some trace of that isotopically distinctive oxygen when the planet first condensed 4.6 billion years ago, but it could not be detected today. Oxygen in the atmosphere, in water, in rocks and in living organisms passes continually through an interlocking web of chemical cycles. Precisely because the isotopes are chemically similar the isotopically unusual oxygen would mix with all the rest. The anomalies could not be recognized today by the analysis of terrestrial materials alone, but they could be observed by comparing oxygen

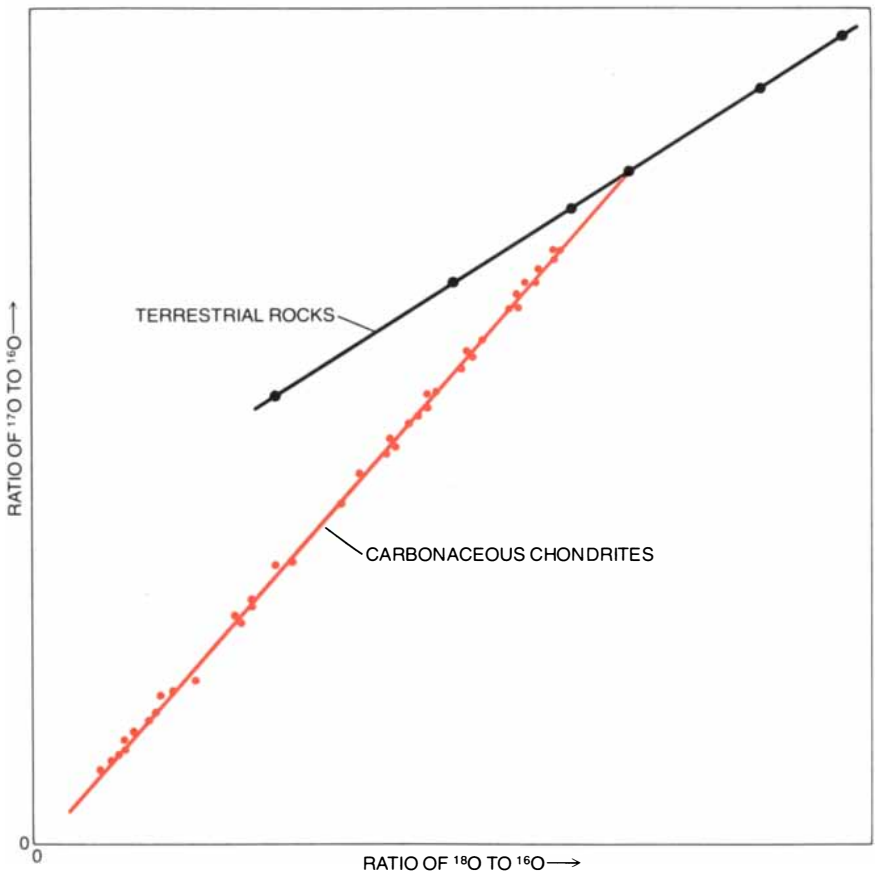


sorption of a proton and emission of a neutron, produce small quantities of the radioactive isotope Al-26. The Al-26 is for the most part made in supernovas and decays with a half-life of 720,000 years to Mg-26. Excess of Mg-26 with Al-27 in a meteorite can be interpreted as evidence the meteorite condensed not more than a million years after a supernova exploded; if delay had been much longer, virtually all Al-26 would have decayed.

from the earth with oxygen from another planet.

One likely place to search for distinctive isotope ratios would be in comets, which have probably been very little altered by chemical processes. Comets, however, are quite inaccessible. The best sources of primitive solar-system materials that are readily available are meteorites, which apparently never formed aggregates sufficiently large for geochemical cycles to become established. Among the meteorites the most primitive class consists of those called carbonaceous chondrites. They are distinguished by the presence of carbon and by small round inclusions called chondrules, which show evidence of having once been melted. It is thought that the carbonaceous chondrites solidified early in the history of the solar system and that little has happened to alter them since.

Most of the recently discovered isotope anomalies were first observed in material from a single carbonaceous chondrite, which fell in 1969 near the village of Pueblito de Allende in northern Mexico. It is now known simply as the Allende meteorite. The same distinctive ratios have since been found in other carbonaceous chondrites, and so they are not peculiar to the Allende material; on the contrary, they are probably common to all meteorites of this kind. It is an interesting question why earlier examinations of meteoritic material failed to detect the isotopic discrepancies. One part of the explanation is probably that the Allende meteorite was much larger than any other carbonaceous chondrite, and so more material was available for study. The Allende meteorite broke into many fragments, most of them only fist-size, but the original body is estimated to have had a mass of more than two tons. Another factor is that the Allende meteorite fell at a time when several laboratories were being equipped to analyze lunar material brought back by the Apollo expeditions. In those laboratories isotope ratios in the Allende material could be measured with greater precision than had been possible with earlier meteorites. On the other hand, the anomalies might have been found a few years earlier if the same laboratories had not been busy analyzing the moon rocks.



OXYGEN ISOTOPES in many specimens of meteoritic material have a composition notably different from that in terrestrial rocks. Chemical processes can slightly alter all isotope ratios, but the change is always proportional to the atomic mass of the isotopes. For this reason the isotopic composition of the earth's oxygen is not quite uniform, but the variations follow a simple pattern. If the ratio of O-17 to O-16 is increased by one unit, then the ratio of O-18 to O-16 must be increased by two units because the mass difference is twice as great. Thus a graph of the two ratios (*curve in black*) is a straight line with a slope of 1/2. In the meteorites called carbonaceous chondrites, including the Allende meteorite, a different relation has been discovered. In these specimens if the ratio of O-17 to O-16 is raised by one unit, so is the ratio of O-18 to O-16; in other words, the graph has a slope of 1 (*color*). These findings suggest the oxygen in the carbonaceous chondrites is a mixture of two components. One component is normal terrestrial oxygen. The other is pure O-16, which has been added in various proportions ranging up to about 5 percent. The most reasonable source for the extra O-16 is a supernova that exploded too late for the debris to become thoroughly mixed with the rest of the protosolar cloud.

The first anomaly to be discovered in the Allende material was in the isotopes of oxygen. It was found in 1973 by one of us (Clayton) in collaboration with Toshiko Mayeda and Lawrence Grossman of the University of Chicago. Oxygen is a common element (it is a constituent of most minerals), and oxygen isotope ratios had been routinely determined in a variety of solar-system materials. All the earlier measurements had been consistent with the hypothesis of a completely homogeneous protosolar cloud. The discovery of a different ratio in some specimens from the Allende meteorite was startling.

The isotope ratios were measured with a mass spectrometer, the instrument that separates atoms on the basis of their mass. Oxygen was first isolated from the Allende material by chemical means and the oxygen atoms were ionized so that they could be accelerated. The accelerated ions then passed through a magnetic field, where they were deflected by an amount determined by their mass. By positioning an ion detector beyond the magnet the number of atoms of each isotope could be counted.

As was pointed out above, terrestrial oxygen is more than 99 percent O-16; the heavier isotopes are trace constituents. In the Allende material the proportion of O-16 was found to be still higher. Comparison of the various ratios in question showed that the discrepancy could not have been caused by chemical fractionation; it was not proportional to the mass difference. In fact, the ratio of O-17 to O-18 was undisturbed. The oxygen in the meteorite seemed to be a mixture of two components, one having the isotopic composition of normal solar-system oxygen and the other being made up of pure O-16. In some specimens the pure O-16 represented as much as 5 percent of the oxygen.

Since O-16 is already the most abundant isotope of oxygen, the addition of 5 percent more of it changes the isotope ratio only slightly: from 99.756 percent O-16 to 99.768 percent. The ratio is consistent enough in other materials, however, for the small discrepancy to be considered significant. It implies that the protosolar cloud was not entirely homogeneous and that some components of it had a different isotopic composition. If the "extra" O-16 had been in the form of a gas, it would have mixed with the rest

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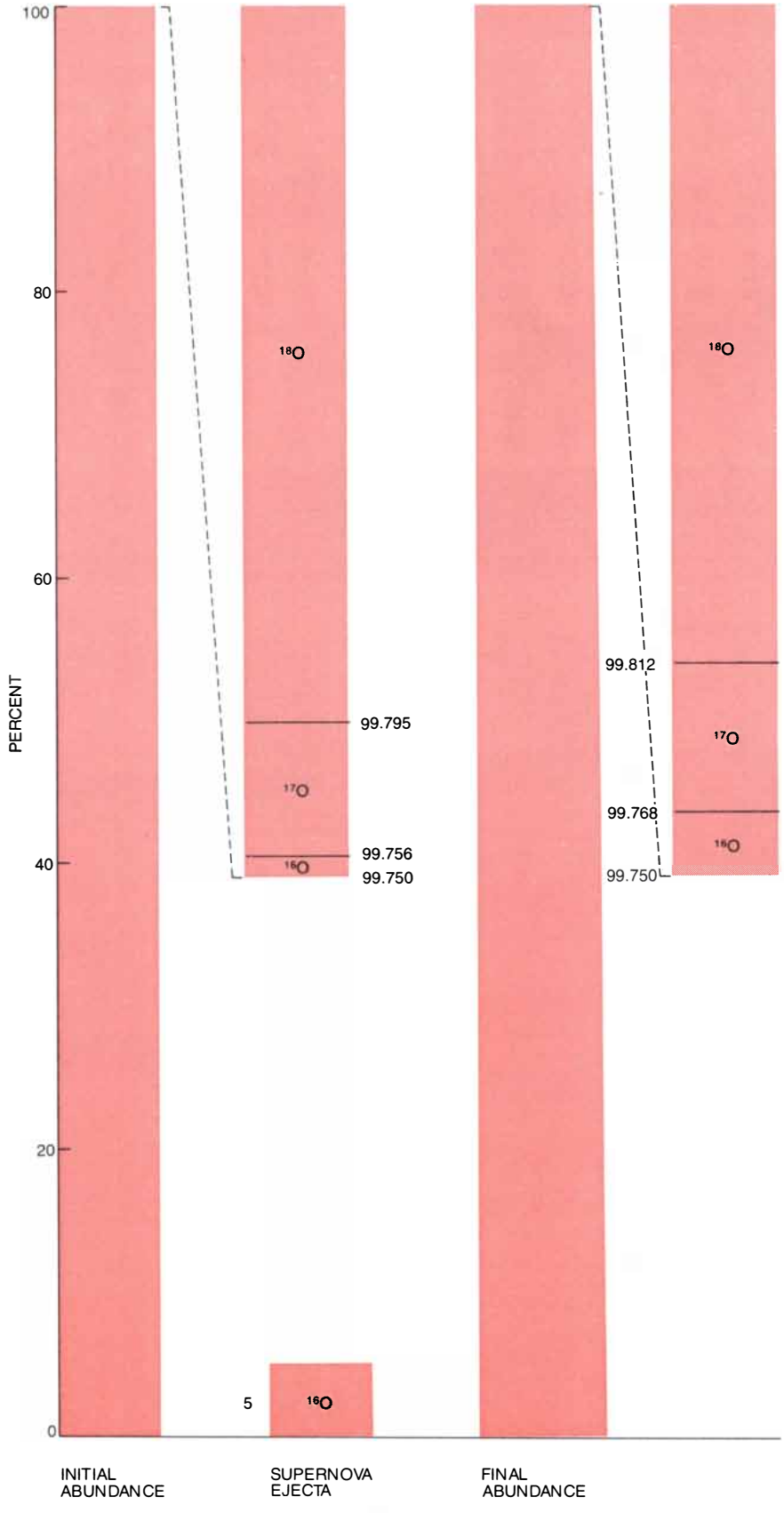

EXCESS OF OXYGEN 16 alters the isotopic composition of the element only slightly because normal oxygen is already more than 99 percent O-16. The composition of terrestrial oxygen (corrected for chemical fractionation) is given at the left, with the uppermost .25 percent shown at an enlarged scale. Mixing such a gas with 5 percent pure oxygen 16 raises the proportion of O-16 only from 99.756 percent to 99.768 percent. Although the enhancement is numerically small, it is significant because the scale of other variations in the ratios is still smaller.

of the cloud and been diluted very rapidly. It is more likely that the anomalous oxygen entered the cloud in chemically combined form within solid grains.

Two possible origins for such grains could be proposed. They might have been primordial grains, and indeed all interstellar grains might have an isotopic composition different from that of interstellar gas. That difference would not be detected in other bodies of the solar system because elements from the solid phase and the gas phase have been thoroughly blended. Alternatively, most gas and dust grains in the cloud might have been identical in isotopic composition, with only a few anomalous grains that were added too late for complete mixing. These grains could have been preserved in some meteorites, whereas they would have been chemically broken down and recombined in the earth and the other planets. As will be seen below, there is strong evidence favoring the latter hypothesis, but the oxygen isotopes alone do not provide a basis for choosing between the two possibilities.

It must be emphasized that the oxygen isotopes carry no information about the date when the peculiar grains were formed. All three oxygen isotopes are stable, and so an unusual isotope ratio (such as 100 percent O-16) could have been frozen into some dust grains hundreds of millions of years before those grains were incorporated into the solar system. The only requirement for explaining the observations is that the grains must have had no chance to mix completely with more typical solar-system materials.

Another isotopic anomaly first observed in the Allende meteorite can be dated. It consists of evidence that when the meteorite formed, it included some quantity of a radioactive isotope of aluminum, Al-26. The evidence was found in experiments carried out by Typhoon Lee, who was then at the California Institute of Technology and is now at the University of Chicago, and by Dimitri A. Papanastassiou and Gerald J. Wasserburg of Cal Tech.

Aluminum has only one stable isotope, with 13 protons and 14 neutrons and hence an atomic mass number of 27. Terrestrial aluminum consists entirely of this isotope. Aluminum 26, with 13 protons and 13 neutrons, has a half-life of 720,000 years, that is, after such an interval half of the Al-26 atoms in a specimen will have decayed. The decay is by positive beta emission: a positron (or antielectron) and a neutrino are emitted and one proton in the nucleus is changed into a neutron. In this transformation the atomic mass number is unchanged but the new nucleus has only 12 protons and 14 neutrons; that makes it a nucleus of magnesium 26, a stable isotope.

Suppose a quantity of Al-26 was in-

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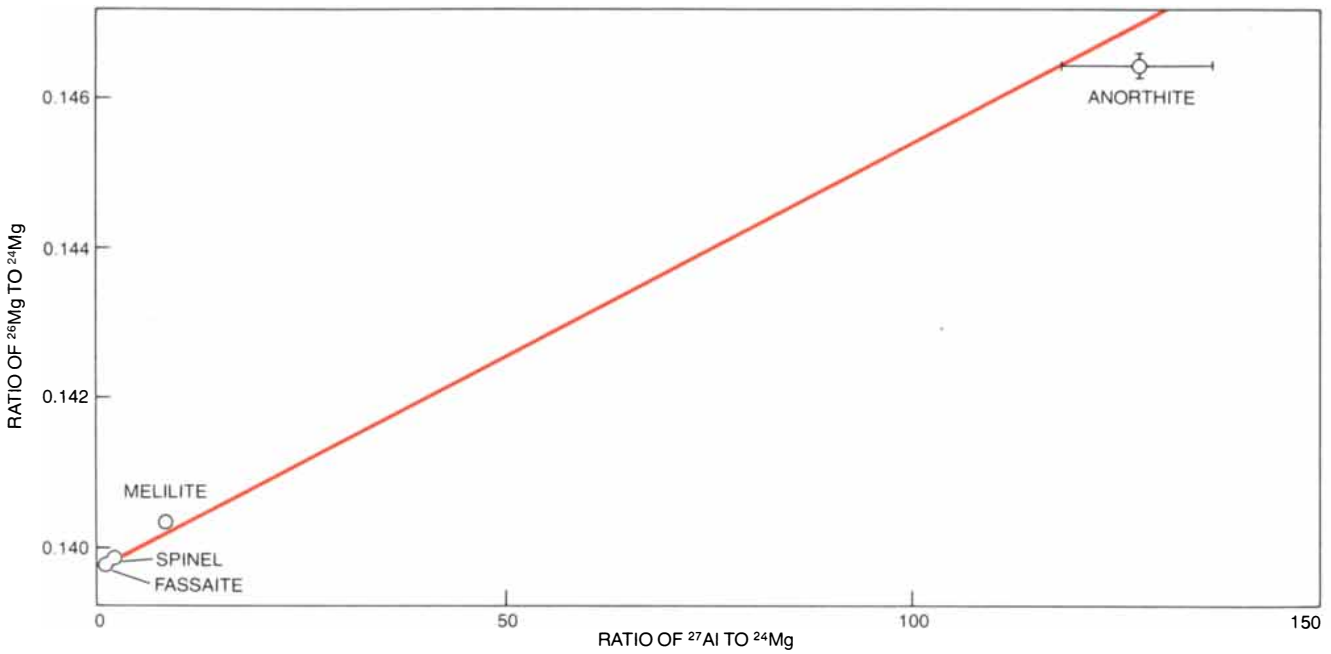
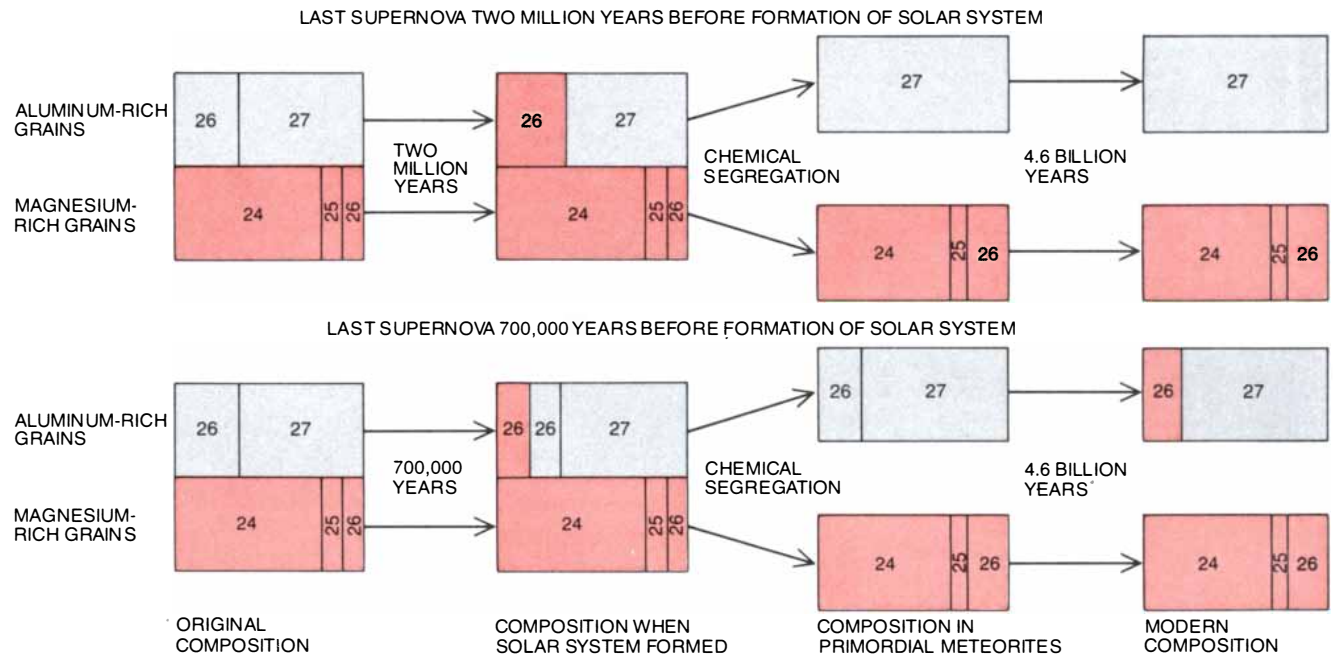


EXCESS OF MAGNESIUM 26 in the Allende meteorite was caused by the decay of aluminum 26. The data are for minerals identified within a single rock inclusion in the meteorite. Normal terrestrial magnesium is 78.99 percent Mg-24, 10 percent Mg-25 and 11.01 percent Mg-26; hence the ratio of Mg-26 to Mg-24 is about .139. Some of the Allende minerals approach this ratio, notably fassaite and spinel. In melilite there is a slight enhancement in Mg-26, and in anorthite there is a substantial enhancement. What demonstrates the origin of the Mg-26 excess is the close correlation with the aluminum content of the mineral (expressed quantitatively as the ratio of Al-27 to Mg-24). Fassaite and spinel contain both aluminum and magnesium, but the magnesium abundance is so great that the small excess of Mg-26 from Al-26 is not experimentally measurable. Melilite is aluminum-rich and magnesium-poor, and anorthite is aluminum-rich and almost devoid of magnesium, and so they display large enhancements of the ratio of Mg-26 to Mg-24. The isotopic enrichment is proportional to the elemental abundance ratio. From the constant of proportionality or from the slope of the graph the original abundance of Al-26 can be calculated: the aluminum in the Allende inclusion has one atom of Al-26 for each 20,000 atoms of Al-27. The measurements were made by Typhoon Lee, Dimitri A. Papanastassiou and Gerald J. Wasserburg of California Institute of Technology.



DECAY OF ALUMINUM 26 provides a means of dating the supernova that produced the isotope. Because Al-26 has a half-life of only 720,000 years little of it survives more than about two million years. If the last supernova that contributed to the solar system had taken place more than two million years before the system condensed, almost all the Al-26 would have decayed before it could be trapped in solid bodies. Chemical processing would then have segregated the aluminum and the magnesium, and no isotope anomaly could be detected. If the last contributing supernova was somewhat later, a substantial fraction of the radioactive isotope would have remained when the meteorites solidified. In the chemical sorting of the elements at condensation that fraction would remain with the rest of the aluminum, and when it finally did decay in a meteorite, it would be subject to little further chemical disturbance. Thus only if the supernova was late enough would it create an excess of Mg-26 in aluminum-rich rocks. Abundance of Al-26 is exaggerated for the purpose of clarity.

troduced into the protosolar cloud just before the carbonaceous chondrites condensed. It would have essentially the same chemical properties as Al-27 and so would appear in a constant ratio with Al-27 in all minerals that include aluminum. After a few million years, however, most of the Al-26 would have decayed, and after the 4.6 billion years that have passed since the formation of the solar system all of it would have been converted into Mg-26. If the rock was never melted or subjected to other processes that could separate the elements, then the amount of Al-26 originally present could be determined simply by measuring the amount of Mg-26.

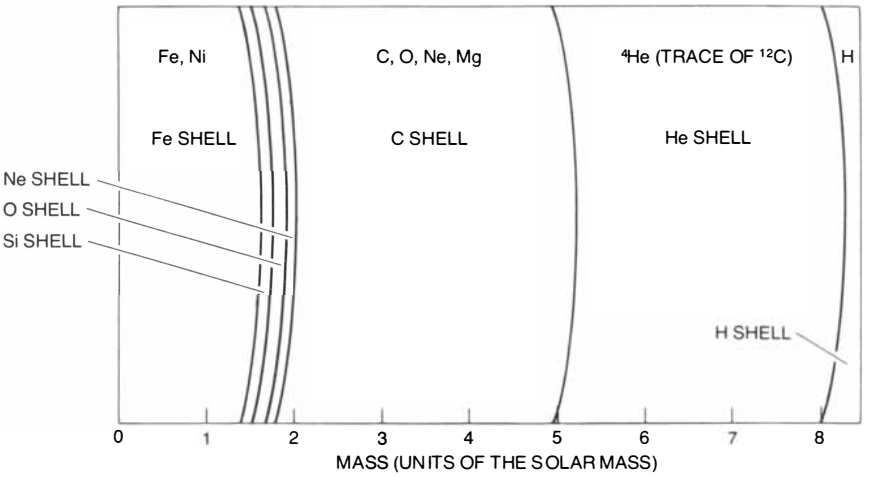
In practice the measurement is not that simple because virtually all minerals include magnesium from other sources; indeed, magnesium is much more abundant than aluminum. There are three stable isotopes of magnesium, with mass numbers of 24, 25 and 26; the normal isotopic composition is 78.99 percent Mg-24, 10 percent Mg-25 and 11.01 percent Mg-26. Thus any Mg-26 created by the decay of Al-26 could be detected only as an excess over the normal abundance of that isotope.

Enhancements of exactly this kind were found in the Allende material by Lee, Papanastassiou and Wasserburg. In some specimens the percent of Mg-26 was increased from its normal level of 11.01 to about 11.5. Anomalies that large were observed only in minerals such as anorthite that are rich in aluminum and poor in magnesium; most of the anomalies were much smaller.

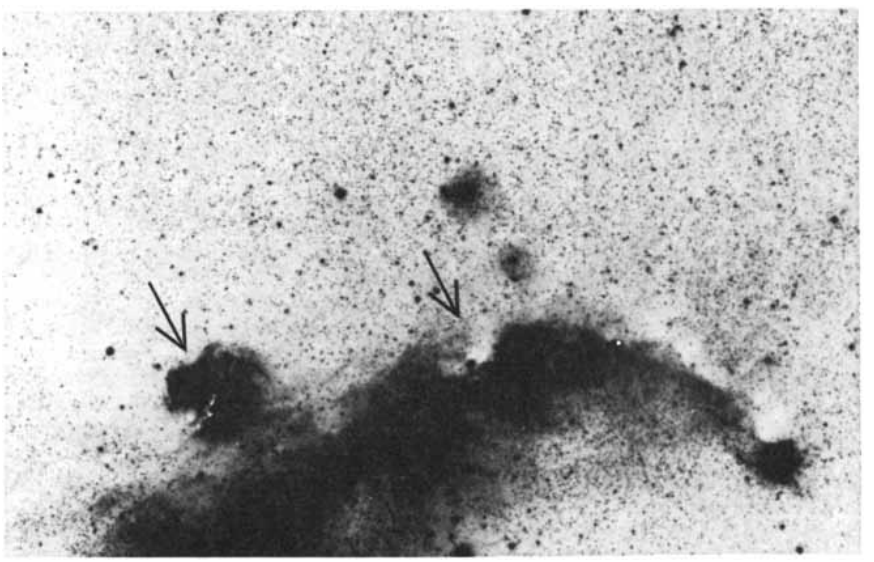
The enhancement in Mg-26 could not have been caused by chemical fractionation; if it had been, there would have been a similar but smaller enhancement in Mg-25, which was not observed. It remained to be demonstrated, however, that the extra Mg-26 was derived from the decay of Al-26; several other nuclear reactions could give rise to the same product. The origin of the Mg-26 could be established, however, by comparing the excess of Mg-26 with the elemental ratio of aluminum to magnesium in each mineral grain. These measurements appear to have a simple linear relation: the greater the Al/Mg ratio, the greater the excess of Mg-26. If the Mg-26 had come from any other source, no correlation would be expected. The correlation of aluminum content and Mg-26 excess in many minerals even makes possible an estimate of how much Al-26 was initially present. It seems the Al-26 was a minor contaminant: about one atom for every 20,000 atoms of the stable isotope Al-27.

The discovery of an Mg-26 excess was particularly important because it supplies a date for the creation of the anomalous material. Since Al-26 is a radioactive isotope, it had to be incorporated into the minerals no more than a few half-lives, or a few million years, after it was created. If there had been any longer delay, all the Al-26 would have been converted into Mg-26. That isotope would have mixed freely with other magnesium, so that no correlation between aluminum and magnesium could be detected. The most reasonable conclusion is that the Al-26 was made in a supernova no more than a few million years before the solar system formed. It is estimated that the condensation of a star the size of the sun takes about 10 million years, and so on the time scale of star formation the two events were essentially simultaneous.

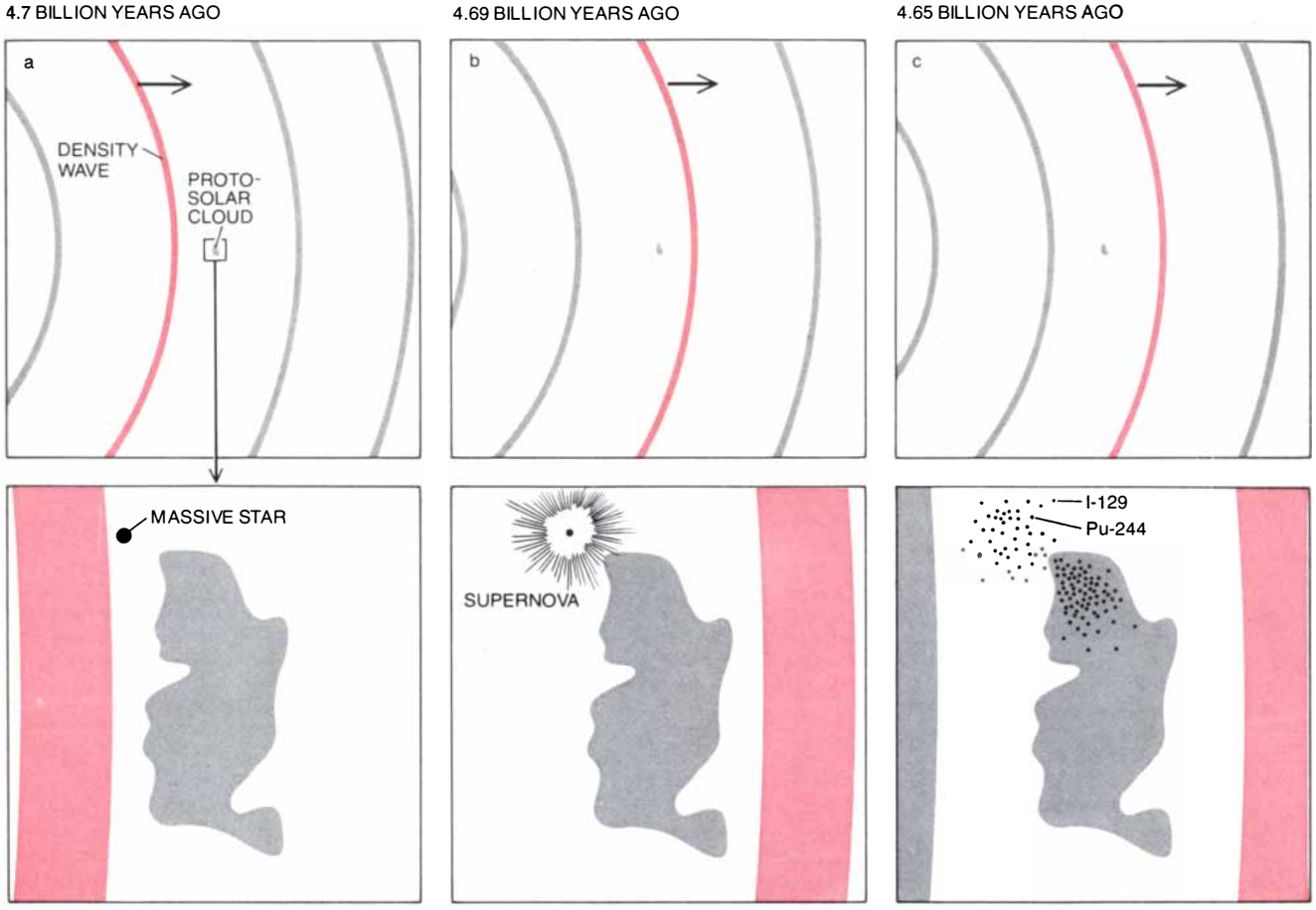
Other explanations are conceivable, but they cannot account for all the data. For example, the Al-26 might have been ejected from a much earlier supernova and have immediately condensed with other elements in solid grains, which later were incorporated without alteration in the meteorites. The radioactivity of the Al-26 would then have been extinct



STRUCTURE OF A SUPERNOVA just before it explodes is a series of shells, which are measured here in units of the sun's mass. The structure is that predicted for a star with an original mass 22 times the mass of the sun; by this stage in its evolution it would have lost, through stellar winds, part of the initial mass, but the actual extent of the outer hydrogen envelope is not known. The star explodes when the core of iron and nickel collapses, releasing energy that blows off the outer layers. Because of differences in temperature and composition each shell contributes a distinctive set of isotopes to the ejecta. Aluminum 26 is probably made only in carbon shell. Heavy elements from silicon to nickel can probably be made only in interior layers.



STAR FORMATION can be observed at the leading edge of an expanding supernova remnant. The bright nebula, which appears dark in this negative image, is in the constellation Canis Major. In the regions marked by arrows, where the ejecta of the supernova evidently collide with matter in the interstellar medium, concentrations of young, bright stars have been discovered. The condensation of the stars may be induced by shock waves from the supernova, and the sun may have formed through a similar interaction with the supernova responsible for the magnesium and oxygen anomalies. This evidence for star formation near supernova remnants was found by William Herbst and George E. Assousa of Carnegie Institution of Washington.



DENSITY WAVES associated with the spiral structure of the galaxy provoke episodes of star formation as they pass a given region within the galaxy once every 100 million years. The isotope anomalies in meteorites seem to include traces from the passage of two successive density waves. About 4.7 billion years ago (*a*) a wave gave rise to the stars, including at least one massive star, in the neighborhood of the cloud of gas and dust that gave rise to the solar system. That star evolved into a supernova (*b*) and injected a quantity of new material into the cloud (*c*). Among the isotopes injected were iodine 129 (half-life 17 million years) and plutonium 244 (half-life 82 million

before the solar system formed, but the macroscopic relation between aluminum and magnesium would not have been preserved. The Al-26 anomaly is uniform throughout centimeter-size volumes of material, and it is unlikely that primordial grains could have been that large; moreover, other elements in the grains have isotope ratios matching the solar-system average. A supernova would not have made Al-26 and simultaneously all other elements with abundances that exactly mimic the composition of the protosolar cloud.

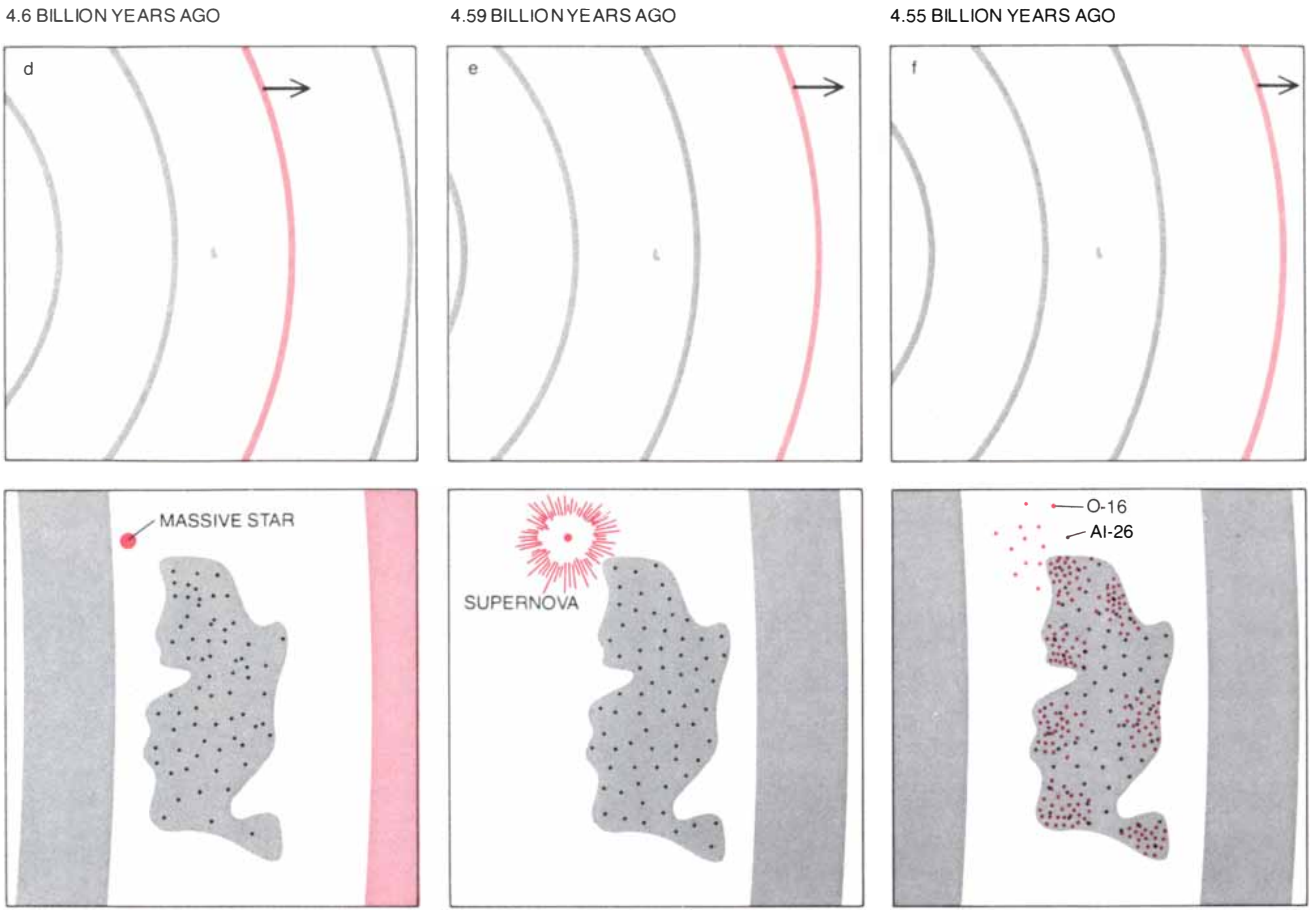
Another possibility is that the Al-26 was made within the allowed interval of a few million years before solidification, but not in a supernova. It could have been manufactured within the protosolar cloud itself if some of the elements already present were exposed to intense radiation. No source of such radiation is known, however, and if it had existed, it would have created many other types of isotopic anomaly that are not observed.

In order to understand why a supernova is the most probable source of Al-26 (and of many other isotopes) it is necessary to consider how the chemical elements were formed. The "big bang" with which the universe began 15 to 20 billion years ago was responsible for very little nucleosynthesis; the matter created in that initial event was almost entirely hydrogen and helium and perhaps traces of a few other light elements such as lithium. All the heavier elements in the universe were made at various stages in the life cycle of stars.

One of the initial stages in stellar nucleosynthesis is the fusion of hydrogen atoms to make helium. This can take place through a direct reaction between hydrogen nuclei and also in a more intricate cycle in which various isotopes of carbon, nitrogen and oxygen effectively serve as catalysts on which helium atoms are built. In a later stage that requires higher temperature helium nuclei fuse to make heavier elements that in turn fuse to make even heavier nuclei. Such fusion generates in particular abundance those nuclei that can be regarded as multiples of the isotope He-4. The first of these, beryllium 8, is unstable and decays if it does not absorb another helium nucleus, but the rest are all abundant isotopes. They include carbon 12, oxygen 16, neon 20, magnesium 24 and silicon 28. If still higher temperatures are available, other fusion reactions can be ignited. In the highest-temperature process that operates in normal stars helium nuclei are stripped from some silicon nuclei and added to other silicon nuclei. In this way iron, with 26 protons, can eventually be created.

A feature common to all these nuclear-fusion reactions is that they liberate energy. In each case the larger nucleus is stabler than the smaller nuclei from which it was assembled, and so heat is released by the fusion. The sequence must stop at iron, however, because that is the stablest of all nuclei. Ejection of this newly made material from its production site in the center of massive stars out into interstellar space requires breaking up the stars in supernova explosions. In addition many other elements between carbon and iron are made solely under the extreme conditions that prevail in supernova explosions themselves.

Only stars that are more than about six times as massive as the sun can



years), some fraction of which survived until the solar system formed. That fraction can be detected in meteorites through the decay products of I-129 and Pu-244, which include isotopes of xenon. About 4.6 billion years ago another wave passed the same region and another generation of massive stars were born (*d*), including one star that was probably within 60 light-years of the protosolar cloud. When this star exploded (*e*), another assemblage of isotopes was added to cloud (*f*). Because those isotopes included the short-lived aluminum 26 it is known that the cloud must have condensed soon afterward, and condensation may have been induced by the supernova explosion.

evolve into supernovas. When such a star has exhausted its reserve of fuels for nuclear fusion, it becomes stratified. At the core there is iron and nickel, then a silicon shell that also includes traces of magnesium and oxygen, and then an oxygen shell, a neon shell and a carbon shell that also has some oxygen, neon and magnesium. At the periphery are the lighter elements: helium (with traces of carbon 12) and an outer envelope of hydrogen.

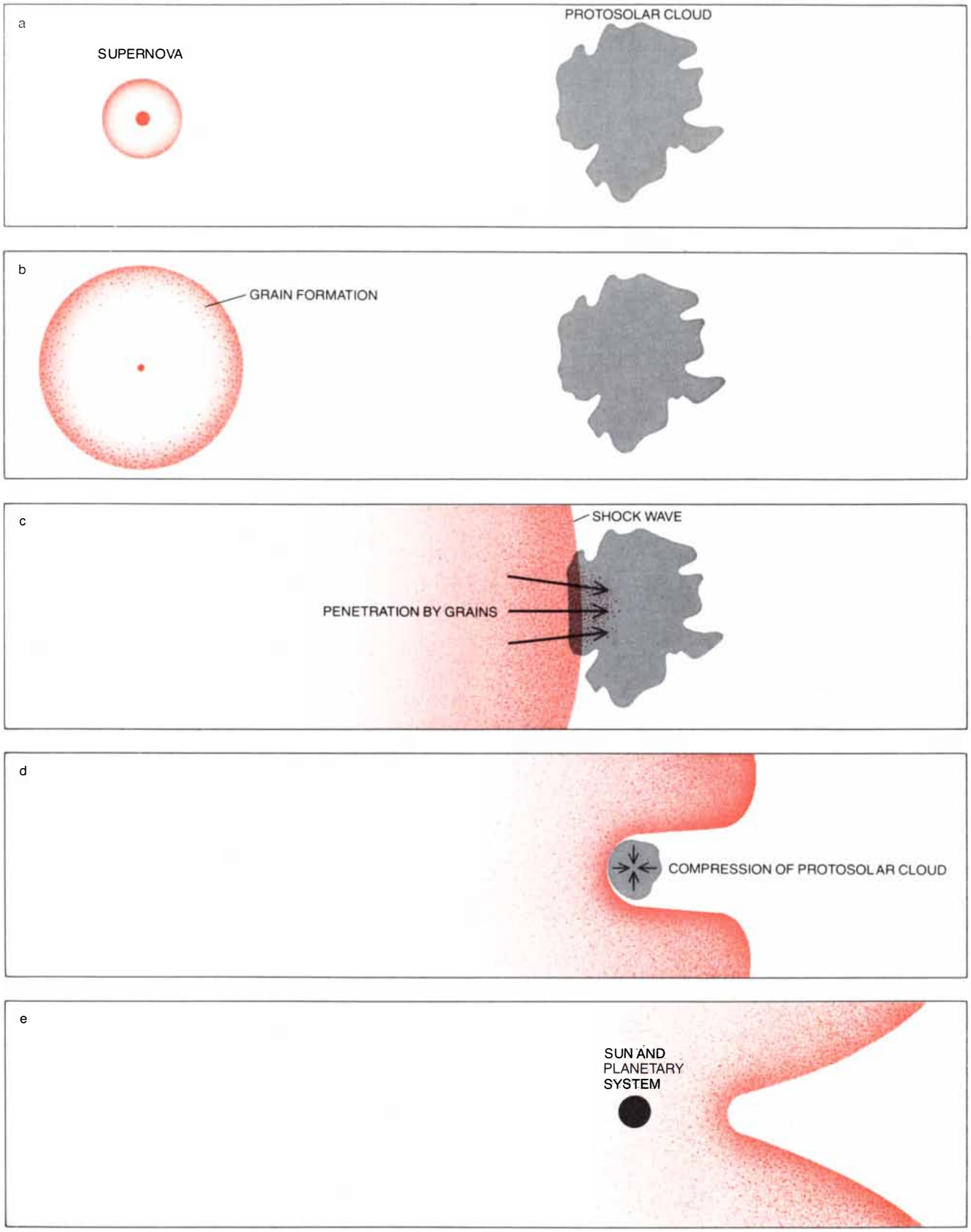
The exact instability that causes such a star to explode is not yet well understood. In some way the energy that sustains the internal pressure of the iron-nickel core is removed from the central region and transferred to the more peripheral layers. This enables the core to collapse under its own gravitational attraction (to form a neutron star or perhaps a black hole), whereas all the outer shells are blown off at high speed. The explosion is so energetic that some supernovas shine brighter than entire galaxies for a short time.

During the explosion the ejected shells are heated to a temperature of several billion degrees Kelvin, making possible nuclear reactions that probably take place nowhere else in the universe (except in specially designed particle accelerators). There is an intense flux of particles, including neutrons, protons and helium nuclei. The neutrons are particularly important in the synthesis of the heavy elements. An iron nucleus, for example, can absorb many neutrons, creating a heavy and extremely unstable isotope of iron that then decays by beta emission. For the elements heavier than lead and bismuth and for some lighter elements the neutrons must be absorbed in rapid succession.

Aluminum 26 is made in the carbon shell of supernovas. Magnesium 24 accumulates in this region through the fusion of pairs of carbon atoms, and the heavier magnesium isotopes are then formed by neutron absorption. Some Al-26 can be made when an Mg-26 nucleus absorbs a proton and immediately emits a neutron. Another production method begins with Mg-24, which can absorb a neutron (to make Mg-25) and then a proton (to make Al-26). In the environment of a star just before and during a supernova explosion many similar reactions with the same end product are possible. None of them is a major nucleosynthetic pathway, but that is not to be expected, since Al-26 and even Al-27 are not particularly abundant nuclei.

Mechanisms of this kind, operating only in supernovas, are responsible for making most of the elements between carbon and iron that are not in the direct helium-nuclei sequence. There are a few exceptions, however, among the more important of which are oxygen 17 and oxygen 18. These isotopes can be formed in supernovas (as a result of neutron capture by O-16, for example), but they do not survive long enough to enter the interstellar medium. O-17 is a fragile nucleus, and at supernova temperatures it breaks down faster than it is formed. O-18 is slightly sturdier, but it readily absorbs a helium nucleus, and most of it is converted in this way into neon 22.

The probable source of the heavier oxygen isotopes found in the solar system is the outer envelope of the senescent stars called red giants. O-17 and O-18 are made there (and in other stars) as



SHOCK WAVE from a nearby supernova explosion may have supplied the compressive forces needed to convert a diffuse cloud of gas and dust into the sun and its planetary system. At first the cloud of material ejected by the supernova must have been in the form of a gas (*a*), but there is reason to believe grains made up of refractory minerals would have condensed fairly early (*b*). When the expanding supernova remnant encountered the protosolar cloud (*c*), some of the grains might have penetrated the cloud like shrapnel, carrying with them the isotope anomalies that are observed today in meteorites. Most of the gas, on the other hand, would have been swept around the outside of the cloud, compressing it (*d*) until it had exceeded a critical density and had collapsed under its own gravitation to form a new star (*e*).

intermediates in the catalytic fusion of hydrogen in the carbon-nitrogen-oxygen cycle. In a red giant O-17 and O-18 might not be destroyed by exposure to higher temperatures, and so some of the atoms could escape in the stellar wind that is continuously cast off by the star's atmosphere. This mechanism could not account for the manufacture of large quantities of O-17 or O-18, but both isotopes are present only in traces. All the O-17 in the protosolar cloud was probably made in this way, and so was most or all of the O-18.

It is notable that both the oxygen and the magnesium anomalies could be accounted for by the introduction of material from just one shell of a supernova: the carbon shell. That is the outermost of the zones containing elements heavier than hydrogen and helium. Al-26 is made only in the carbon shell. O-16 is also present, but there is no O-17 and probably no O-18.

Before the discovery of the Mg-26 excess in the Allende material a few other isotope anomalies had been interpreted as decay products of extinct radioactive species. More than a decade ago John H. Reynolds and his colleagues at the University of California at Berkeley found that in some meteorites there are traces of the inert gas xenon with an unusual isotopic composition. Excess Xe-129 in these meteorites was shown to be a decay product of iodine 129. Four heavier xenon isotopes (Xe-131, Xe-132, Xe-134 and Xe-136) were present in proportions that indicated they were formed by the spontaneous fission of plutonium 244.

Both iodine and plutonium are made in supernovas and nowhere else. From the half-lives of the parent isotopes (17 million years for I-129 and 82 million years for Pu-244) it was possible to deduce how much time had elapsed between the formation of the iodine and plutonium and the trapping of the xenon in the solid matrix of the meteorites. The radioactive isotopes were made about 100 million years before the meteorites condensed. Clearly they could not have come from the same event that gave rise to the magnesium anomalies.

The interval of 100 million years between the two supernovas has an appealing although conjectural explanation. In the disk of our galaxy major episodes of star formation are associated with the spiral arms, which appear bright precisely because young stars are concentrated there. The spiral arms are thought to be density waves that propagate around the center of the galaxy, rather like the compressions and rarefactions of a sound wave. The compressions induce clouds of dust and gas to collapse into stars, and the most massive of these stars live only a few million years before they explode as supernovas. What is most significant, a density

wave passes a given neighborhood in the galaxy about once every 100 million years, and so major contributions of heavy elements to the interstellar gas would be expected at about the same interval.

An obvious objection could be made to this hypothesis. It is not surprising that O-16 and Al-26 manufactured by the earlier supernova left no traces in meteorites: the O-16 would have been thoroughly mixed with all the other oxygen present, and all the Al-26 would have decayed before the solar system condensed. It is disturbing, however, that no evidence of I-129 or Pu-244 from the later supernova has been detected. Such an absence of evidence may never be satisfactorily explained, but two possibilities deserve consideration. First, it should be pointed out that I-129 and Pu-244 are made only by the rapid capture of many neutrons. This process is not well understood, and it is entirely possible it does not take place in all supernovas. Perhaps no I-129 and Pu-244 nuclei entered the protosolar cloud after the most recent supernova because none were made in that explosion. Another possibility is that only the outer zones of the later supernova were able to penetrate the protosolar cloud. The heavier elements may come from deeper layers.

In addition to the extinct radioactive species other anomalies have been found among the stable isotopes of xenon, and still more are known in two other noble gases: krypton and neon. These findings have not been completely explained, although the neon anomaly (which was discovered in 1972 by David Black of the Ames Research Center of the National Aeronautics and Space Administration), as well as the others, may require a nuclear transformation outside the solar system.

Other isotope ratios that are nonstandard have also been detected in material from the Allende meteorite. In the Allende minerals the excesses of Mg-26 and of O-16 are not strongly correlated; a mineral grain that has a large excess of O-16 will not necessarily have a large one of Mg-26, since the Mg-26 excesses are found only in minerals rich in aluminum. In two Allende specimens, however, both anomalies are large, and they have a somewhat different character from the isotopic disturbances in the rest of the material. Part of the effect is a consequence of nuclear processing, but there has also been extensive chemical fractionation: about 10 times as much as in other samples. In one of these specimens unusual isotope ratios have been measured not only for oxygen and magnesium but also for silicon, calcium, strontium, barium, neodymium and samarium. In fact, every element examined in that specimen has been found to be isotopically anomalous. The most reasonable explanation is that the specimen received an exceptionally large proportion of matter from the recent supernova, which condensed before it could mix with other components of the cloud. In particular, the specimen may have been contaminated with a generous share of material from the carbon shell of the supernova.

Given the rarity of supernovas, it would have been a most unlikely coincidence for one to explode at just the time and place where the solar system was about to take form. The close association between the two events need not have been a coincidence; on the contrary, both theoretical arguments and the observation of distant supernova remnants suggest that the explosion may have been instrumental in creating the solar system.

The theoretical calculations show that a sufficiently diffuse isolated cloud of gas and dust with a mass comparable to that of the sun cannot collapse under the influence of its own gravitation without some outside stimulus. Gravitational forces decline as the square of the distance, so that in a cloud of gas and fine dust the cohesive force is determined in large part by the density. Until the density exceeds some critical value the internal pressure of the gas is enough to prevent the cloud from condensing. Once the critical density is reached, however, the collapse is spontaneous.

The need for an initiating event is a long-standing problem in the theory of star formation. The possibility that the explosion of a nearby star might provide the necessary compression was proposed more than 30 years ago; it was discussed in particular by Fred Hoyle and by E. J. Öpik. More recently Paul Woodward of the Lawrence Livermore Laboratory of the University of California has shown that expanding shock waves could apply enough compressive force to create a star. As the shock front passes a diffuse cloud of gas the cloud is enveloped and squeezed into a smaller volume. These generalized shock calculations can be applied to the specific case of a supernova shock hitting an interstellar gas cloud.

Photographs that seem to show this process in action have recently been made by William Herbst and George E. Assousa of the Carnegie Institution of Washington. The photographs are of expanding nebulas left behind by supernovas elsewhere in the galaxy. At the leading edge of such supernova remnants Herbst and Assousa have found concentrations of young, bright stars.

The distance from the protosolar cloud to the supernova that triggered its collapse can be estimated from the energy required for compression, from the observed dilution of the isotope anomalies and from the size of star-forming regions, including those observed by Herbst and Assousa. The best estimate consistent with all these constraints is that the supernova was no farther than about 60 light-years from the cloud, which would make it one of the nearer stars. There is no hope today of identifying the remnant core of the supernova. The explosion itself probably gave the core a high velocity with respect to the solar system, and so it must be far away now. Moreover, there have been some 40 to 50 galactic density waves since then, each one adding another generation of stars and supernovas.

The survival of minerals bearing isotopes that can be traced to a particular supernova is more plausible if those isotopes entered the protosolar cloud as solid grains than it is if they were injected in gaseous form. Gases mix so quickly that disparate isotope ratios would probably be equalized in less than a million years. Steven Margolis of the University of Chicago has recently shown that grains are also more likely to penetrate the protosolar cloud; the grains act like shrapnel, whereas gases from the supernova tend to blow around the cloud. Once in the cloud the grains tend to bunch together, thereby improving the probability that an isotope anomaly will be observable even if the total mass contributed by the most recent supernova was small compared with the mass of the solar system.

These findings are meaningful only if grains are actually formed in supernova explosions. Margolis and Sydney Falk, also of the University of Chicago, with James Lattimer of the University of Illinois have found that the condensation of solid grains is predicted by a standard model of supernova explosions. The grains form not in the explosion itself but as the nebula expands and cools. They derive from interior shells, where the heavier elements are found, and some of the grains that solidify at the highest temperature are just the ones that would have the greatest excess of oxygen 16. Such refractory minerals would be among the first to form and among the most resistant to later vaporization. It is not reasonable to expect that any of the mineral grains found in meteorites today were made in the supernova and have been preserved unaltered; even carbonaceous chondrites have undergone some vaporization, melting or chemical processing. In the modern grains the supernova material was nonetheless an important constituent.

Measured isotope ratios can be combined with other evidence to construct a tentative account of the events that gave rise to the solar system. Some aspects of this account are necessarily speculative, in particular the conclusion that a supernova triggered the collapse of the protosolar cloud. The isotope anomalies have no bearing on this question and show only that the two events happened at about the same time and place. The hypothesis of causality seems

more plausible, however, than that of mere chance association.

At the time the solar system formed, the galaxy had been evolving for at least seven billion years and perhaps for as long as 15 billion, and so there had already been many generations of stars. The dust and gas that is abundant in the plane of the galaxy had been enriched in the heavier elements by stellar nucleosynthesis and supernovas in those earlier generations. It can be assumed that the composition of the dust and gas was uniform throughout the region where the solar system took form as a result of the blending of the contributions of many supernovas and other sources.

About 4.7 billion years ago one in a series of density waves associated with the spiral structure of the galaxy passed through the region. In the wake of the density wave some stars were formed, including a few massive ones that quickly consumed their nuclear fuel and exploded as supernovas. At least one supernova in this generation created iodine 129 and plutonium 244, some of which entered the protosolar cloud. No doubt aluminum 26 was made as well, but all of it decayed during the next several million years. The decay products of such short-lived radioactive species, along with stable isotopes from the supernova, became mixed with the cloud and left no trace.

About 100 million years later, or 4.6 billion years ago, another density wave passed and another generation of massive stars arose. This time a supernova exploded within about 60 light-years of the protosolar cloud; indeed, the supernova may have been created from another part of the same cloud. No iodine or plutonium from that supernova or from any other in the same generation was incorporated into the solar system, and so it seems the nearby supernova may have been one of the first in its generation. Aluminum 26, oxygen 16 and other newly formed nuclei did reach the cloud, along with a shock wave that induced it to collapse into a star and planetary system. In most of the bodies of the new solar system chemical processing obliterated all evidence of the supernova products. Only in the smallest and coldest bodies, the meteorites, were peculiar isotope ratios preserved. Some of those bodies condensed early enough for the radioactivity of aluminum 26 to leave fossil traces.

The words nova and supernova are derived from the Latin *stella nova,* "new star." That was a descriptive term at a time when the phenomenon was perceived as the sudden appearance of a star where none had been visible, but the name took on a degree of irony when it was learned that a supernova represents not the creation of a star but the cataclysmic death of one. Now, however, it appears that a supernova did preside at the birth of at least one star: the sun.

The Prehistoric Ground Drawings of Peru

They look so much as if they were intended to be viewed from the air that they have stimulated much vivid speculation. The archaeological evidence indicates who made them and perhaps also why they were made

by William H. Isbell

In the coastal deserts of Peru are the remains of ancient irrigation systems that held a particular fascination for Paul Kosok of Long Island University, a student of pre-Columbian South America. Some 40 years ago, while he was mapping what he took to be shallow irrigation ditches leading away from tributaries of the Rio Grande on the south coast, Kosok encountered something quite unexpected. In the valley of one such tributary, the Rio Nazca, he came on the giant image of a bird, more than 100 feet long, silhouetted as though it was meant to be viewed from above.

Irrigation ditches seldom if ever form pictures of animals. Kosok inquired among his Peruvian colleagues and learned that many even larger "dirt drawings" of a geometric nature had been noted in the same area. They included long lines (usually called "roads"), zigzags, trapezoids and spirals. Kosok's discovery of a seminaturalistic dirt drawing, however, was a surprise.

Among those who had studied the geometric figures was Toribio Mejía Xesspe of the National University of San Marcos. In a paper published in 1938 he had argued that the ground drawings of the Nazca area were unrelated to irrigation and must have served some ceremonial function in pre-Columbian times. Reconnaissance continued. A huge spider was the next seminaturalistic ground drawing to be added to the list, and others soon followed. Today the total number of such figures exceeds 30.

Before Kosok left Peru in 1941 he speculated that the "roads," at least, might represent ancient astronomical sight lines. He made this suggestion as a possibility worth investigating to Maria Reiche, a German-trained student of mathematics and astronomy who lived in Lima. She has been studying the ground drawings ever since.

What can archaeology and its related disciplines do to explain an odd phenomenon such as the Peruvian ground drawings? Three questions that seem difficult to answer arise immediately: When were the drawings made? Who made them? Why did they make them? In the years since Kosok brought these curiosities to the attention of the general public the first two of the questions have been answered beyond doubt. As for the third question, a number of reasonable conjectures can be proposed. Here I shall review the steps that have led both to the answers and to the conjectures.

The south coast of Peru consists of a range of low hills that runs generally from north to south. Between this coastal rise of land and the foothills of the Andes to the east lies a long lowland basin. For thousands of years the runoff from the higher ground to the west and east carried erosion products into the basin. Most of the eroded material is fine light-colored soil. Occasional flash floods also carried in larger erosion products: stones ranging in size from tiny pebbles to boulders.

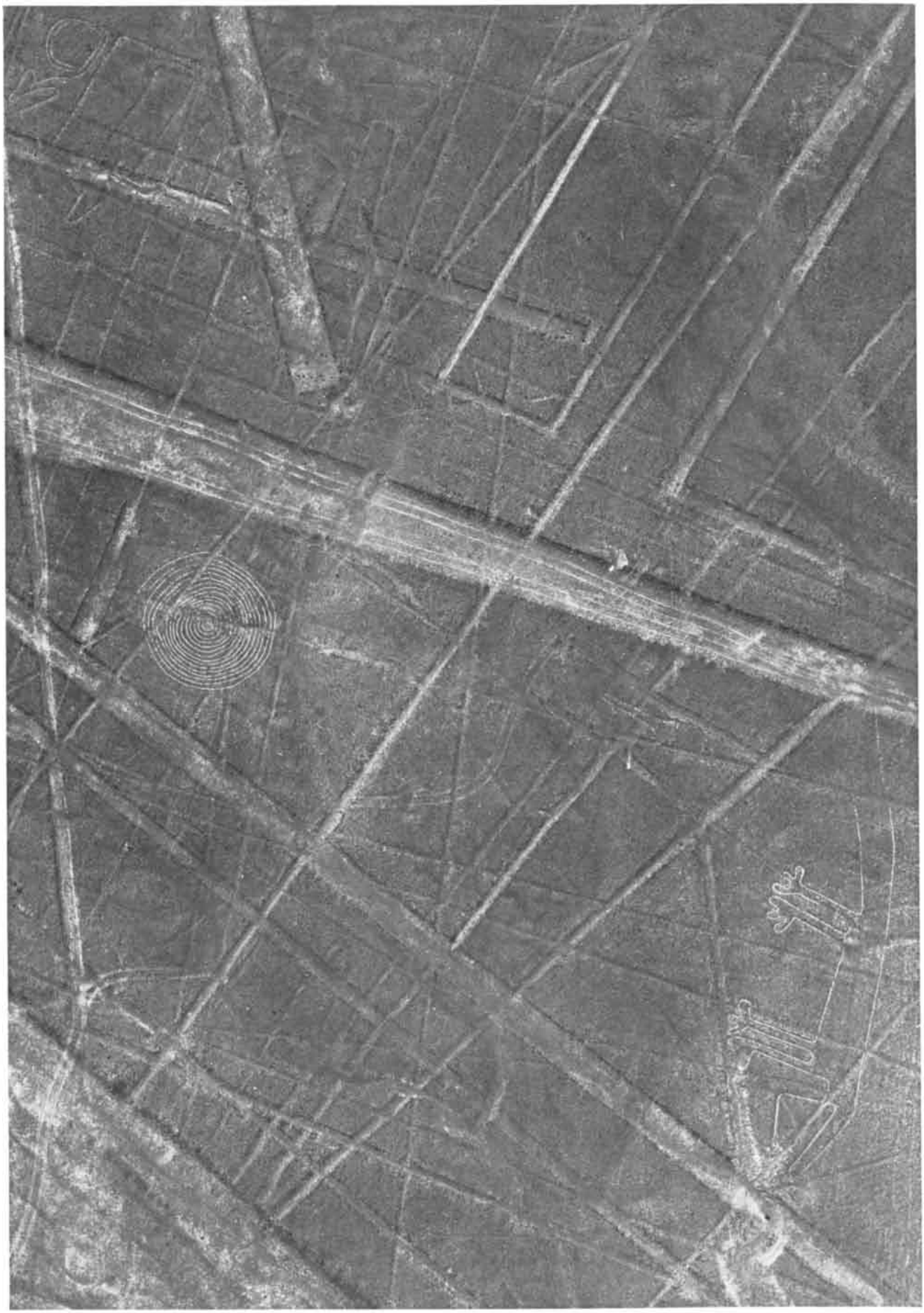
Where the Rio Nazca runs down from the foothills to join the Rio Grande these thousands of years of erosional filling have created a wide and level plain. The strong south winds that blew across the plain carried away much of the dusty surface soil, leaving behind a "desert pavement" of pebbles and boulders. In the early morning the stones were damp with dew, but for the rest of the day they were exposed to the hot desert sun. As a result the stones oxidized until their color became a dark red brown.

This change in color actually reduced the amount of wind erosion in the desert. The south wind still blows today, but as the damp stones dry and get hot in the sun their radiation helps to maintain a surface layer of hot air that serves as a buffer against the wind. As for rain erosion, rainfall is so rare along the south coast of Peru that its erosive effects have been negligible for at least 3,000 years.

The geological circumstances that have produced hundreds of square miles of natural blackboard in southern Peru are nowhere seen better than in the plateau above the valley of the entrenched Rio Nazca: an area about 30 miles long and 15 miles wide known as the Pampa Colorada (the Red Plain). Here if one picks up one of the red brown stones, the light soil that lies under it is exposed to view. Pick up a row of rocks and a light-colored line appears. That is how the ground drawings were made: by selective displacement of the desert pavement.

Natural blackboards are well known to archaeologists in areas other than Peru. In southern Britain, where a thin dark soil overlies formations of chalk, the ancient inhabitants selectively exposed the chalk to form, among other images, the great "white horse" effigies of Wiltshire and Kent. Desert pavement was also removed to form figures in the deserts of southern California, as surveys by Dean R. Snow of the State University of New York at Albany have shown. Indeed, if wind and water erosion were as slight in other desert areas of the world as they are on the south coast of Peru, the total number of ground drawings known today might be substantially greater. However that may be, all such figures present a challenge. How can one determine when the work was done?

DESERT "BLACKBOARD" of the ground drawings, the Pampa Colorada near Nazca, appears in the aerial photograph on the opposite page. A variety of drawings are visible. Roadlike lines run in different directions. The broader cleared areas are trapezoidal in outline. A typical spiral appears at the left center. An animal effigy, perhaps a lizard, appears at the bottom right.



The prehistoric pottery found at grave sites in southern Peru, such as the great mortuary center at Cahuachi, is so distinctive in decoration that it has been given the name Nazca, after the modern city and the river valley where many examples of these wares have been unearthed. The Nazca wares were made from about 200 B.C. to about A.D. 600. Students of Andean archaeology call this span in the prehistory of Peru the Early Intermediate Period.

Some Nazca pots are effigies: they are made in the shape of animals and human beings. Others are painted with animal figures: fish, a trophy-bearing killer whale, seabirds, hummingbirds, reptiles, monkeys and llamas. When it was learned that a similar repertory of semi-naturalistic animal figures was to be found among the ground drawings of the Pampa Colorada, it was hard to avoid the conclusion that the same prehistoric population was responsible for both creations.

WEST COAST OF SOUTH AMERICA is dominated by the steeply rising Andes. In Peru the foothills of the great mountain range reduce the coastal plain to a narrow strip of desert made fertile only where rivers carry highland rains down to the Pacific. Rain along the coast of southern Peru is almost nonexistent.

This evidence, however, was only iconographic; a more direct kind of evidence was soon forthcoming. A limited amount of broken pottery is to be found on the Pampa Colorada. Since the area is too arid for settlement, it seems reasonable to conclude that the potsherds must have been left by temporary visitors to the desert: casual travelers, traders, pilgrims (if the ground drawings were ritual ones) or work gangs (if the making of the ground drawings was an organized effort). In the early 1970's Gerald S. Hawkins of the Smithsonian Astrophysical Observatory collected a number of sherds from the Pampa Colorada and asked Gordon R. Willey of Harvard University and John H. Rowe of the University of California at Berkeley to identify them. Willey and Rowe found that 85 percent of the sherds were Nazca wares. The remaining 15 percent were wares of a subsequent period: the interval between A.D. 900 and 1400. At about the same time Rodger Ravines of the National Cultural Institute of Peru made a collection of sherds from sites on the periphery of the Pampa Colorada; they proved to be exclusively Nazca wares. The peripheral sites give the appearance of being temporary shelters; perhaps they were camps for work gangs.

This evidence, a positive identification of users of Nazca pottery as visitors to the ground drawings, taken together with the presence of the same animal figures in both mediums, settled once and for all the question of who had so artfully disturbed the desert pavement of the Pampa Colorada. The fact remains that the interval between 200 B.C. and A.D. 600 is almost a millennium. Might it be possible to find more precisely when during the Early Intermediate Period such activity took place? Precise dating of this kind became possible after World War II with the development of carbon-14 analysis. Some of the long lines laid out on the Pampa Colorada terminate where a wood stake was driven into the ground. In 1953 W. Duncan Strong of Columbia University collected a sample from such a stake for carbon-14 analysis. The analysis showed that the wood was from a tree that had been cut down in A.D. 525 (± 80), very late in the Early Intermediate Period. To be sure, the finding can at best only suggest when the long line associated with this particular stake was laid out (and perhaps not even that if one considers that the stake might be the second, the third or the 30th replacement of the original one). Nevertheless, the carbon-14 date falls within the limits of Nazca times and therefore lends weight to the other evidence.

Now that the questions "Who?" and "When?" are answered, it is time to consider the question "Why?" Again archaeology and its related disciplines,

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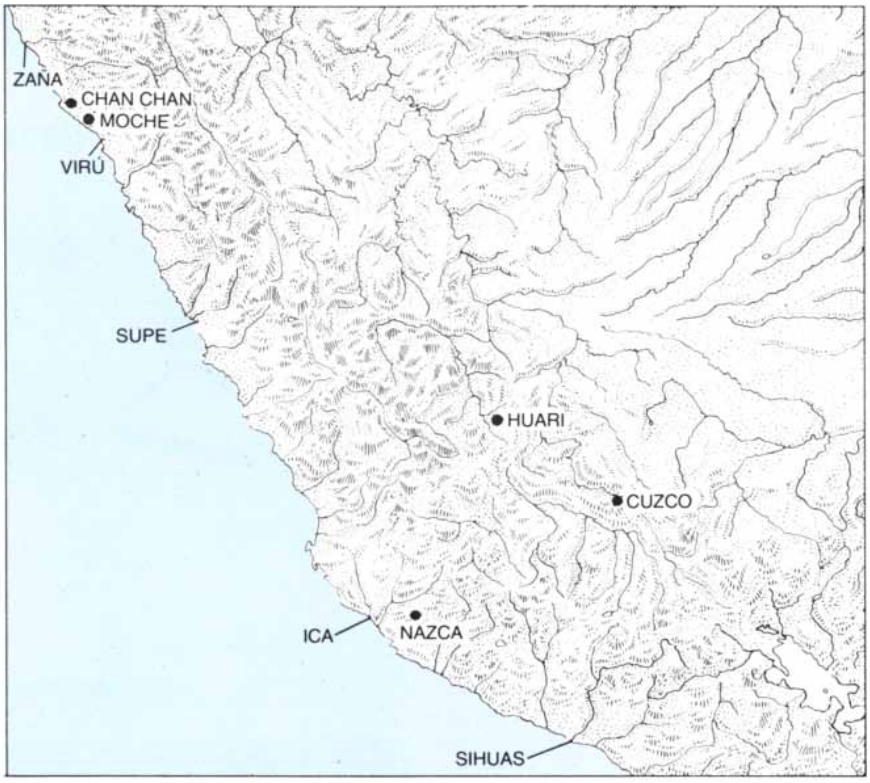
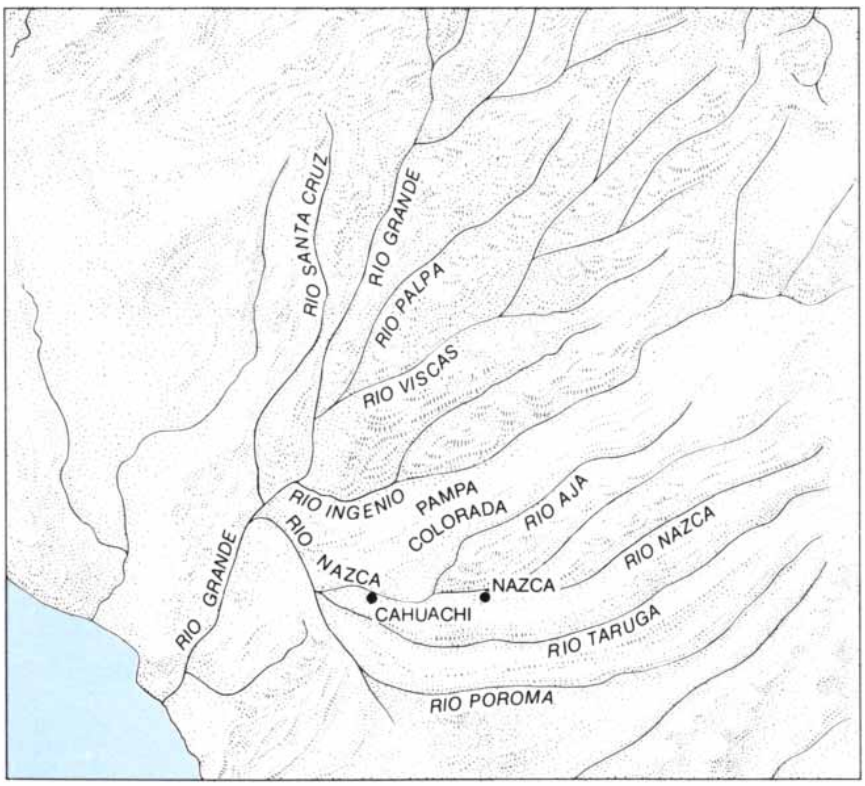


GROUND DRAWINGS have been located in the coastal deserts of Peru from as far north as the Virú valley to as far south as the Sihuas valley. They are found in the vicinity of Supe, Lima and Ica and have been reported but not confirmed in the Zaña valley. They are commonest in the vicinity of Nazca, where ancient graves have been found to contain distinctive pottery.



DESERT PLATEAU north of the Rio Nazca, the Pampa Colorada, is 30 miles long and 15 miles wide. It has the greatest concentration of ground drawings in Peru. The nearby ruins of Cahuachi, a mortuary site of the Peruvian Early Intermediate Period (200 B.C.–A.D. 600), is one of the numerous sources of the Nazca-style pottery that is indigenous to this part of Peru.

ethnology in particular, offer useful clues. For example, it may seem peculiar that any population would invest a significant amount of energy in constructing displays that are best seen from the air rather than from the ground. Indeed, the people who made the chalk figures in Britain did so on hillsides where they are clearly visible. On the other hand, parallels to the Nazca displays do exist. Among the ambitious earthworks raised by the Hopewell cultists of pre-Columbian North America are a number of figures that would certainly be less readily recognized from the ground than from the air. The great serpent mound in Ohio is an outstanding example. The same is true of the California desert figures documented by Snow. Since this feature of the Nazca ground drawings is not unique, it would seem unnecessary to suppose the drawings were made to be viewed from the air, even if one could imagine how it was done.

What about the cost in energy that had to be paid to shift stones and create a ground drawing? Here again archaeology offers a clue. Elsewhere in Peru during the Early Intermediate Period the local farming populations were engaged in work-gang labor of staggering proportions. For example, the largest prehistoric pyramid in Peru is located in the valley of the Rio Moche. An enormous temple platform, the Huaca del Sol, called for the manufacture of 140 million adobe bricks. Studies of the construction methods and of the bricks themselves indicate that the work was done by crews of unskilled laborers. Each crew, probably composed of men recruited from a single region, manufactured its own bricks, transported them to the construction site and there built one or more of the columns of brick that make up the pyramid. Each crew's work is still identifiable by the distinctive marks on different batches of brick.

The pyramidal structures and other monumental buildings of the Early Intermediate Period in northern and central Peru evidently represent the apogee of a pre-Columbian period of Andean ceremonial architecture. Some temple platforms are also found along the south coast of Peru, but they are modest compared with the massive adobe edifices raised to the north. By the same token ground drawings were laid out at desert sites along the north and central coast of Peru, but they are modest by Nazca standards.

Those who are not familiar with the ground drawings may find it hard to compare the effort involved in their creation with the effort involved in making and laying bricks. The reason is that the discussion so far has been confined largely to the animal effigies. In terms of the tonnage of stone shifted the animal portrayals represent only a fraction of the total energy input. For example, an

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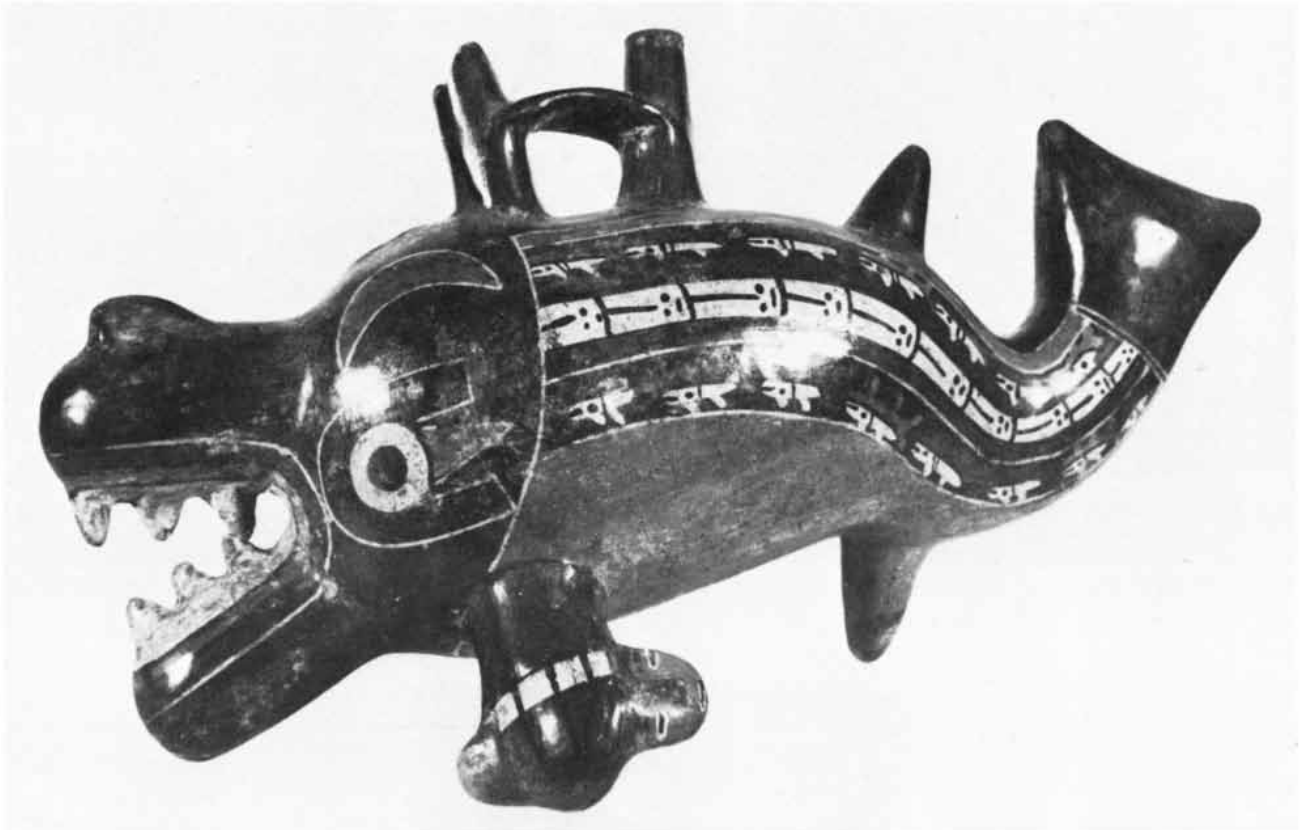


KILLER WHALE is the subject of this ground drawing on the Pampa Colorada (*top*). The circular object seen to dangle below the jaw of the whale is a human head, a war trophy that is regularly depicted in Peruvian pottery designs and other decorations of the pre-Columbian period. The effigy pot (*bottom*) also depicts a killer whale, complete with a trophy head. The effigy was unearthed near the Pampa Colorada; it was made during the Early Intermediate Period of Peruvian prehistory. It appears here courtesy of Wilfredo Loayza.

animal may be sketched out by a single continuous line. Many of the lines, however, originate at a distant trapezoid or rectangle and then return to it.

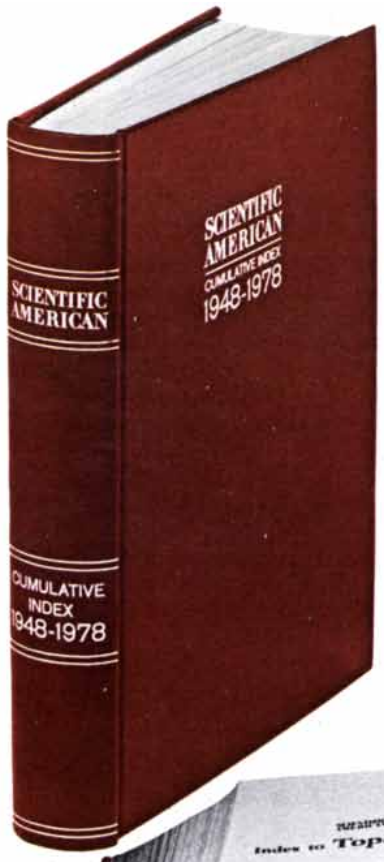
The geometric figure that provides the point of origin may be more than a kilometer long. The same figure may also be the point of origin for a series of zigzags or for a single line that runs straight across the desert eight kilometers or more before terminating at a stake or a heap of stones. Only if one were to measure the effort required to duplicate a representative ground drawing today would it be possible to estimate the total prehistoric investment of labor at the Pampa Colorada in any but the most general way. It nonetheless seems reasonable to suppose the ground-drawing efforts in the Nazca area represent an energy investment roughly comparable to that which created the monumental adobe structures to the north.

Whether or not the two efforts were equal in scale, both seem to have fulfilled similar economic functions. These functions are related to the drafting of community labor for public works. The nationwide controls exercised by the Incas at the time of Pizarro's conquest of Peru are well known. It is less well known that the earliest of the Incas' imperial predecessors had a similarly centralized regime. Whereas the Incas' capital was at Cuzco, that of the earlier empire was at Huari.

Provincial administrative centers, all linked to Huari, collected and stored large quantities of foodstuff and goods produced in the rural hinterland. If there were local or regional variations in agricultural or cottage-industry productivity, the overall economy was balanced by adding to the centralized stores or by exchanges among the provincial centers. Such economic uniformity enabled the population of prehistoric Peru to expand and then to stabilize at a level higher than that in the preceding period of regional autonomy.

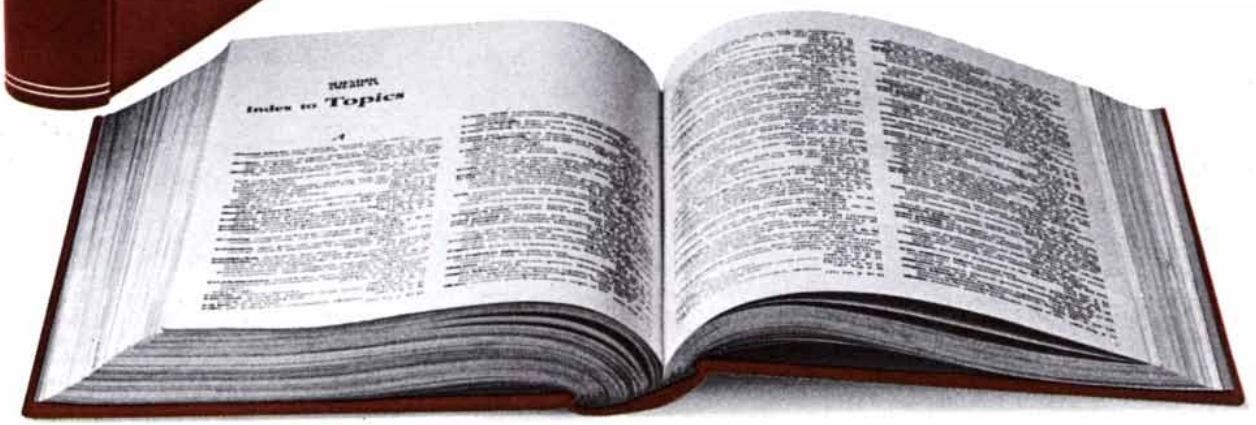
Such was far from the case during the Early Intermediate Period. That some kind of control was exercised over community labor is apparent in the construction of the great adobe temple platforms. There is no evidence, however, that the people of the period built administrative structures or storage facilities such as were characteristic of the imperial regimes of Huari and Cuzco. This suggests that each region was subject to local economic fluctuations and directly related population changes.

Consider the effect of such fluctuations. A series of good agricultural years in a region would have led, in the absence of any local control mechanism, to a population increase. Thereafter a series of bad years would have been disastrous for the larger population. The way to avoid this kind of response to economic fluctuations is to keep the



An advance announcement of the new SCIENTIFIC AMERICAN CUMULATIVE INDEX MAY 1948-JUNE 1978

This November the Editors of SCIENTIFIC AMERICAN will publish a Cumulative Index to the 362 issues of the magazine from May 1948 through June 1978. This new Index embraces all the issues published under the present editorial direction, recording 30 momentous years of intellectual history.



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

Listing of Tables of Contents
A chronological listing of the contents of all 362 issues that permits ready identification, by titles and authors, of the articles cited in the two foregoing indexes.

Index to Authors
An alphabetical listing of all authors of articles.

Index to Titles
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The Index to Topics is a rotated key-word index. That is: The topics cited in a given article are entered together in a cluster:

DNA, genetics, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

Each of these "key words" takes its turn as the first term in the cluster in its entry and re-entry down through the alphabet of the Index of Topics:

DNA, genetics, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

genetics, DNA, molecular structure, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

molecular structure, DNA, genetics, x-ray crystallography, DNA double helix resolved 1954 Oct. p. 54-61 [5]

x-ray crystallography, DNA, genetics, molecular structure, DNA double helix resolved 1954 Oct. p. 54-61 [5]

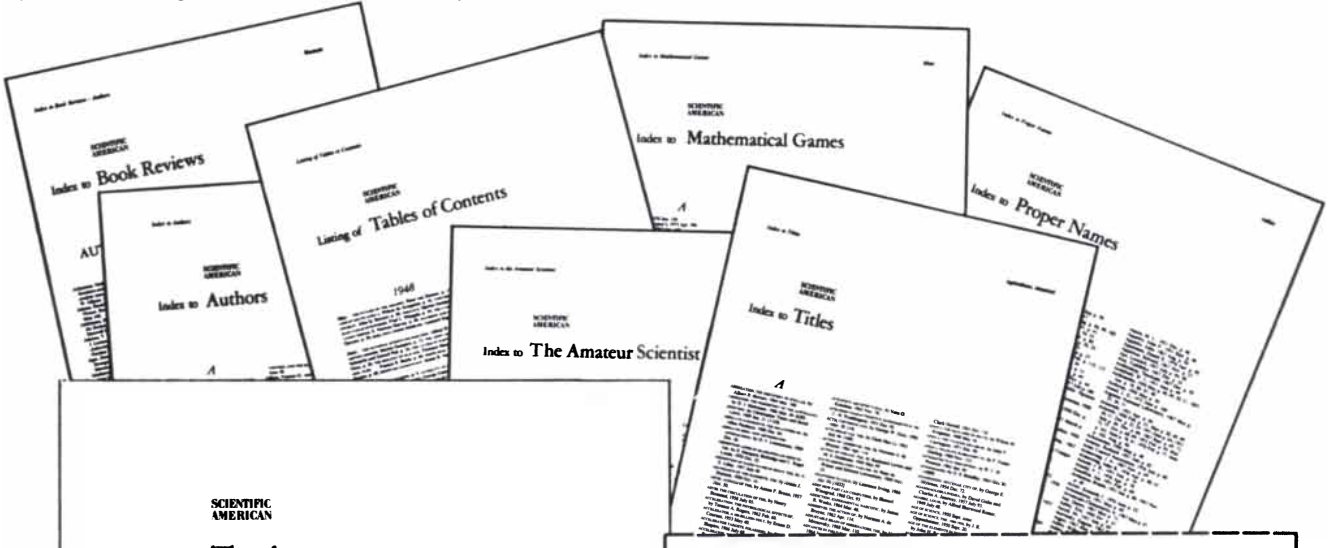
In most cases, a secondary citation, highlighting some aspect of the article, rides along with the rotating primary citations (In the example above: DNA double helix resolved). Each entry serves, therefore, as a "miniabstract" of the original. The alphabetical sequencing of the key words, in turn, brings together in chronological order references to each key word from various issues of the magazine. A portion of the grouping of clusters for "x-ray crystallography" follows:

x-ray crystallography, DNA, genetics, molecular structure, DNA double helix resolved 1954 Oct. p. 54-61 [5]
amino acids, myoglobin, proteins, 3-D structure of protein molecule 1961 Dec. p. 96-110 [121]
crystal structure, solid state, semiconductors 1962 Dec. p. 39-48 [249]
Bragg's law, crystal structure, diffraction, fourier series 1968 July p. 58-70 [325]
photoelectric effect, x-ray absorption 1976 Apr. p. 96-103

Articles are referenced by first and last page numbers. Thus, the entry for x-ray crystallography informs the reader that first appearance of the term is in the October 1954 issue, pages 54-61. Reference to the Listing of Tables of Contents discloses that the article is "The Structure of the Hereditary Material" by F.H.C. Crick.

References to about one-third of the articles close with a bracketed number. This is the offprint number and identifies articles republished as offprints. Thus, the Crick article in the example is identified as Offprint #5.

Reference to the Index of Authors will disclose, as well, all of the articles written for SCIENTIFIC AMERICAN by F.H.C. Crick.



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surplus of the good years from fueling an increase in population. An artificial leveling of the economy will inhibit population growth, holding the total below the one that taxes the maximum carrying capacity of the regional economy.

How might this leveling be achieved? One way is to cultivate a common concern with ceremonial activities that call for a large investment of labor. In Nazca times the kinds of centralized food storage characteristic of the Huari and Cuzco regimes would not have existed, and surpluses would have been dispersed not on a provincial and state level but on a local or even familial one. If an autonomous region suffered bad years, drawing on such decentralized stores would help to tide it over. If, on the other hand, the region enjoyed good years, the accumulated private stores could be tapped to provide support for

PERUVIAN SCHOLAR Maria Reiche (*left*) **demonstrates the surveying methods she has used for more than 30 years in recording Nazca ground drawings. Her audience is Patricia J. Knobloch of the State University of New York at Binghamton, a visiting archaeologist. The rocks that form the "desert pavement" at the Pampa Colorada range in size from pebbles to boulders.**

ZIGZAG PATTERN on the Pampa Colorada was formed, as were all the ground figures, by selectively removing the rocks that cover the desert floor, thereby revealing the lighter-colored earth under them. Here some of the shifted rocks were piled up at the bends of the figure.

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THREE GROUND FIGURES (*top*) are compared with portrayals of the same animals that appear on Nazca pottery (*bottom*). At left is a stylized monkey with a much exaggerated tail. The drawing of a monkey appears on a double-spout pot photographed by Loayza. The bird figure at center may represent a frigate bird; these birds have a conspicuous throat pouch. The drawing of a similar bird figure ap-

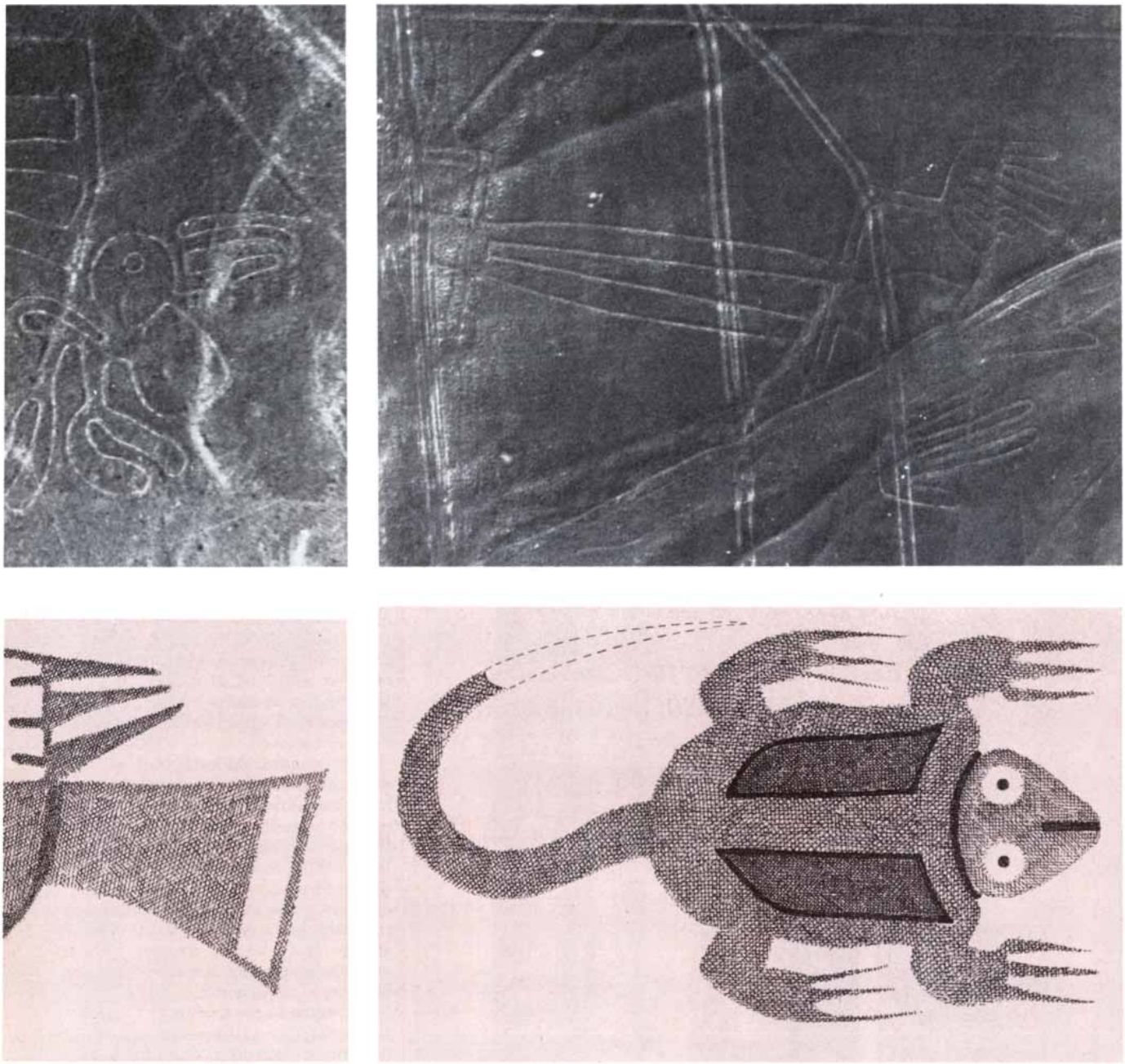
local work gangs engaged in ceremonial activities such as building temple platforms or laying out ground drawings. In either event the population would remain relatively stable.

Seen in this light the basic function (or, if one prefers the terminology of Darwinian evolution, the selective advantage) of laying out ground drawings has nothing to do with whether they were viewed from the ground or from above, or for that matter with whether they were viewed at all. The function lies in the fact that societies with a cultural mechanism for investing unpredictable surpluses in ceremonial activities have a selective advantage over societies lacking such a mechanism. They regulate their population, and societies that do not are doomed to cycles of "boom" and "bust."

Were the leaders of these regional societies in the Early Intermediate Period of Peruvian prehistory consciously aware of such complex concepts as the allocation of surplus resources to prevent an excess of population? Whether or not they were aware of them makes little difference; those who had such a system eventually replaced their neighbors, and the successful ceremonial behavior was thereby perpetuated. At the conscious level such continuity may have been based on a decision-making process no more profound than the argument that "this is the way we have always done it."

Much human behavior is based on this kind of "custom," a simple following of behavior patterns that have been successful in the past. In nonliterate societies the information on such behavior is often codified as ritual to ensure that it is conveyed to future generations. A pertinent example is contained in the study of a modern but barely literate Peruvian highland village by my wife, Billie Jean Isbell of Cornell University.

Her research has revealed that these farming families depend for their economic independence on a strategy of cultivating a variety of crops at different elevations. The villagers have a specific



pears on a Nazca pot in the collection of the Putnam Museum in Davenport, Iowa. The lizardlike figure at the right has a long tail that does not appear in this aerial photograph, but its hind legs were not executed with the same detail as its forelegs. The drawing of a similar lizard appears on a Nazca pot in the collection of the Robert H. Lowie Museum of Anthropology at University of California at Berkeley.

name for each crop zone. The distinction between the zones has been symbolized by the construction of a chapel at the boundary of each one. The annual harvest ritual involves a series of visits to the chapels and the harvesting of a sample of the produce grown in each zone. A cross is taken from each chapel and is decorated with the harvested plants. All the crosses are then brought to the village and presented to the village priest.

Even if a young villager fails to learn how to farm from his family and his village elders, the message of this annual ritual could scarcely be overlooked: "Here are the sections that divide the earth. Here are the crops that are grown in each section. It pleases God (and the priest) that all these crops are grown every year." Conscious recognition of the economic advantages of mixed farming may not even exist among the villagers, but the pattern of behavior that the ritual symbolically reinforces helps to protect its practitioners from the danger of single-crop failure and the social disruption that accompanies dependence on wage labor.

R. Tom Zuidema of the University of Illinois has reconstructed similar rituals observed by the people of Cuzco when the city was the capital of the Inca empire. At that time imaginary lines radiated in all directions from Cuzco. The lines were imaginary in that they were unmarked, but the orientation of each line was indicated by a series of shrines. Every day of the year a different kin group among the city dwellers worshiped at a different shrine; in effect the floor of the valley of Cuzco had been mapped out in an annual ritual calendar. Information about the agricultural cycle, social obligations, military activities and many other topics was thereby symbolically communicated to the people of Cuzco. The fact that the Incas felt a concern for this kind of informative mapping is demonstrated by the ground plan of the capital itself. The Incas called Cuzco "the puma" and its inhabitants "members of the body of the puma." The city was laid out in the

shape of a puma, although the animal form was somewhat distorted by the fact that it had to conform to the topography of the valley.

I have suggested that the ground drawings at Nazca were primarily a product of social mechanisms for regulating the balance between resources and population. Zuidema's findings on the symbolic ground-mapping practices of the Incas (who eventually succeeded to authority over the Nazca region) and Billie Jean Isbell's documentation of agricultural ritual among the highland Indians of Peru today suggest that the Nazca ground drawings also contained certain symbolic information, mapped on the ground for successive generations to observe, recognize and memorize.

What were these mapped messages? As Reiche has pointed out for many years, certain of the Pampa Colorada lines mark the position of the sun at the summer and winter solstices and certain other lines also appear to have calendrical significance. A computerized analysis of line orientation conducted by Hawkins, although it failed to demonstrate that a majority of the lines have astronomical significance, showed that twice as many of them were oriented with respect to annual solar and lunar extremes than would be expected on the basis of chance.

Both studies indicate that at least some of the Nazca ground drawings have calendrical potential. The mapping of calendrical data on the ground, if it was combined with ritual observations, could have communicated not only information of agricultural significance but also other kinds of information useful to a complex but preliterate society faced with a pressing need to store the knowledge acquired from generations of experience.

To return to the questions I raised at the outset: Can archaeology and related disciplines determine when the ground drawings of the Pampa Colorada were made, who made them and why? It seems clear that the answers to the first two questions are that most if not all of the drawings are the work of the same people who shaped and painted the lovely pottery of Nazca in the period between 200 B.C. and A.D. 600. The graves of this prehistoric farming people and the ruined towns and villages where they once lived both lie near the drawings.

As for the question why, it also seems clear that the making of the drawings, like the building of the enormous adobe-brick structures to the north, served to regulate population increases related to changes in the available energy. It is one thing, of course, to recognize the function served by energy investments of this regulatory kind and quite another to gain an understanding of the tangible form the investment takes. I none-

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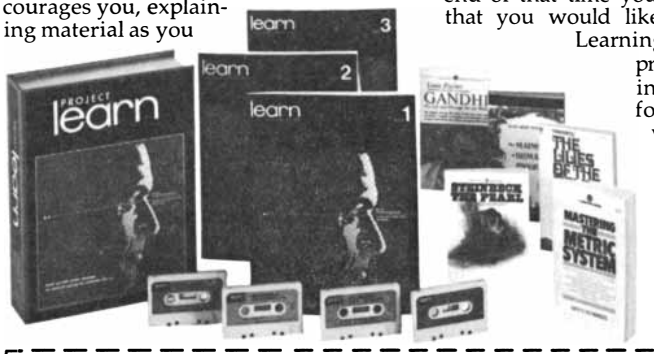

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theless find it a credible hypothesis that the ground drawings reflect the general need by the various preliterate societies of Peru to record or, perhaps more accurately, to store significant information about how their system worked.

The storage of inventories by means of the well-known Peruvian string-and-knot system of enumeration, the quipu, was evidently a practice adopted early in the prehistory of the Andes. Calendrical data, particularly when their use calls for the cross-check of actual astronomical observation, might be impractical or impossible to store by means of quipus. I suggest that such kinds of information were symbolically coded and recorded in the most durable medium available: the surface of the earth itself.

If the Pampa Colorada ground drawings were the only ones in Peru, such a hypothesis might carry little weight. Actually ground drawings have been found in many other places. A rectangular figure 60 meters long and 30 meters wide and including geometric "decorations" has been mapped in an area above the Sihuas valley south of Nazca. "Road" lines are present in the Ica valley just north of Nazca, in the vicinity of Lima still farther to the north, north of Lima in the Virú valley near the monumental Huaca del Sol and reportedly in the Zaña valley 180 kilometers north of Virú. In the Supe valley between Lima and Virú, Alberto Carbajāl, Carlos Williams and I recently photographed previously unreported lines, geometric figures, chains of spirals and a ground drawing of a human face 43 meters wide. Low-altitude aerial photography and ground surveys of other Peruvian desert-pavement areas might reveal many more figures. It is plain that energy was invested in the production of ground drawings even in parts of Peru where the major community-labor investment was in the construction of adobe platforms and other monumental works. The ground drawings along the north and central coast may be modest by Nazca standards, but they demonstrate that such figures were not exclusively a south-coast phenomenon.

In the centuries following the Early Intermediate Period the energy investment in temple platforms continued but on a far smaller and less impressive scale. The same appears to be true of the ground figures. Evidently the emerging state authority centered at Huari saw to it that the main community effort was redirected into the construction of administrative buildings, storage facilities, fortifications and what seem to have been manufacturing centers. Regional autonomy gave way to centralized authority, setting the stage for the eventual rise of the Inca empire. One can logically expect that the earlier practice of regional data storage and retrieval, written on the earth and vested in local ritual, then slowly ceased to be.

Pattern Formation in Biological Development

In the embryo of many organisms the differentiating cells become organized in space by first learning just where they are and then interpreting that information according to their genetic program

by Lewis Wolpert

How does a single cell, a fertilized egg, develop into an intricate system of many different cell types organized in predictable patterns to form a particular kind of adult animal? Most efforts to answer this central question of developmental biology focus on how the cells of the dividing egg become different from one another and so give rise to the various cell types, ranging from cartilage and muscle to nerve cells and blood cells, that make up an adult animal. Because each cell type is characterized by the presence of particular proteins, and because it is generally accepted that the genetic information in every cell is the same and remains unchanged during development, attention has largely been directed to learning how the genes that code for specific proteins are regulated, or turned on and off, in different cell types.

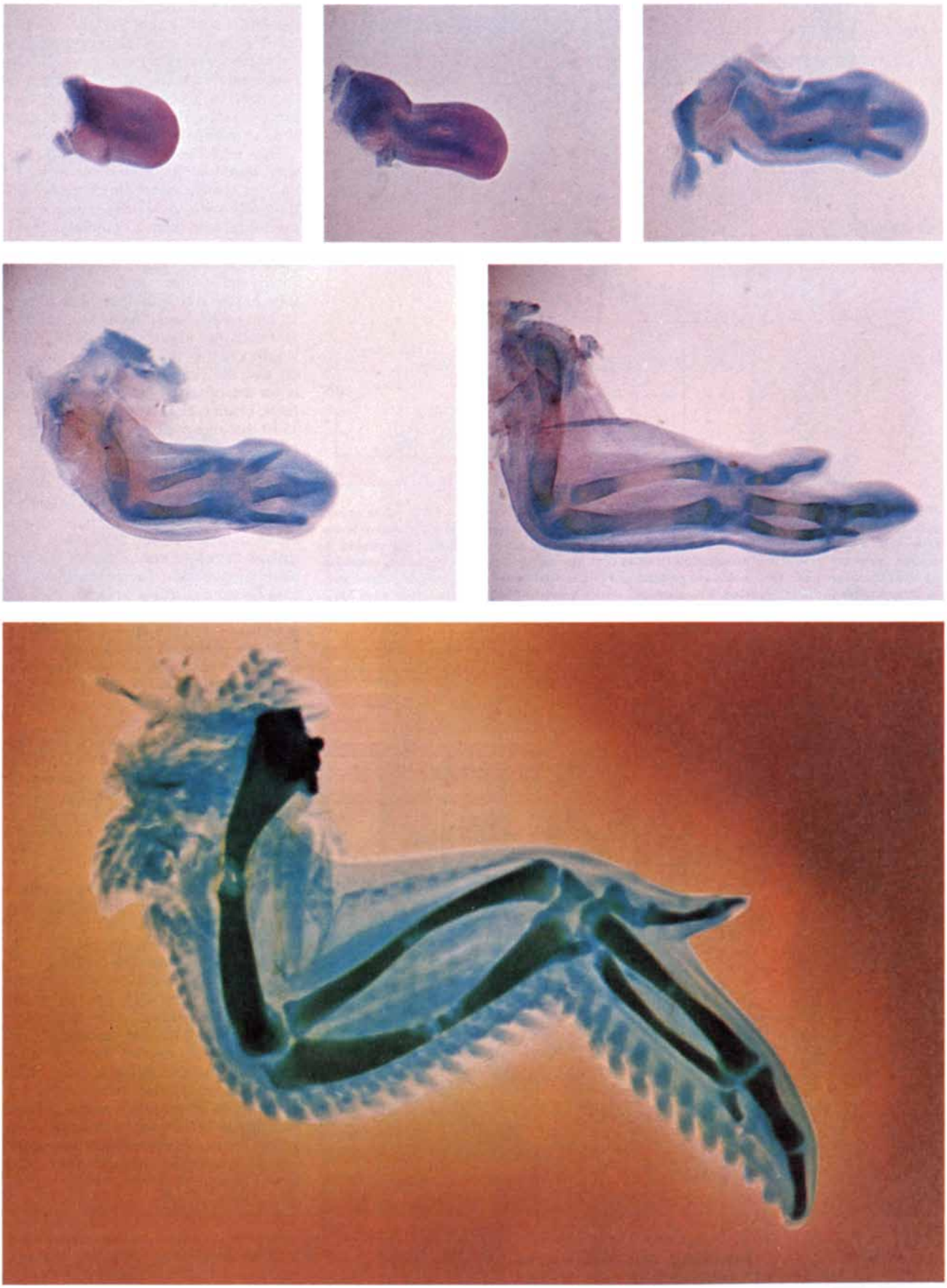
Cellular differentiation is, however, only one aspect of development. The various forms that characterize the adult animal arise largely from a rather different process: pattern formation. Consider the arm and the leg. They both contain the same types of differentiated cells—muscle, cartilage, connective tissue, skin—but the spatial organization of the cells is different. It is this spatial organization of differentiated cell types that is the essence of pattern formation. The histologist recognizes some 200 cell types in the human body, and the chimpanzee has exactly the same cell types; the difference between a man and a chimpanzee is a difference in the spatial organization of the cells. Among the vertebrates as a whole—fishes, amphibians, reptiles and mammals—there is some variation in cell type, but the key to the different organization of all these forms does not lie in the cells as such; it lies in how these basic building units are arranged in space during development. To emphasize the point: knowing how cartilage, muscle and tendon differentiate tells one very little about how the five fingers of the hand take shape.

One way to think about pattern formation is in terms of the French flag. Consider a linear array of cells, each of which can differentiate into a blue, a red or a white cell [*see top illustration on page 156*]. How might the cells in the line be organized to make a French flag, one-third blue, one-third white and and one-third red? There are a number of possible solutions to the problem, but the obvious one is for the cells to come to "know" their position with respect to the ends of the line and to be programmed to differentiate appropriately on the basis of such positional knowledge. If a cell is in the right-hand third of the line, it will differentiate as red; if in the middle third, as white; if in the left-hand third, as blue. Such a mechanism for pattern formation can be viewed as a two-step process: first the cells are assigned positional information and then they interpret that information according to their genetic program.

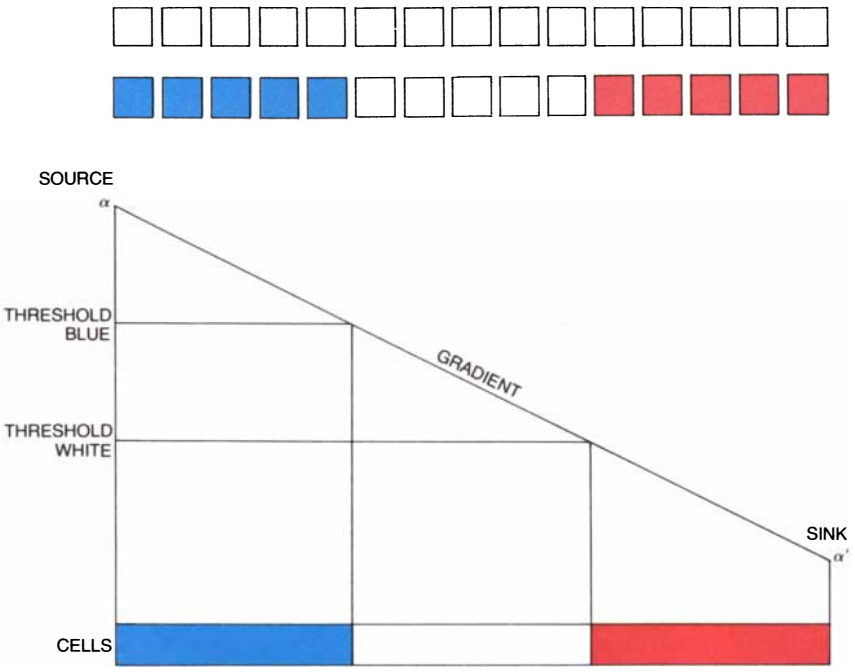
This conceptually simple mechanism has some interesting features. The only communication the cells need to have with one another is a message specifying positional information, and that can be quite simple. Moreover, the same interactions and positional information can give rise to a variety of patterns depending on the particular developmental program according to which the information is interpreted. For example, the American flag consists of cells of the same colors as the French flag. If the two flags develop on the basis of positional information specified by the same two-dimensional coordinate system, then a graft of a piece of one flag into the other flag should behave according to its position and its genetic program. A small piece of "undifferentiated" American flag grafted into the upper left-hand corner of the French flag should develop into white stars in a blue field; grafted near the lower right-hand corner, it should develop into horizontal red and white stripes.

There is good evidence for this kind of development in biological systems. Curt Stern of the University of California at Berkeley and his colleagues achieved what are in effect just such grafts by making genetic mosaics. In the fruit fly *Drosophila* a mutation in a single gene gives rise to a mutant form, *aristapedia*, with a leg where the antenna should be. By genetic manipulation it is possible to have both wild-type, or normal, cells and *aristapedia* cells in the antenna region. The cells behave according to their position and their differing genetic programs. If cells at the tip of the antenna are wild-type, they form normal antenna-tip structures, but if they bear the *aristapedia* gene, they form leg structures, and not just any leg structures but the end structures of the leg. This suggests that positional information (how near the tip?) is the same in the antenna as in the leg; it is the interpretation that is different. A variety of other pattern mutants behave similarly in mosaics, the cells developing according to their position and their genetic constitution. The exciting possibility, then, is that positional information may have an underlying universality.

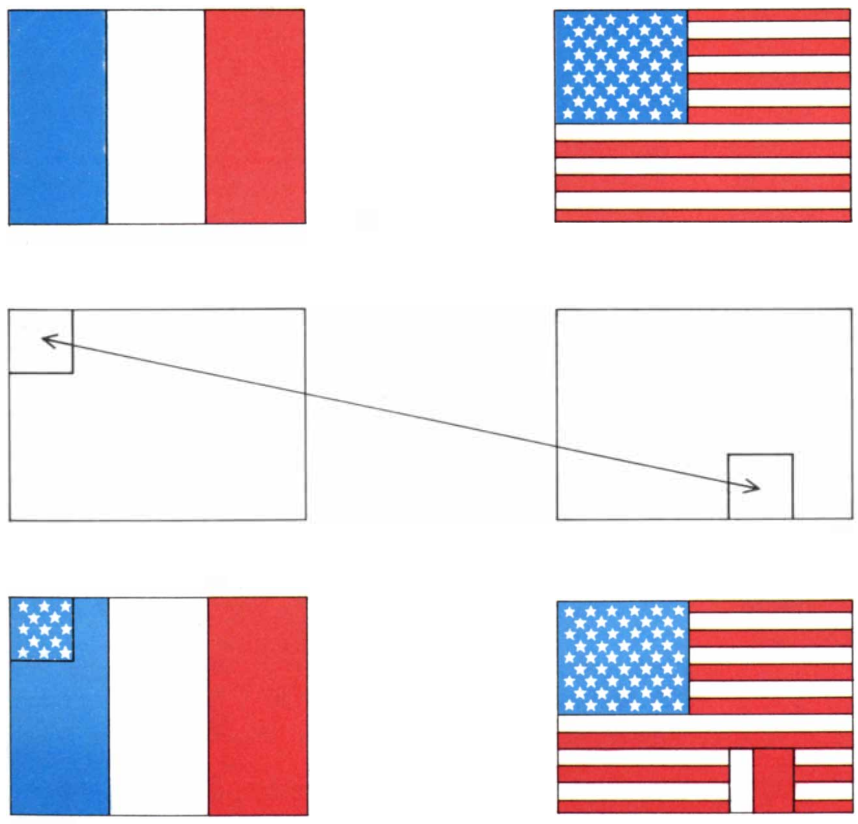
The idea that position determines how cells will develop was stated explicitly by Hans A. E. Driesch at the end of the 19th century and was implied in the gradient theories of pattern formation championed in the 1920's by C. M. Child of the University of Chicago. Thinking about pattern formation in terms of positional information enables one to analyze this aspect of development in rigorous terms and forces one to think about the mechanisms by which position is specified. The specification of position implies a coordinate system, and such a system in turn requires a special "boundary region," with reference to which position is measured; polarity, which determines the direction in which position is measured, and some quantity that can measure position. An approach based on positional information makes



WING BUD OF A CHICK is seen at successive stages of its incubation: after four, five and six days (*top*), seven and eight days (*middle*) and 10 days (*bottom*). The cartilaginous structures (*see top illustration on page 158*) are easily recognized in a stained whole mount of the tissue because they take up a specific dye. The photographs were made by Dennis Summerbell and Jim Smith in author's laboratory.



FLAG ANALOGY shows how a line of cells (*top*) that can differentiate as blue, white or red cells (*second line*) can be organized to form the French flag. Here positional information is delivered by a gradient of a diffusible morphogen, and the cells have appropriate thresholds. A source keeps the gradient concentration fixed at α at one end and a sink keeps concentration at α' at the other end. Thresholds are cellular properties that enable the gradient in positional information to be interpreted. For example, above concentration T_B a cell becomes blue.



GRAFTED FLAG MATERIAL develops on the basis of position and "genetic program." Undifferentiated American-flag material grafted in upper left-hand corner of French flag develops as stars; similarly, a piece of French flag grafted to American flag develops in accordance with its own genetic program, which near bottom right calls for vertical white and red patches.

more concrete the old concept of embryonic fields within which development proceeds and is regulated: the fields can now be viewed as particular coordinate systems. And if position is specified by a coordinate system, then positional information may be quite similar in widely different organisms.

How might position be specified? One way would be for a gradient to be set up—for some property to decrease continuously with increasing distance in a positional field from a boundary, or reference, region. One general feature of positional fields is that they are always small and another feature is that the time required to establish them is long; all known positional fields are less than 100 cells (or about one millimeter) in length and they are usually much smaller, and the time taken to set them up is on the order of hours. Noting these facts, Francis H. C. Crick pointed out in 1970 that one plausible means of specifying position would be the diffusion through the field of a "morphogen," a substance whose concentration could be sensed by individual cells. Given a source of a fixed concentration of the morphogen at one end of the field and a sink at the other end, a linear gradient could be established across the field. Alfred Gierer and Hans Meinhardt of the Max Planck Institute for Virus Research in Tübingen later showed how a diffusion gradient can be set up without a localized source or sink [see "Hydra as a Model for the Development of Biological Form," by Alfred Gierer; SCIENTIFIC AMERICAN, December, 1974].

However such a gradient is established, it can be interpreted by cells if their genetic program is specified in terms of thresholds: if above a certain concentration the cells differentiate as one type and below it they differentiate as another type. In my laboratory at the Middlesex Hospital Medical School in London, Julian Lewis, Jonathan Slack and I have found that it should be possible to specify some 30 different cell states along a line of about 100 cells. The factor that limits the precision with which this can be done is the accuracy with which thresholds can be established for individual cells, which depends in turn on the accuracy with which cells can control the concentration of the molecules inside them. That rather basic cellular property is not known, but an accuracy with a 20 percent error seems to be a reasonable guess. Part of the variability characteristic of developmental (and other cellular) processes must arise from this intrinsic variability.

Dennis Summerbell, Lewis and I have proposed another model, specifically for growing systems, in which cells measure distance by measuring the time they spend in a particular region we call the "progress zone." Since the cells are

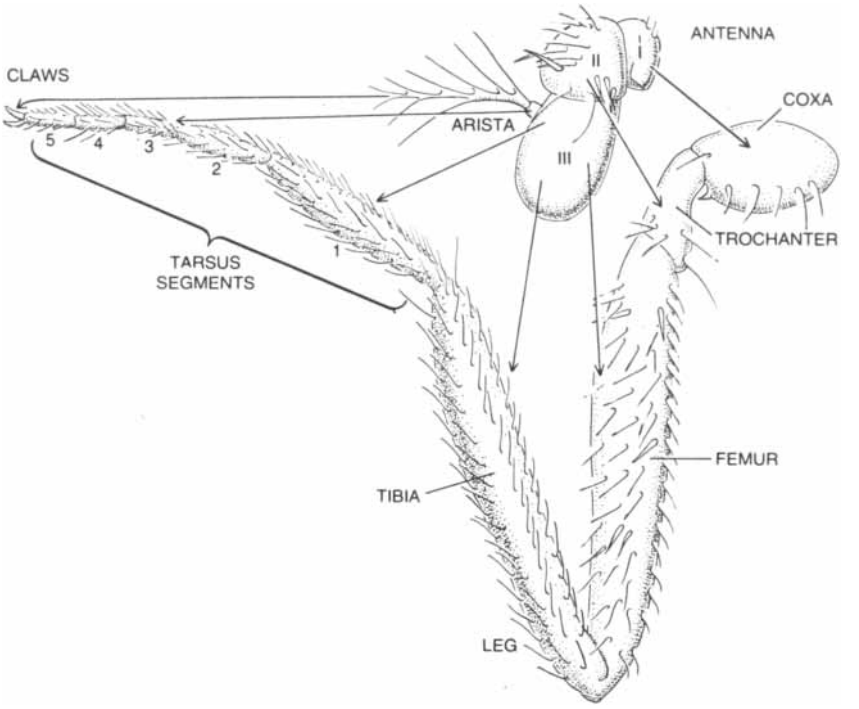
dividing and since the width of the zone remains constant, cells are always leaving the zone—being left behind as the zone advances. The cells that come out first are at the beginning of the line (in the sense of the line of cells in the flag analogy) and the cells that come out last are at the end of the line; if the cells can measure the time they spend in the progress zone, they will have acquired information about their position.

Here I shall primarily be illustrating the diffusion-gradient and progress-zone models with respect to the development of the wing of the chick. I should note that these models appear to involve rather simple cell-to-cell interactions. There is a widespread belief that cells have complex conversations with one another during development. The possibility should be considered that in pattern formation, at least, their conversations may instead be very limited, even boring.

The wing of the chick develops from a paddlelike bud very similar to the arm bud of a human embryo. It starts off as a small bulge that appears about two days after the egg is laid and at a time when the main axial structures such as the somites have already been laid down. The pattern of cartilage, muscle and tendons takes shape within a loose network of mesenchymal cells encased in a sheet of ectodermal cells that will become skin. After 10 days in the incubator the basic pattern of the limb bones—humerus, radius and ulna, wrist and digits—is well established in the form of cartilage (most of which will later turn into bone). In fixed preparations the cartilage takes up a dye that makes it clearly visible through the skin.

Most of the important discoveries about interactions within the developing bud were made by John W. Saunders, Jr., of the State University of New York at Albany and his colleagues. He found that a thickened region of the ectoderm running like a ridge across the tip of the limb bud is essential for development. If this apical ectodermal ridge is removed while the cartilaginous elements are being laid down, parts of the limb will fail to develop. The later the ridge is removed, the more structures develop. If the ridge is excised at an early stage, only the humerus may be formed; if it is removed later, only the digits may fail to develop. This shows that the structures are specified in a proximodistal sequence, that is, beginning near the point of attachment of the limb to the body and proceeding outward toward the tip of the limb. That sequence is clearly observed in the growing bud, in which the humerus becomes visible long before the digits appear.

If the pattern of cellular differentiation in the limb bud proceeds on the basis of positional information, the cells

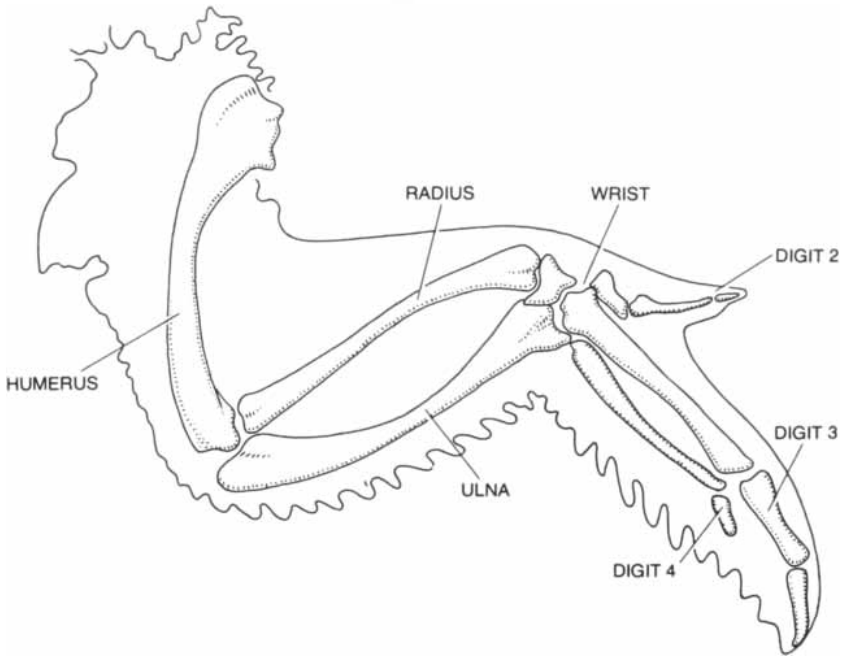


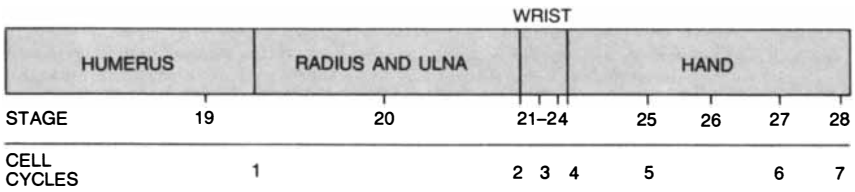
GENETIC MOSAIC combining the cells of the normal fruit fly *Drosophila melanogaster* and those of the *aristapedia* mutant, in which a leg is formed where an antenna should be, develops as in the flag analogy. Cells behave according to position and genetic program: mutant cells located at the base of the developing antenna form basal leg structures, whereas those near the tip of the antenna form claws or tarsal segments. The arrows indicate the leg and antenna regions that appear to have similar positional values. This drawing is adapted from the work of Howard A. Schneiderman and John Postlethwait at the University of California at Irvine.

can be thought of as being assigned positional values in a three-dimensional coordinate system; the interpretation of those positional values would give rise to the observed pattern of cartilage, muscle and tendon differentiation. It would be somewhat like sculpting by numbers. The three natural axes of the limb are the proximodistal (from upper limb to digits), anteroposterior (front to back) and dorsoventral (top to bottom) axes. Here I shall consider only the first two of these axes, for which Summerbell, Lewis, Cheryll Tickle and I have proposed two different mechanisms to specify positional information. For the proximodistal axis we propose a mechanism in which time provides information about position. The mechanism we suggest for the anteroposterior axis is a signal from a boundary region, which sets up a gradient in positional values.

The specification of proximodistal positional values appears to take place within a progress zone near the tip of the limb bud. The zone is always associated with the apical ectodermal ridge, and some influence from the ridge presumably brings it into being. The progress zone is about 350 micrometers (thousandths of a millimeter) long. It contains a population of dividing cells that are like fibroblasts in general appearance. We assume arbitrarily that positional value decreases autonomously with time spent in the zone, that is, the longer a cell remains in the zone, the lower its positional value will be. Since all the cells are dividing, cells will continually be leaving the zone, and those that come out first will form proximal structures whereas those that come out late will form the tips of the digits; the gradient in positional value generated by this process will specify the series of elements along the proximodistal axis. One can now see why removal of the apical ectodermal ridge leads to truncation of the limb: the progress zone is abolished, and so no new positional values are generated.

This model suggests that if there are no long-range interactions between the mesenchymal cells, a progress zone should continue to develop autonomously when it is excised and grafted to another site. If the zone from a young bud is grafted in place of the zone in a bud in which the positional values corresponding to the humerus and the radius and ulna have already been generated, the grafted zone should generate a second set of such values; this should lead to duplication of elements along the proximodistal axis. The converse experiment, in which an older progress zone is grafted to a young bud, should lead to the absence of proximal structures: the digits should appear but the humerus, ulna or radius should be missing. Our experimental grafts conform rather well





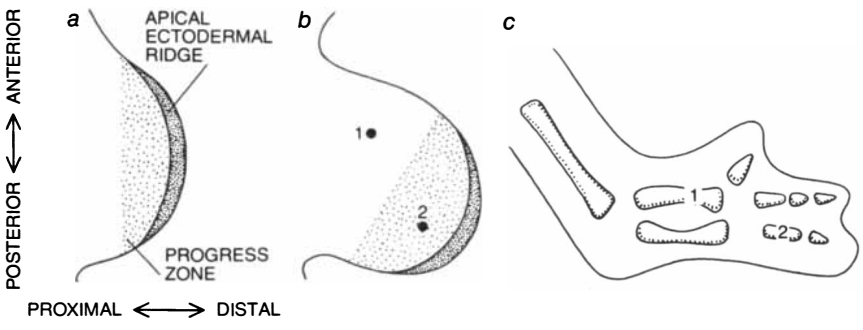
CARTILAGINOUS ELEMENTS of the chick limb are identified in this drawing. The bar below the drawing shows the effect on limb development when the apical ectodermal ridge, a paddlelike thickening at the tip of the limb bud, is removed at different times. Time is indicated in terms of a standard series of developmental stages and in terms of cell cycles. For example, if the ridge is removed at Stage 20, only the humerus and half of the radius and ulna will develop. What is notable here is that two cell cycles are required to lay down short wrist region.

to the theory [*see illustration on opposite page*]. (I should point out, however, that Madeleine Kieny and her colleagues at the University of Grenoble have had different results, finding less of this kind of autonomy and more evidence for regulation and interaction to achieve a more normal set of structures.)

We had difficulty getting further experimental evidence for the progress-zone model, but some recent experiments with X-ray irradiation were encouraging. Tickle and I studied the effect of large doses of X rays (up to 2,000 rads) on limb-bud development. Such doses kill the embryo, and so we grafted the irradiated bud to a site on an unirradiated host embryo. We found that as the radiation was increased it was the proximal structures that were lost; the distal ones (the digits) were relatively normal. It may seem surprising that irradiation should least affect structures laid down at a later stage, but that is just what our model predicts. If irradiation kills a large percentage of the cells in the progress zone, the remaining cells must stay in the zone longer as it becomes repopulated; they acquire a lower positional value and so give rise to distal structures. The model thus begins to provide clues to certain congenital malformations of human limbs such as phocomelia, or seal limb, that result in a similar arrangement of parts. The drug thalidomide could cause phocomelia, among other abnormalities, in a fetus when it was taken by a pregnant woman. Its mode of action is unknown, but our results imply that it may somehow have destroyed cells in the early limb bud of the embryo.

When one records the length of time (in terms of cell-division cycles) cells destined to form particular structures spend in the progress zone, one is struck by the relatively long time required for laying down the very short wrist region. An analysis conducted by Lewis and Summerbell accounted for the apparent disproportion, which turns out to have important implications for the growth process. The various segments of the limb are not very different in size when they emerge from the progress zone; in fact, their initial length is roughly equal to the amount of material that leaves the zone during one cell cycle, or about 350 micrometers. Although the wrist is short, it is relatively complex, apparently consisting of two cartilaginous elements laid down in sequence, and that explains the length of time needed for laying it down. It is short only because it does not grow much after emerging from the zone, whereas the other limb structures do grow. The wrist and the adjacent ulna start off at about the same length, but after some 10 days the ulna is about 16 times longer than it was and the wrist has only doubled in size.

Nigel Holder found that this relative lack of growth is an autonomous property of the wrist region, since it persists when the isolated wrist is cultured or is grafted to other parts of the limb. It would appear that the positional values imparted to the cartilage lead to different growth programs in different regions; two bits of cartilage that seem to be similar but are in different regions may in fact have different properties. Lewis and I have called this situation, in which cells of the same differentiation class have different properties programmed by different positional values, "nonequivalence." The ultimate length of cartilaginous elements is determined by their size on emerging from the progress zone and by their program of growth, and both determinants are specified by positional values. These values can be altered during evolution,



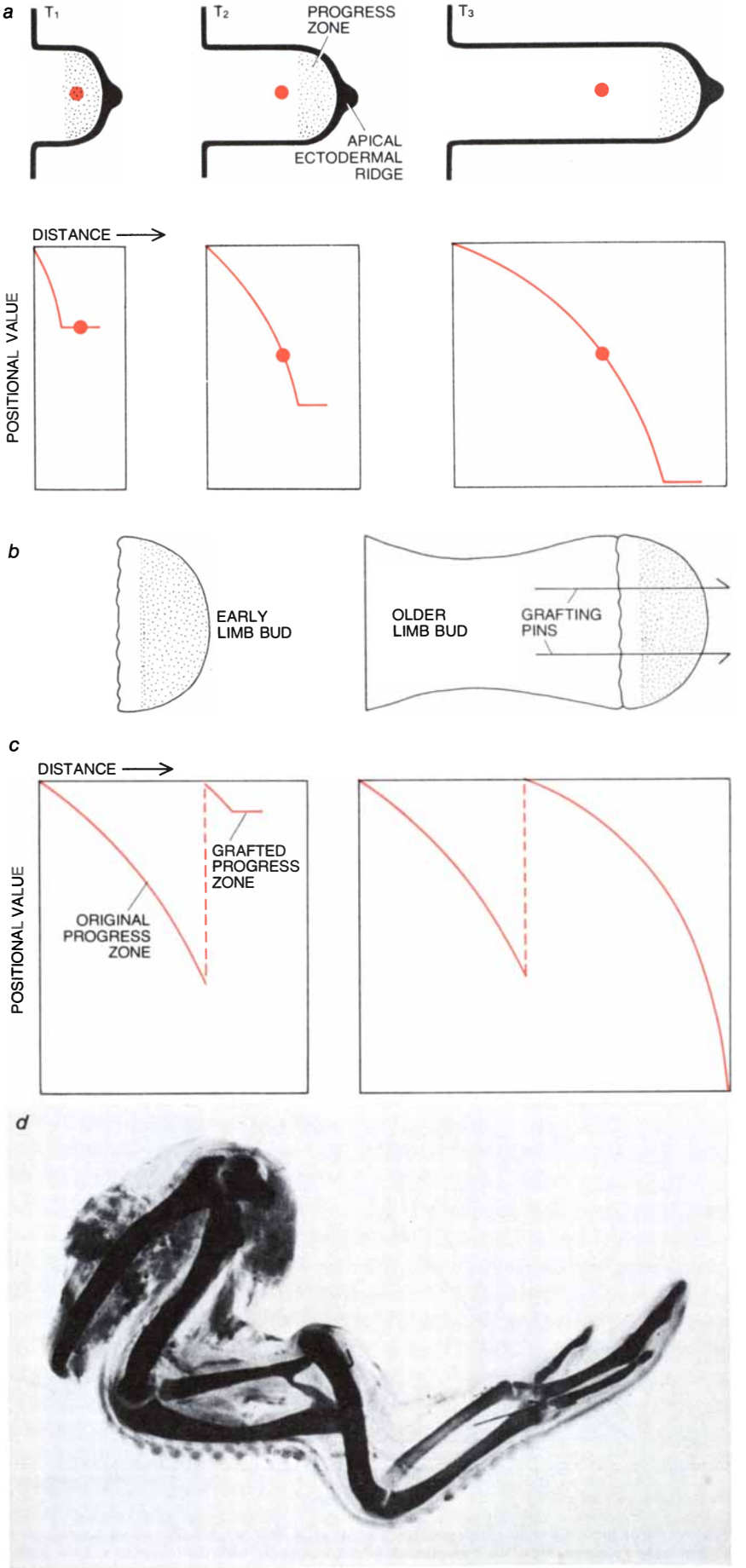
LIMB BUD is diagrammed as it is seen from above, showing the proximodistal axis (from the point of attachment toward the tip) and the anteroposterior (front to back) axis. According to the author's model, positional values along the proximodistal axis are specified by the amount of time a cell spends in the progress zone, which is associated with the apical ectodermal ridge (*a*). The cells in Region 1 have had their position specified; the position of the cells in Region 2 is still being specified (*b*); the two regions will ultimately come to form different structures (*c*).

and the alterations presumably account for some of the differences in the size and form of vertebrate limbs.

Our morphogen-gradient model for the anteroposterior axis is based on another discovery by Saunders. He found a small region of cells at the posterior margin of the wing bud that, if grafted to a site near the front of the bud, could cause the limb to form additional digits—roughly a mirror-image duplication along the anteroposterior axis. We think a graded signal from this region, which is called the zone of polarizing activity, provides positional information along the anteroposterior axis. Our hypothesis is that a gradient is set up in a morphogen issuing from the zone and that the various digits, for example, are specified at various thresholds. The digits, conventionally numbered 2, 3 and 4, are convenient markers because they are easily distinguished from one another in the chick wing. To test the hypothesis we therefore grafted a zone of polarizing activity to successive sites along the anteroposterior axis and looked to see whether or not the pattern of digits conformed with the model's predictions.

If positional information is delivered along a gradient and is interpreted in terms of thresholds, then digit No. 4, closest to the normal zone of polarizing activity, should have the highest threshold and digit No. 2 should have the lowest. A new zone of polarizing activity grafted quite far forward on the bud, with the original zone left in its normal posterior position, should give rise to a mirror duplication [*see illustration on page 161*]. That is, the pattern of digits should be 4, 3, 2, 2, 3, 4. And so it was in our experiment. If the graft is placed nearer the middle of the bud, the gradient should be such that the predicted pattern (reading from the anterior edge of the wing to the posterior edge) is 2, 3, 4, 4, 3, 3, 4, and we obtained limbs with approximately that pattern. On the whole the patterns observed in various experiments conformed rather well to the predicted patterns.

Three further observations support



TIME MEASUREMENT in the progress zone (*stippled area*) is demonstrated for a group of cells (*colored dot in drawing* a) after one, two and three cell cycles (T_1–T_3). The cells' positional value falls (*colored curve*) while they remain in the zone but stays constant after they leave the zone. If the progress zone of an early limb bud is grafted in place of the zone on an older bud (*b*), and if the progress zones behave autonomously, a new gradient should be generated in tandem with original gradient in positional value (*c*). This can cause structures to be repeated along the proximodistal axis. One possible sequence is humerus, radius and ulna, humerus, radius and ulna, wrist and digits. This sequence is shown in Summerbell's picture of limb (*d*).

the idea of a graded signal. First, if a second zone of polarizing activity is placed next to the host's zone, it has no apparent effect; if the zone acts as the source of a morphogen whose concentration is regulated to remain fixed, that is to be expected. Second, if the graft is placed very far forward, no additional digits form; the signal is not strong enough to rise above the threshold. As the graft is implanted successively farther back, the first additional digit to appear is No. 2; it has the lowest threshold. Third, the model predicts that increasing attenuation of the signal from a zone of polarizing activity should interfere successively with the formation of digits 4, 3 and 2. Jim Smith subjected zones to extremely high X-ray irradiation before grafting them to a position where the resulting pattern of digits is usually 4, 3, 2; he found that with increasing irradiation (and therefore increasing attenuation) it was in fact digit No. 4 that first failed to appear, then No. 3 and finally No. 2.

One of the implications of a mechanism of pattern formation based on positional information is that signals like the ones that have an effect in the chick limb bud might have an effect in all vertebrates, with the difference in limb pattern reflecting differences in interpretation. We were therefore pleased when Tickle found that a bit of tissue taken from the presumed region of the zone of polarizing activity in the mouse embryo specified additional chick digits when it was grafted to a chick limb bud. Jeffrey A. MacCabe of the University of Tennessee got the same result with hamster embryos. John F. Fallon of the University of Wisconsin has shown that the zone of polarizing activity from the limb of a turtle embryo and that from the limb of a human embryo have similar effects in chicks. The signal seems to be the same in the vertebrates; what has changed in evolution is the response.

In spite of the conformation of the experiments to our model it is important to point out that direct evidence for a diffusible morphogen is still lacking. Other models, which establish graded positional values in other ways, could also account for the observed results.

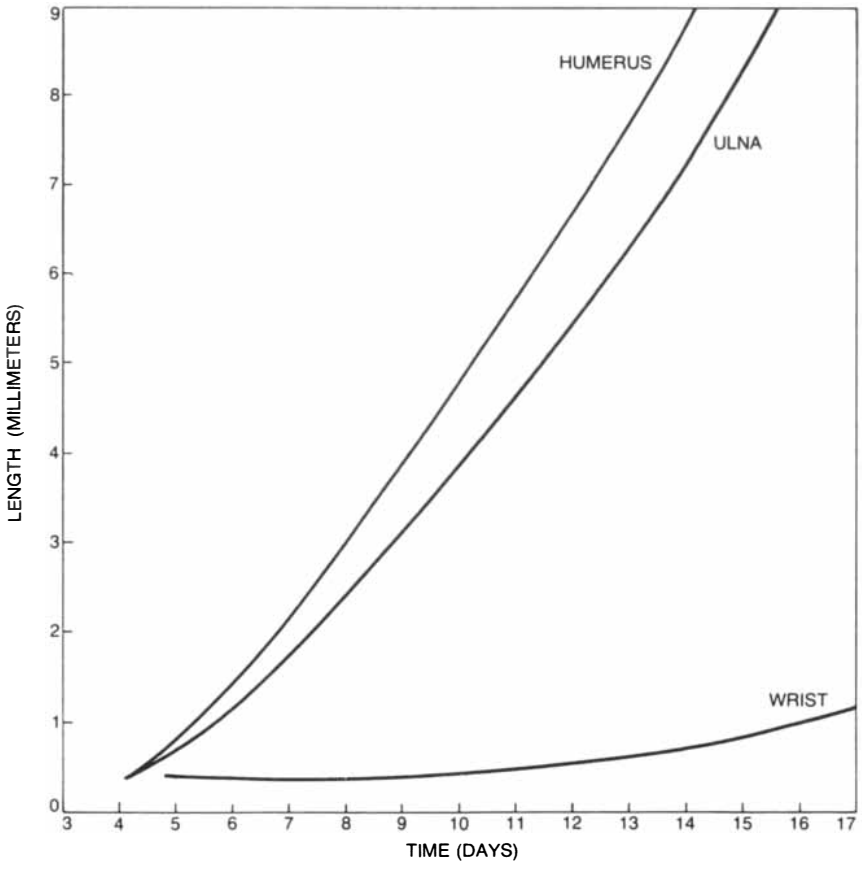
Up to this point I have considered only the cartilaginous elements of the chick limb. The pattern of muscles and tendons is just as important and is somewhat more complex. Geoffrey Shellswell and I have examined the development of muscle and tendon patterns in the context of our ideas about positional information, concentrating on the distal part of the limb: radius and ulna, wrist and digits. Although cartilaginous elements can be examined easily in the intact limb, for muscle and tendon it is necessary to follow the tedious procedure of cutting serial sections and reconstituting the pattern from them.

If pattern results from the interpretation of positional information in a three-dimensional coordinate system—if it really is like sculpting by numbers—then tendons, muscles and cartilage should develop autonomously, purely on the basis of position. Therefore one of the first questions we asked was: How autonomous is the development of muscle, tendon and cartilage? There is a muscle called the flexor digitorum profundus (FDP) that is anchored to the ulna near the elbow and connected by a long tendon to the tip of digit No. 3. We asked: Does the development of the tendon depend on the development of its muscle? What will happen to the tendon's development if its normal proximal site of attachment is missing? We grafted the tip of an early limb bud to the flank of the embryo. The FDP tendon developed normally even though its muscle was not there, and the muscle left behind in the stump of the bud developed normally even though its tendon was absent.

That experiment and others showed in general that muscle, tendon and cartilage develop autonomously once their position has been specified in the early bud. There does, however, seem to be a seek-and-join rule for tendons, which seldom end in "midair" following a graft operation but rather attach themselves to nearby tendons, muscle or cartilage. For example, it is possible to invert the tip of the early limb bud dorsoventrally (upside down) by grafting a tip from a left-limb bud to a right-limb bud. In that case the ventral tendons of the graft join up with the dorsal host tendons closest to them, and dorsal muscles may integrate with ventral muscles.

We believe the pattern of muscles and tendons is specified by the same coordinate system as the cartilaginous elements. Another indication of this is the fact that a graft of the zone of polarizing activity of the type causing a mirror-image duplication of the bones causes a comparable mirror-image duplication of the muscles and tendons.

This discussion of muscles and tendons may have misled the reader by implying that the interpretation by cells of their positional values is responsible not only for the pattern of muscle differentiation but also for determining which cells will form muscle in the first place. Actually the specification of cell differentiation into muscle does not depend on position in the limb bud. There is excellent evidence from B. Christ, H. Jacob and M. Jacob at the University of Bochum and from Kieny and Alain Chevalier at Grenoble that muscle cells have a lineage different from that of the other mesenchymal cells. They migrate into the bud from the somites at an early



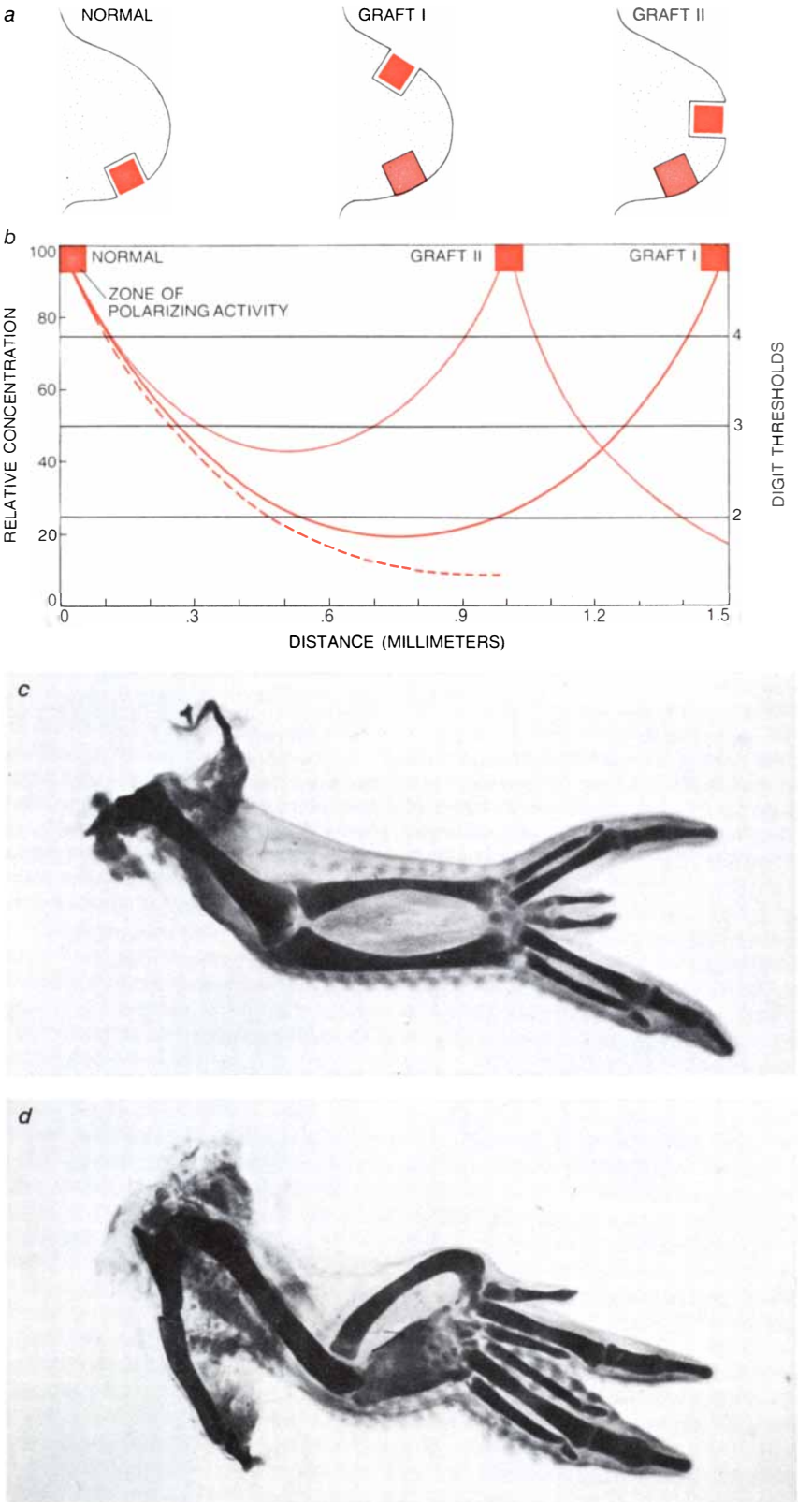
GROWTH of three different cartilaginous elements after they are first laid down varies widely. The wrist grows hardly at all, Summerbell found, compared with the humerus and the ulna.

stage, and apparently it makes no difference which somite is their source, suggesting that particular cells are not necessarily destined for particular muscles. Unlike cartilage cells, muscle cells are "equivalent."

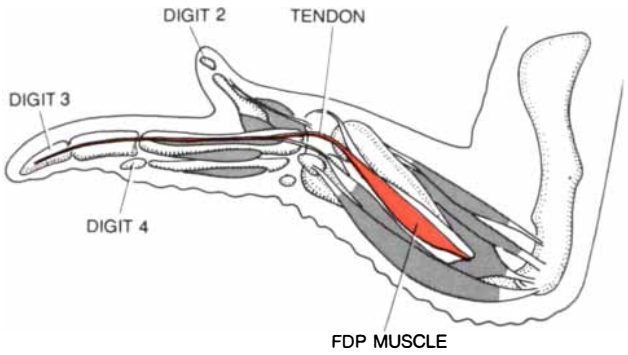
If muscle cells are in effect predifferentiated, what specifies the pattern of a particular muscle? To understand how this specification may be achieved it is necessary first to understand how an individual muscle develops. Muscle first becomes visible in the limb in the form of large dorsal and ventral blocks, which subsequently go through a series of divisions to become individual muscles. The early blocks are made up of precursor muscle cells and precursor connective-tissue cells. Our suggestion is that the muscle cells are all equivalent and that the pattern of the muscles is determined by connective-tissue cells. According to this view, the connective cells in the regions where the muscle blocks take shape have properties such that precursor muscle cells migrating in from the somite tend to adhere better to these connective cells than to others and therefore accumulate to form the dorsal and ventral blocks. The properties of the connective-tissue cells change with time, presumably in accordance with their interpretation of positional information. If cells at, say, the center of the ventral block come to have a lower affinity for muscle cells, then muscle cells will migrate away from them, thereby subdividing the muscle. It is as if the future connective-tissue cells were acting as a template for the muscle cells.

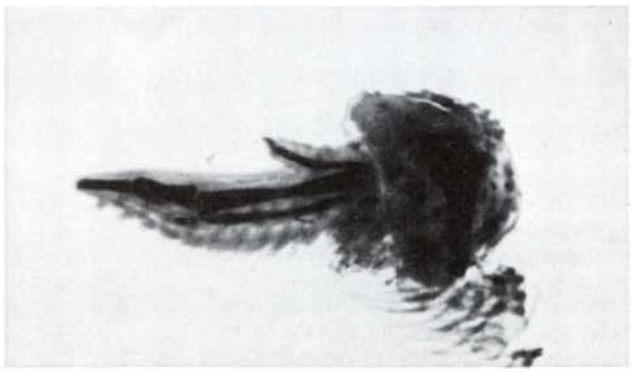
The process is analogous to the movement and patterning of mesenchymal cells in the sea-urchin embryo, which Trygve Gustafson of the University of Stockholm and I studied some years ago. Here the moving cells could be observed directly with time-lapse cinematography, and it was clear to us that the pseudopodia, the temporary protrusions by means of which the cells move, were continually making and breaking contact with the substratum; the changing patterns in the distribution of the cells appeared to reflect a changing stability in their contact with the substratum, much as the patterning of muscle in the chick limb seems to reflect contacts between muscle cells and a connective-tissue substratum. The patterning of muscles by connective tissue would have important implications for the patterning of nerves in a developing limb and how they connect with muscles. We do not know how correct connections between nerve cells and muscles are established, but if some kind of specificity is involved, the specificity may reside in connective tissue rather than in muscle cells themselves.

There is now substantial evidence that gradients in positional information underlie pattern formation in a variety



ZONE OF POLARIZING ACTIVITY (*colored square*) is assumed to be the source of a morphogen whose gradient specifies anteroposterior positional information. A normal zone at the posterior margin of the bud (*a*) sets up a gradient (*broken curve in* b) that interacts with cellular thresholds to specify the normal pattern of digits 2, 3 and 4. If an additional zone of polarizing activity from a late-stage bud is grafted near the front of an early bud (*I*), the gradient created by it and the host's zone of polarizing activity (*solid curve in* b) specifies a mirror-image duplication of digits (*photograph* c). Grafting a zone near the middle of the bud (*II*) should result in a different gradient (*light curve in* b). The experimental result was close to the prediction (*photograph* d). The grafts were done by Smith, and photographs were supplied by him.



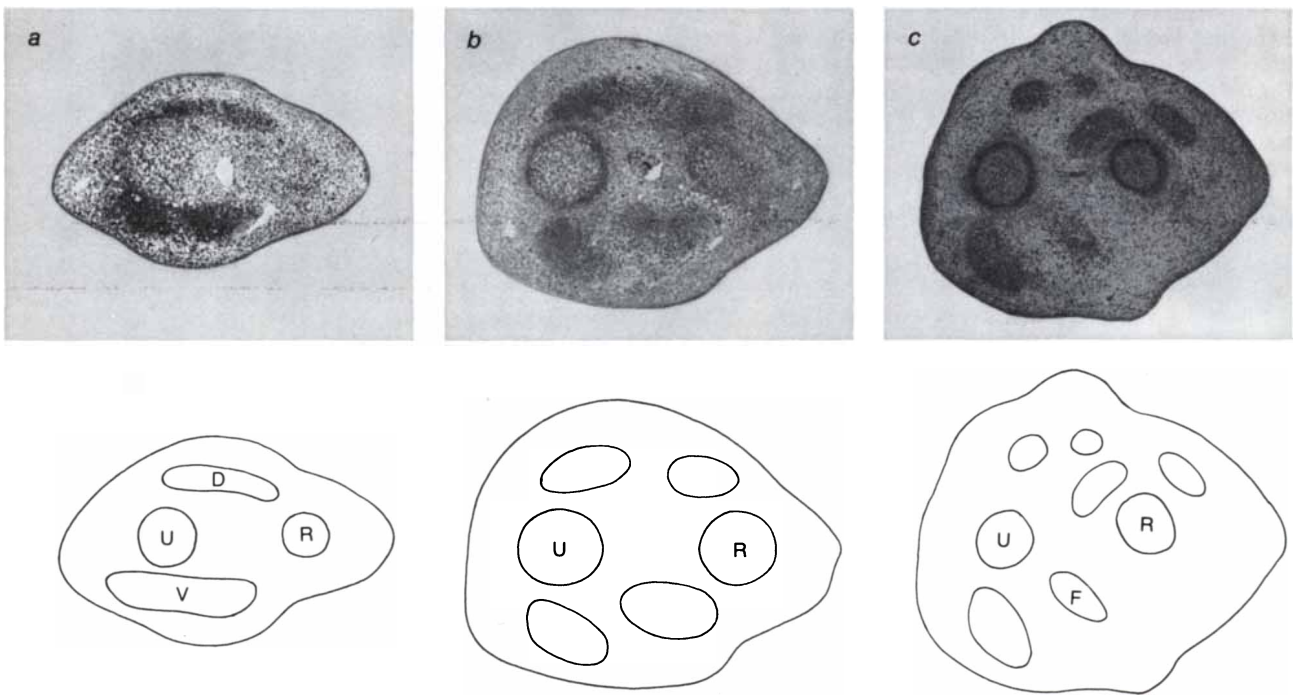


MUSCLES OF AN EMBRYONIC CHICK WING, seen from below, include one designated FDP (*color*), which is attached by a long tendon to the tip of digit No. 3 (*left*). If early in development the tip of the bud is grafted to the flank of the embryo, a more or less normal hand develops without an upper limb (*right*). The tendon in this case has been shown by the work of Geoffrey Shellswell to develop autonomously; the tendon is normal even though the muscle attached to it is absent. The photograph was made by Summerbell.

of organisms. Some of the evidence is old; the role of gradients in early sea-urchin development, for example, was proposed by the Swedish investigators John Runnström and Sven O. Hörstadius in the 1920's and 1930's. The recent evidence is particularly impressive in the case of insects. Both Peter A. Lawrence of the British Medical Research Council's Laboratory of Molecular Biology in Cambridge and Horst Bohn of the Zoological Institute in Munich have reported that pattern in the insect epidermis can be understood in terms of gradients. Of particular importance is the recent discovery of compartments in insect development by Antonio Garcia-Bellido at the University of Madrid. These are groups of cells in a particular position whose developmental program is changed at the same time. A succession of such events divides the embryonic wing, for example, into a number of discrete regions. The genes associated with the formation of compartments can be identified and manipulated, so that studying this process is a promising approach to the task of linking gene action with pattern formation.

Klaus Sander of the University of Freiburg has shown how gradients can control the earliest patterning in a developing insect egg. It seems that the posterior margin of the egg of the leafhopper can be considered the source of a gradient much like the zone of polarizing activity in the chick limb. The formal similarities of the two systems are striking. Moving some of the cytoplasm from the posterior end of the egg toward the anterior end can give rise to a pattern of embryo segments just like the pattern of digits obtained by grafting an additional zone of polarizing activity to the early wing bud. Both the posterior cytoplasm of the egg and the zone of polarizing activity of the wing bud appear to act as boundary regions that provide a positional signal. Analogous regions are found in other animals: the classical "organizer" in amphibian embryos, the head of the hydra and what are called micromeres in sea-urchin embryos.

Mechanisms based on positional in-



INDIVIDUAL MUSCLES begin to develop as is shown in photomicrographs in which a cross section of the limb is enlarged some 35 diameters. At first (*a*) muscle cells are grouped in large dorsal (*D*) and ventral (*V*) muscle blocks above and below the ulna (*U*) and radius (*R*). About 12 hours later each block has split in two (*b*). After another half day the dorsal masses have divided again; the ventral masses will divide later. The FDP muscle will arise from division of one ventral mass (*F*). The photographs were made by Shellswell.

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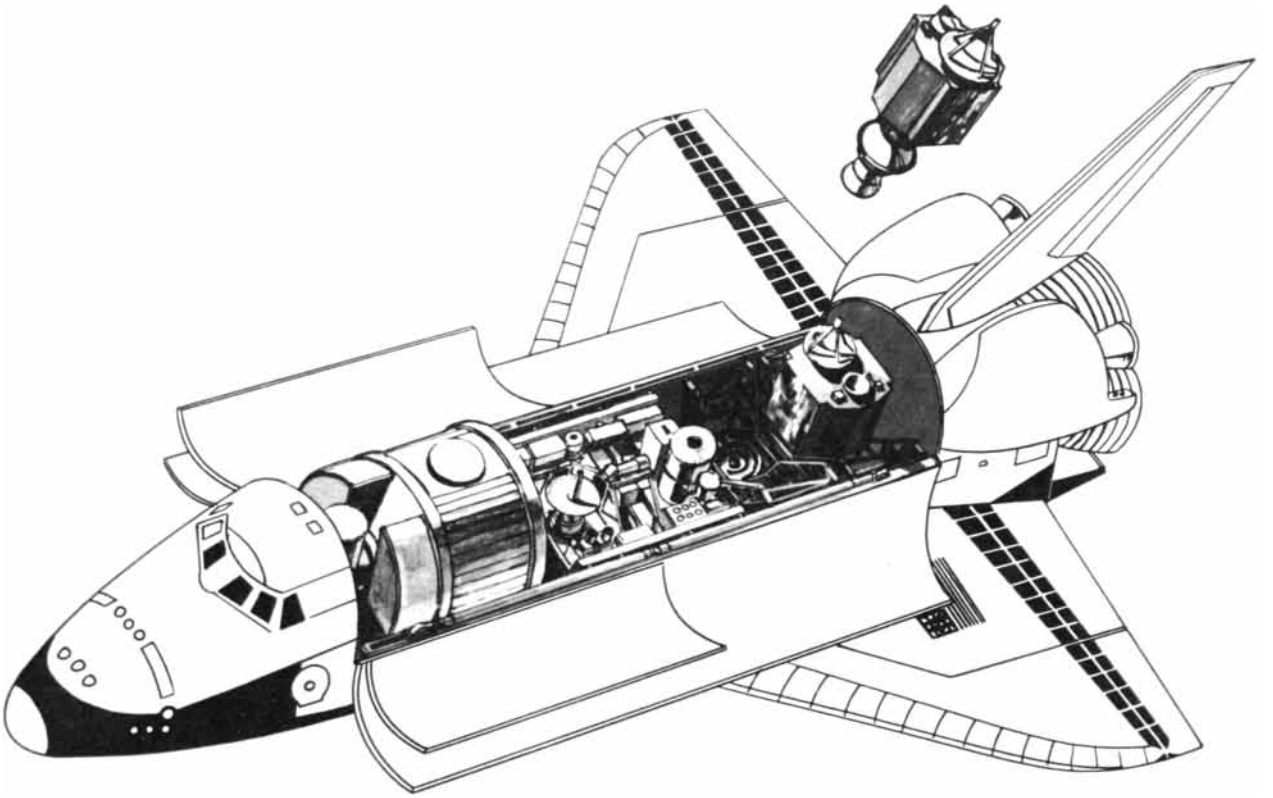

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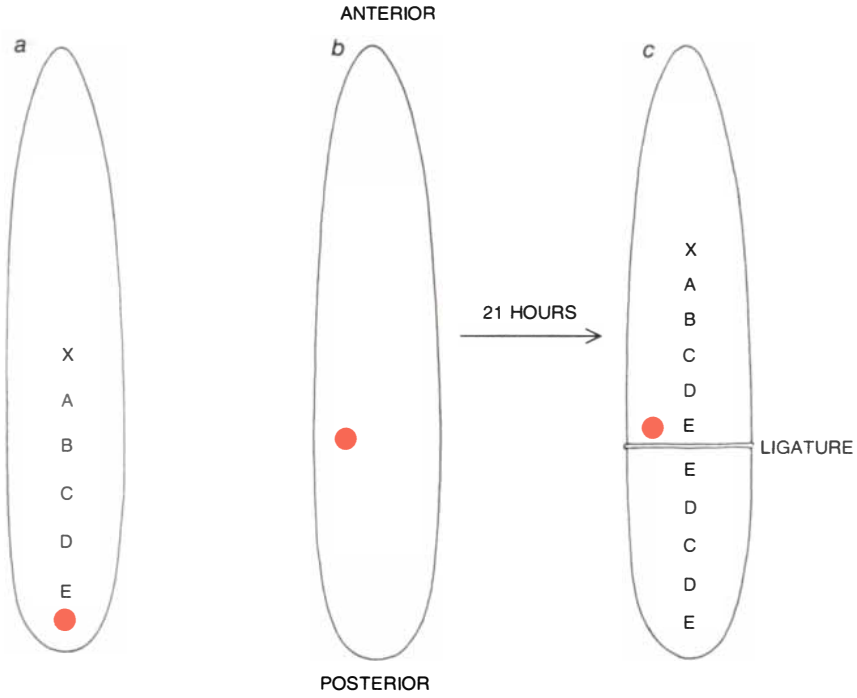
formation are, to be sure, not the only ones by which pattern can be specified during development. Another mechanism involves the presence of determinants of some kind at specific locations within the cytoplasm of the egg; as the egg divides, cells in different regions acquire different cytoplasmic components that specify the course of their differentiation. Karl Illmensee and Anthony P. Mahowald of Indiana University found that what is called the polar plasm at the posterior end of the insect egg specifies the development of germ cells in the insect. By transplanting the cytoplasm to the anterior end of the egg they caused cells that would normally form head structures to develop instead as germ cells. Cytoplasmic localization of this kind is the exception rather than the rule, at least for vertebrate animals, and does not account for most of the overt patterns that are seen. A large number of experiments indicate that most patterns arise as the result of cell-to-cell interaction; if parts of the early embryo are removed or rearranged, some form of regulation arranges things so that a normal animal develops.

Both such regulation of pattern when a part is removed during development and the regeneration of a missing structure in an adult animal can be understood in terms of positional information. Regulation and regeneration call for the replacement of missing positional values by new values, which are interpreted by the cells. There are two main ways in which this can happen. as Thomas Hunt Morgan realized early in this century. In morphallaxis (as in the regeneration of a hydra or in most of the regulation within the early embryo) the regenerated structure is molded from the remaining tissue without the proliferation of cells. Morphallaxis can now be understood as the establishment of a new boundary region at the cut surface and the specification of new positional values with respect to that boundary. In epimorphosis (regeneration of the amphibian limb is a classic example) the regenerated structure arises through growth: the proliferation of a small group of cells at the cut surface. New positional values are generated in the new tissue.

Some major insights have recently been supplied by the work of Peter J. Bryant and Susan V. Bryant of the University of California at Irvine and Vernon French of the University of Edinburgh [see "Biological Regeneration and Pattern Formation," by Peter J. Bryant, Susan V. Bryant and Vernon French; SCIENTIFIC AMERICAN, July, 1977]. They developed a model based on a polar-coordinate system, in which the positional value of any cell is defined by two coordinates, one meridional and one along a proximodistal axis. An important feature of their model is that intercalary, or interpolated, regeneration takes place whenever discordant positional values come to be adjacent to each other; new positional values are generated in the growing tissue until the discordance is eliminated. These workers have shown that their model can account for a variety of phenomena (in insect and amphibian limbs and in the imaginal disk of insect larvae), some of which were complete mysteries until they were analyzed. That the same kinds of phenomena are observed in various animals and that they obey the same rules is encouraging if one believes in the universality of mechanisms for pattern formation.



EGG OF LEAFHOPPER (*a*) has a region at the posterior end (*colored dot*) that has an effect much like that of the zone of polarizing activity in the chick limb. The insect's egg normally gives rise to embryonic segments *A* through *E*. (Region *X* does not give rise to anything in the embryo proper.) By moving the region to a more anterior position (*b*) and then ligating the egg, Klaus Sander of the University of Freiburg obtained embryos with a new pattern of segments (*c*) much like the digit pattern in a chick wing bud when a zone is moved near the middle.

I have tried to show that the concept of positional information provides a useful framework within which the development and regulation of biological patterns can be understood and investigated. There is accumulating evidence (some of the most impressive of it from studies of insect development, which has only been touched on here) that cells have a property corresponding to their positional value and that the rules for pattern formation and regulation are very similar in very different systems. If these views are correct, those of us who work on such problems are in the situation of genetics long before DNA was identified as the genetic material: we have rules governing the phenomenology but the molecular basis of the phenomena is completely unknown. We have no idea how positional signaling is accomplished (it could involve simple ions or complex nucleic acids) or how cells record and remember their positional value. Moreover, if positional information is similar in different systems, the wide variation in patterns must stem from differing interpretation of positional values by cells. Just how the information is interpreted is obviously a central problem.

It is sometimes held that no real progress has been made until a biological mechanism is placed on a firm molecular basis (until, in this case, the molecular nature of the gradients, or positional signals, is known). Such a view denies the existence of different levels of organization at which one can meaningfully investigate biological processes. Developmental biologists would like to know the molecular basis of pattern formation, but at present there is no obvious way to find it. Our problems are similar to those of any workers trying to reduce cellular behavior to molecular terms, particularly when it involves reactions within cells that lead to changes in cell state or behavior. Perhaps we should be less apologetic and remember that the study of genetics was (and is) effective at levels other than the level of DNA, and that unless we have the right phenomenology we do not know what we are trying to explain or where to look for the explanation.

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An Oceanic Mass Migration of Land Birds

Every fall millions of songbirds and small shorebirds leave the east coast of North America for the Caribbean and South America. Their difficult journey has now been followed with the aid of radar

by Timothy C. Williams and Janet M. Williams

For about two months after the summer visitors leave the beaches of New England and the Canadian Maritime Provinces those areas experience a far more massive departure that goes unnoticed by most of the remaining inhabitants. More than 100 million birds, most of them fairly small, cross those shores on their annual flight southward over the Atlantic from eastern North America to the Caribbean and South America. A patient observer with a powerful pair of binoculars might see a few of the birds as they traverse the face of a full moon or pass through a beam of light pointed upward at night, but for the most part the participants in the migration cannot be seen directly. With the aid of John M. Teal and John W. Kanwisher of the Woods Hole Oceanographic Institution, Leonard C. Ireland of the Bermuda Biological Station and others we have exploited a network of radars to observe the behavior of the birds. The studies have yielded much information about this remarkable migration and have indicated why some birds succeed at it and others, which seem to be out over the ocean by mistake or misfortune, perish in large numbers.

The birds we have observed by radar along the Atlantic coast during the last week of September and the first half of October are most likely shorebirds (such as sandpipers and plovers) and small songbirds (such as warblers). The vast majority of the birds begin their journey at night, after a cold-front weather system has moved southeast over the coast. If you stand in a quiet area of Cape Cod early of an October evening with a brisk northwest wind at your back, you can hear great numbers of small birds calling to one another as they pass overhead. If you then were to go to any of the three large radar installations on the Cape (Air Force surveillance, air-traffic control or weather radar), you would find the center portion of the screen filled with small bright dots moving in a roughly southeasterly direction.

Such a radar screen represents a map of the area surveyed by the apparatus; north is at the top, and the distance of an object from the radar installation is indicated by concentric range rings at intervals representing about 10 kilometers. The location of any object detected is represented on the screen by a bright dot. The radars to which we had access displayed each object in this way from once to 15 times per minute.

In order to record information from the radar screen we made time-exposure photographs. Any slowly moving object such as a bird would show up in the photograph as a series of small dots or as a streak. By briefly closing and then reopening the shutter toward the end of the time exposure we could ascertain the direction of motion of the bird. By measuring the length of the streak, and therefore the distance traveled, we could (knowing the duration of the time exposure) compute the speed of the bird. The number of birds detected per unit of area served as a basis for estimating the density of migration, which we classified in four categories: no movement, light migration, moderate migration and heavy migration. Most of the radar units could also estimate the altitude of birds from the angle of elevation of the radar beam and the distance of the birds from the radar.

We began our research on these southerly migrations by observing birds as they moved over Cape Cod. Like William H. Drury and Ian C. T. Nisbet of the Massachusetts Audubon Society before us, we were fascinated by the great numbers of birds (up to 12 million per night) that left Cape Cod moving southeast toward the middle of the Atlantic. To determine what happened to these birds we watched from radars on the islands of Bermuda and Antigua. We found that many but not all of the birds continued flying southeast over Bermuda but arrived in the Caribbean flying southwest. Land birds and most shorebirds would have no chance to land during that flight of more than 3,000 kilometers. Moreover, they could not navigate by following coastlines or other landmarks; some other system of guidance was necessary.

The only way we could study the movement of the birds while they were over water was with radars at coastal sites and on islands and ships along the route. These observations had to be made simultaneously with similar radars and under similar conditions. Therefore during the last week of September and the first two weeks of October for six years we enlisted the cooperation of six national governments, four Federal agencies, the Woods Hole Oceanographic Institution and a large number of our friends and students to man as many as nine radar stations along the route of the migration.

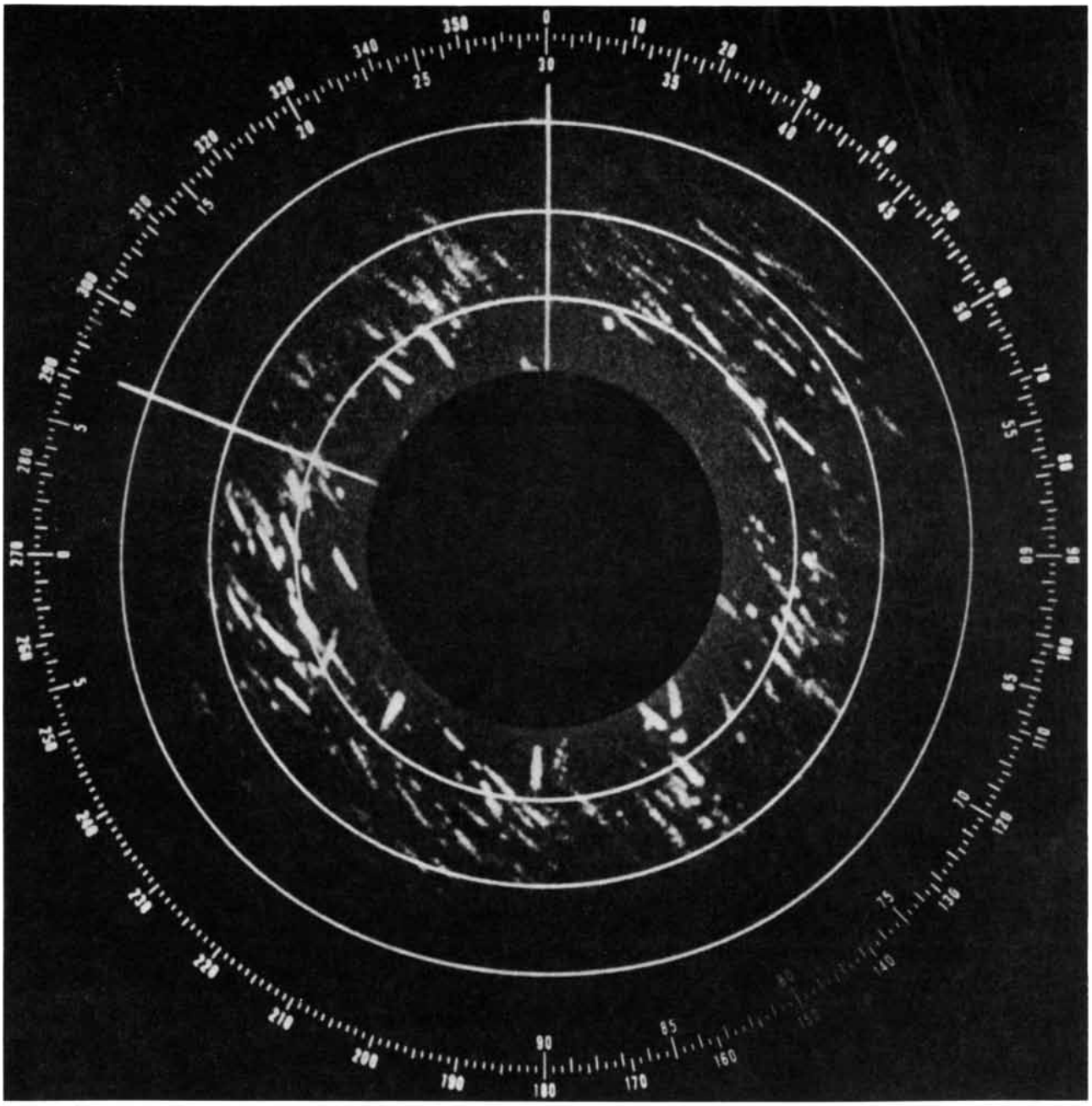
The basic patterns of migration that we found appear to involve at least two routes from North America to South America. On one route the birds follow the coast southwest to the vicinity of Florida and then turn southeast to move along the Caribbean islands. The second route involves birds leaving the coast from at least as far north as Nova Scotia and as far south as Virginia, and thereafter moving southeast (a direction of flight observed from ships in all the areas of the Atlantic we studied). We suppose the birds turn in the area of the Sargasso Sea (approximately the southern limit of our observations) as they encounter the northeast trade winds. Aided by those winds, they move in a southwesterly direction over the region occupied by the Caribbean islands.

At all the radar sites we found that the migrations proceeded in waves. Several days would pass with little or no activity, and then for a day or two birds would move in large numbers. The intervals between periods of migratory activity

became longer as one moved away from the coast. At coastal sites some movement could almost always be observed at night. At Bermuda we encountered occasional periods without migration, and in the Caribbean several days often passed with no migrants being observed.

By plotting the data obtained by radar on a series of photographs made from weather satellites operated by the National Oceanic and Atmospheric Administration (NOAA) one can establish a correlation between migratory activity and the state of the weather. An example is provided by the satellite photographs for October 3 through October 6, 1973 [*see illustration on page 173*]. On the first day a departure of birds from the North American coast was beginning. A cold front had just moved offshore from Cape Cod to Florida. As the cloud patterns show, the front crossed the shoreline between Cape Cod and Halifax. Coastal radars recorded heavy movements of birds that night. Birds were moving both along the coast and offshore.

By October 4 the frontal system had become stationary between Bermuda and the coast. Birds observed from a ship penetrated the frontal system all day, moving southeast and reaching the Bermuda area by midafternoon. On October 5 these birds were between Bermuda and the Caribbean. At Bermuda



MIGRATING BIRDS show up as white streaks on this photograph of a radar screen on the Caribbean island of Antigua. North is at the top. The white rings represent 10-kilometer intervals from the radar station. The center of the display is blacked out to prevent overexposure of the photograph from ground clutter. The photograph is a five-minute time exposure, in which the largest concentration of streaks representing birds is in the range circles from 20 to 45 kilometers. A dot at the end of a streak, caused by briefly closing the shutter of the camera, shows direction of movement. The white line at the left shows the angle of elevation of the radar beam, which was intersecting a layer of birds at altitudes of from three to six kilometers. Most of the birds were moving southeast; a few were moving southwest.

ATLANTIC MIGRANTS, drawn to a common scale, are portrayed. Included are three shorebirds, the Hudsonian godwit (*a*), the American golden plover (*b*) and the white-rumped sandpiper (*c*), and one songbird, the blackpoll warbler (*d*). Perhaps half of the migrants are songbirds. An indication of the scale is provided by the warbler, which in life is from 4.5 to 5.5 inches long and weighs less than an ounce.

the movement had shifted from southeasterly to southerly (possibly reflecting birds moving south from Halifax the previous night). Bird movements at the ship, which was about 400 kilometers behind (northwest of) the weather front, appeared to be scattered in all directions, although the density of birds was scored as being heavy.

On October 6 the wave of migration reached the Caribbean, with heavy movements reported at Antigua during the day and at Barbados during the evening. The total time of flight from North America to Antigua was about 64 hours and to Barbados about 72.

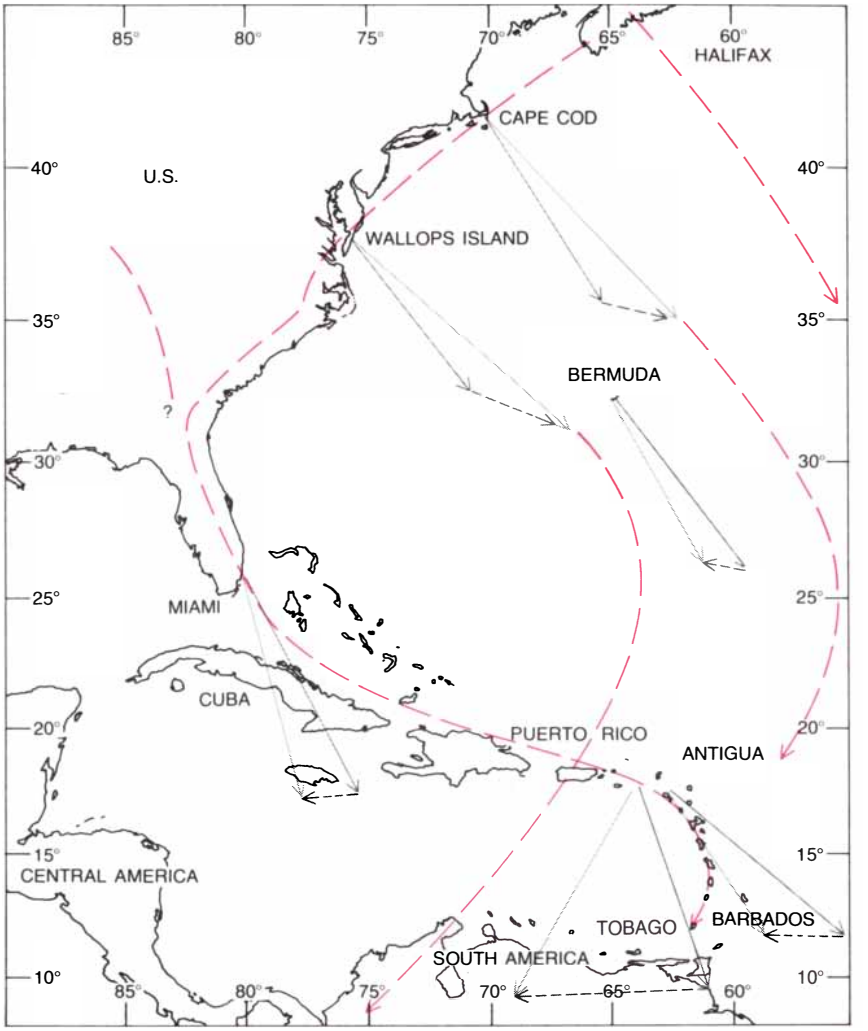
The timing of this migration is typical of the data we have been able to gather. Departures from the coast are triggered by favorable flight conditions behind a cold front. The significant feature of the weather is strong northwest winds, which help the birds to move from the coast to the area of Bermuda in an average of only 18 hours. Radar indicates that few birds land on Bermuda; the great majority of them continue southeast over the island, usually in light and variable winds, until they reach the area of the Sargasso Sea, where they encounter the northeast trade winds that assist them in reaching the Caribbean. This second part of the journey is much slower than the first; the birds appear to fly for about 48 hours between Bermuda and Antigua. The radars at Antigua indicate that, as at Bermuda, few of the birds land; instead most of them seem to continue flying for another 18 hours to reach South America. The total time of nonstop flight over the ocean hence appears to be 86 hours, plus or minus 12.

To the best of our knowledge this migration is the longest (in both time and distance) nonstop flight known for small birds. It also seems to take place at the greatest height above the ground of any bird migration. From radar observations we found that the densest migrations from the North American coast to Bermuda are at an altitude of two kilometers (about 6,500 feet) or somewhat less, although some birds are detected at five kilometers (about 16,000 feet). At Bermuda a different pattern begins. Most birds fly at an altitude of from one to two kilometers. By the time they reach Antigua they are up between three and six kilometers, and on some days the radar showed significant numbers of birds flying over the island at 6.5 kilometers (21,000 feet). Although we made many fewer observations at Barbados and Tobago, it appeared that the birds were by then dropping in altitude, until at Tobago we recorded no birds above 800 meters. Evidently in approaching the South American coast the birds come down gradually in preparation for landing.

Birds at an altitude of six kilometers above Antigua are flying in air at a temperature of zero degrees Celsius, and the air has only about half as much oxygen as air at sea level. The advantage of flying at such heights seems to be that it puts the birds in a region of favorable wind conditions. We plotted the average wind velocity at various altitudes on the days when we detected moderate or heavy migrations at Antigua at an average altitude above 4.2 kilometers. The average direction of bird movement on those days was southeast. Our data for altitudes below four kilometers showed strong east-southeast winds, which were avoided by the high-flying birds.

Physiologically flight at such altitudes is made possible by the distinctive respiratory system of birds. The system embodies a number of adaptations for flight, but in this connection the crucial one is the countercurrent flow of blood and air in the bird's lung. It is the key to the bird's ability to extract oxygen efficiently and so to fly at high altitudes.

Observations made both visually (with the aid of binoculars) and by radar from ships at sea yielded a much clearer picture of how the birds behave during their long flight over the ocean and also indicated what kinds of birds might be making the flight. In order to follow our discussion of these results one needs to be clear about the distinction between a bird's track and its heading. If a bird is flying in a wind, the



AREA OF MIGRATION from North America to the Caribbean and South America appears based on radar observations from Halifax, Cape Cod, Wallops Island, Bermuda, Miami, Puerto Rico, Antigua, Barbados and Tobago. The broken colored lines indicate two sets of possible migratory routes, one for birds flying along or near the North American coast and the other for birds making most of the trip over the ocean. (The data for Puerto Rico are derived from observations by W. J. Richardson of Environmental Research Associates in Toronto.) The gray lines forming triangles show the relation of the wind to the heading and track of the birds. In each case the broken line shows the direction of the wind (with the relative wind speed indicated by the length of the line), the dark gray line represents the average heading of the birds and the light gray line shows their average track. The birds consistently have a southeasterly heading, but the trade winds that blow from the northeast in the Caribbean create a drift that has the effect of turning the migrating birds toward the southwest as they approach their destination.

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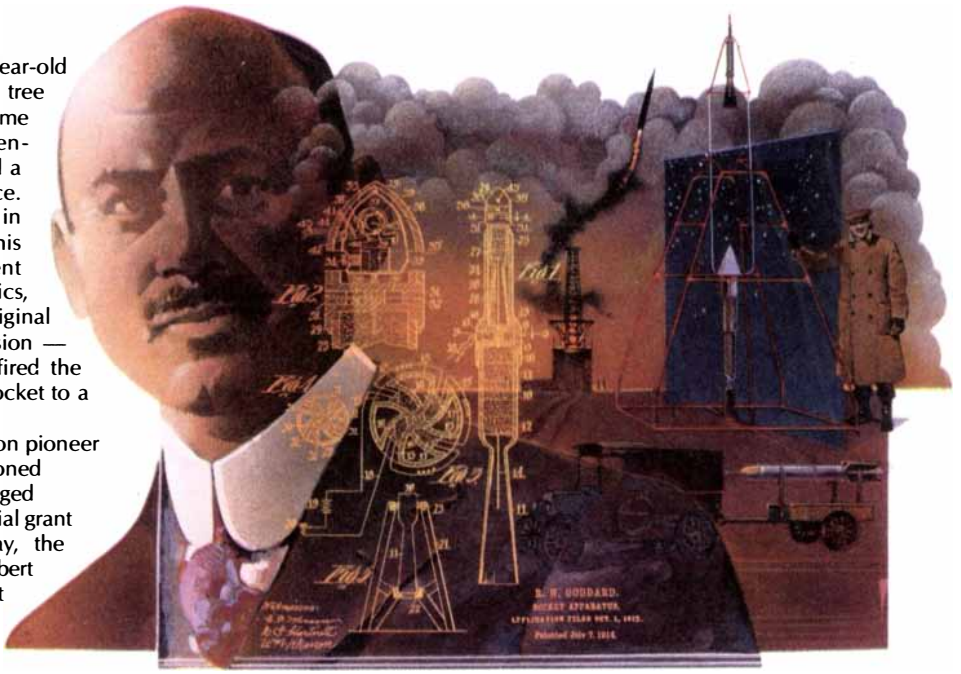

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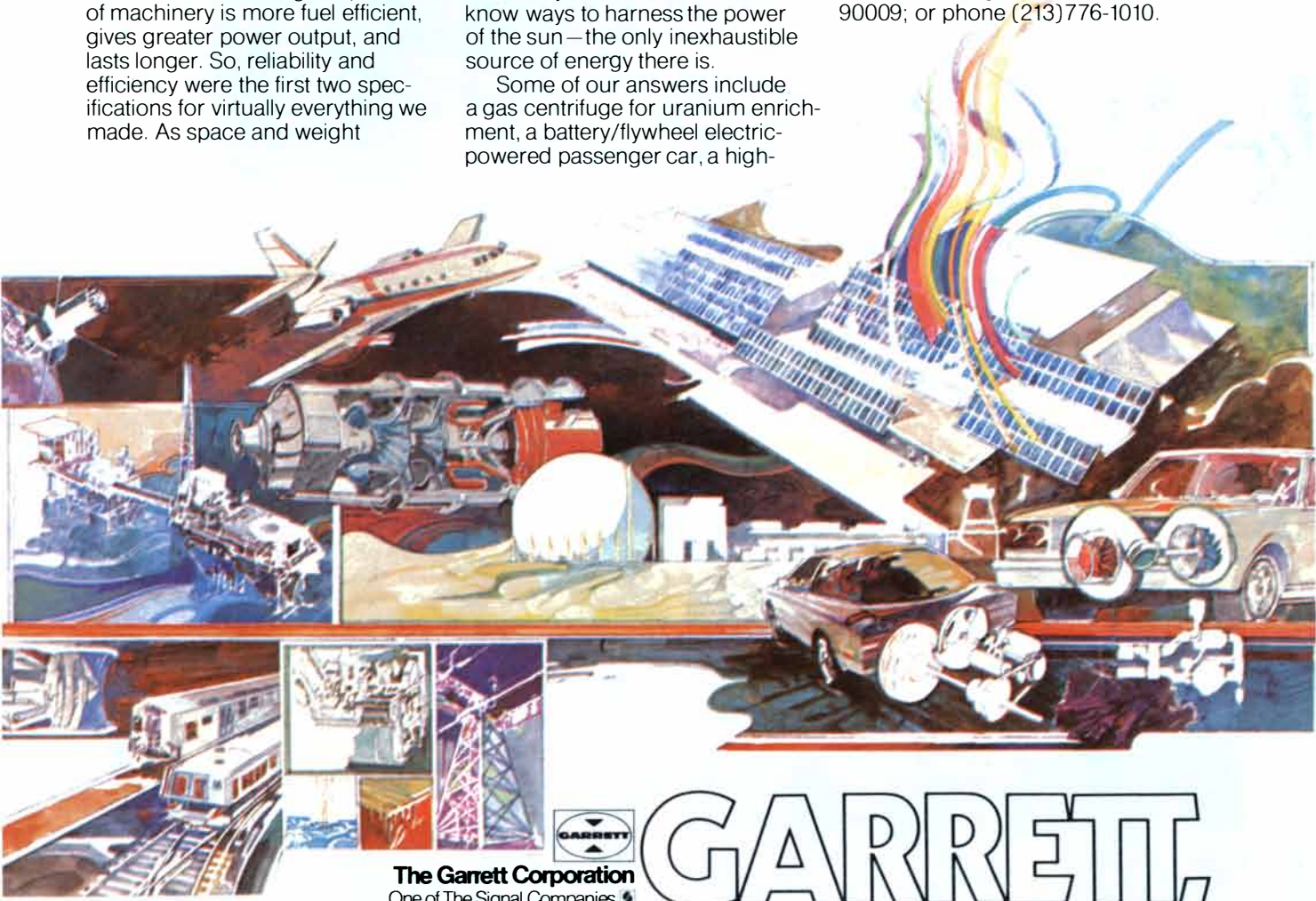

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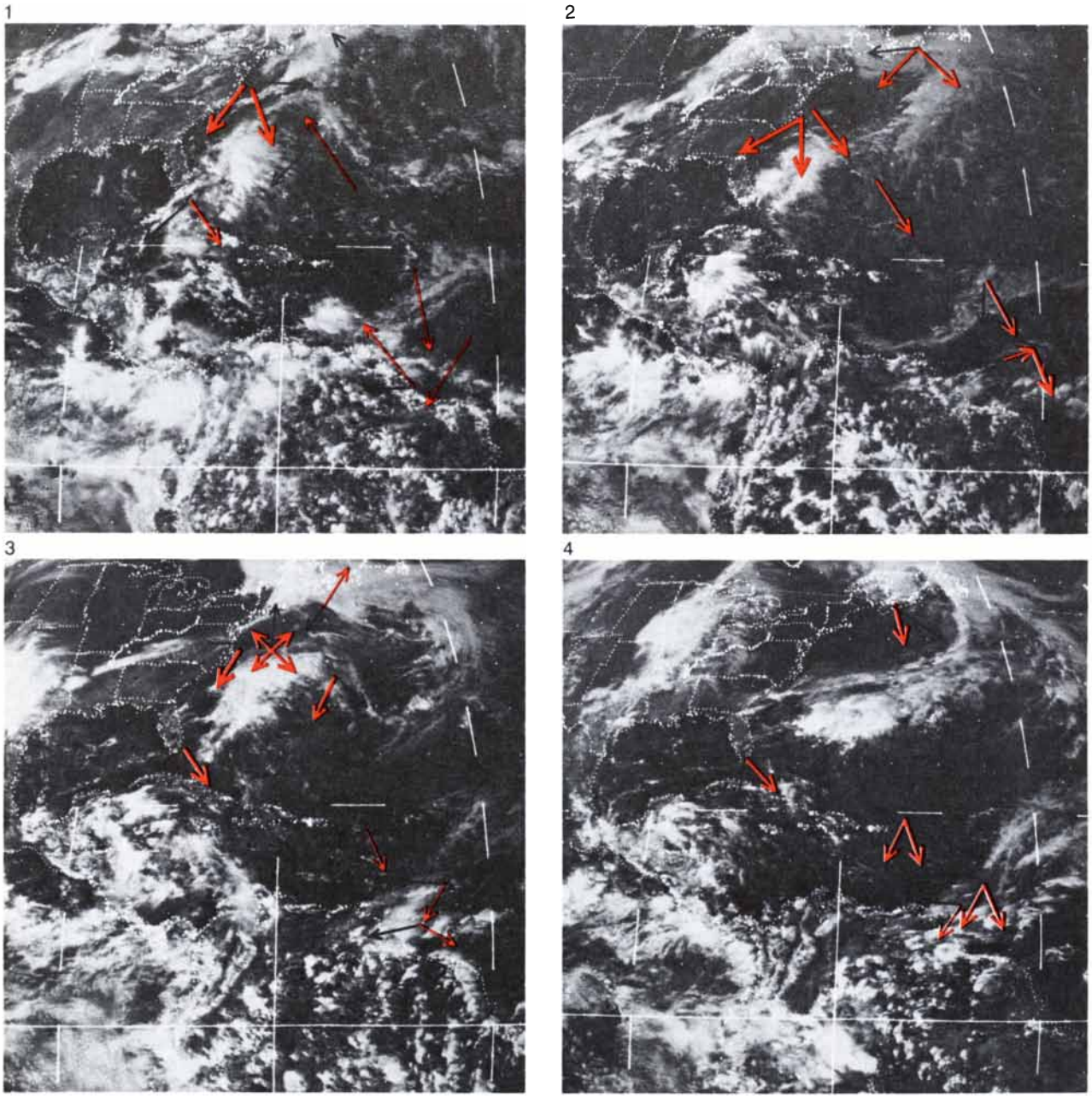
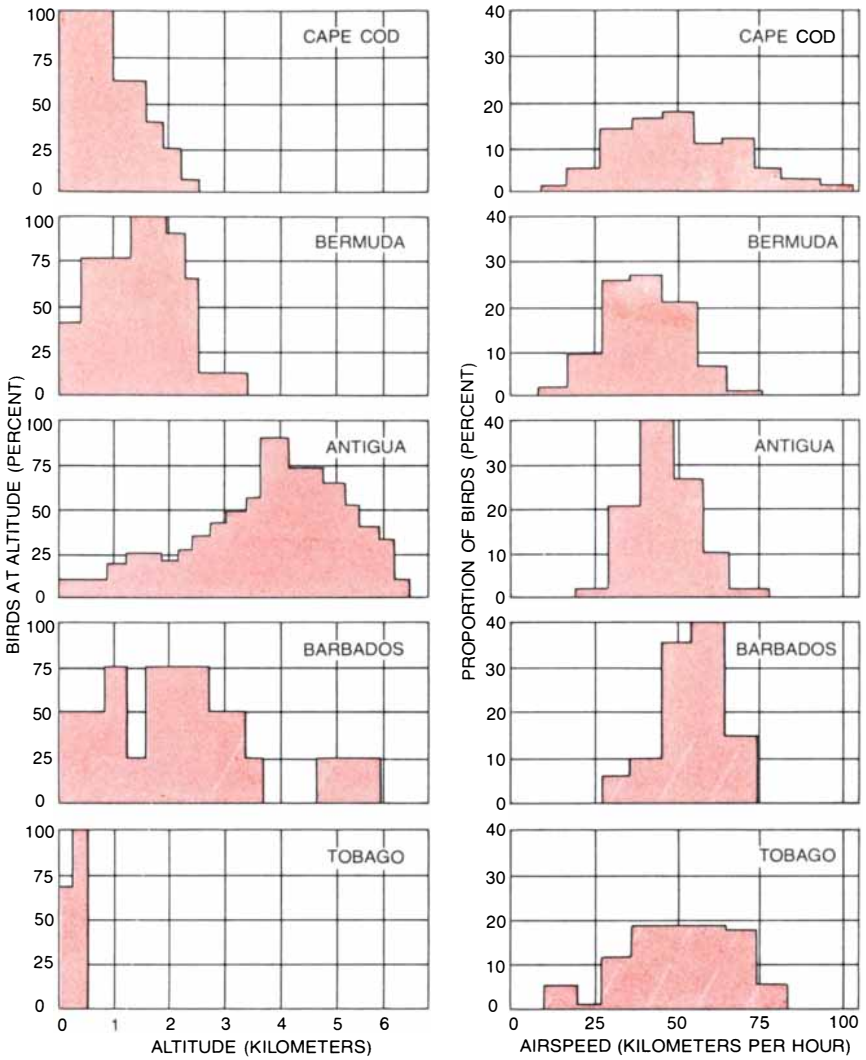
movement shown on a radar screen (the track) does not necessarily correspond to the direction in which the bird is orienting its body (the heading). The wind introduces drift, that is, it blows the bird to the downwind side of its heading.

Another factor to be taken into account is the bird's airspeed, which is of course the speed of its flight through the air. Airspeed and heading are calculated from our radar data by means of the direction and speed of the wind as determined by a weather balloon at the altitude of the bird. In order to distinguish the behavior of birds from their drift caused by the winds we have plotted both track and heading for observations of bird migrations at sea. Following the lead of Ronald P. Larkin of Rockefeller University, who analyzed the first two years of these observations at sea, we have divided all the observations from ships into periods of consistent migratory behavior.

A plot of these data on a map reveals four rather different categories of behavior [*see top illustration on page 175*]. The first category consists of the periods when no significant amount of migration is detected. The second consists of birds with headings from south to southeast and tracks that are southerly. These birds, if they continued the pattern, would be likely to reach South America. The third category consists of groups of birds that appear to be disoriented.



PROGRESS OF MIGRATION during four days in October, 1973, is plotted on weather-satellite photographs made by the National Oceanic and Atmospheric Administration (NOAA). The colored arrows represent the average track of a bird migration, and the thickness of an arrow indicates whether the migration was light, medium or heavy. The black arrows show the wind direction at the altitude of the birds; the longer the arrow, the higher the average wind speed. A migration began October 3 under typical conditions (*1*), after a cold front had just moved offshore from Cape Cod to Florida. The accompanying northwest winds aided the birds. By the next day (*2*) the frontal system was stationary between Bermuda and the coast, and most of the birds had reached Bermuda. Once past Bermuda (*3 and 4*) they encountered the northeast trade winds that shifted them toward their destinations in the Caribbean and South America. The birds were at Barbados by the fourth day after about 72 hours of flight. The total time of nonstop flight over the ocean was about 86 hours.



ALTITUDE AND SPEED of migrating birds, as ascertained by radar observations, are charted. The plot of altitude (*left*) shows the percent of birds found at given altitudes during times of moderate or heavy migration. The average altitude reaches a peak at Antigua and then declines as the birds approach their destination. The plot of airspeed (*right*) shows the percent of birds detected at each speed. The loss of both the faster and the slower birds between Cape Cod and Antigua suggests that only certain species are adapted to this long migration. The number flying at less than 50 kilometers per hour suggests that many of the birds are small songbirds.

Their headings are widely scattered, and any net progress of a group is largely attributable to drift caused by the wind. The calculated airspeeds of these birds are generally quite low, less than 20 kilometers per hour. It appears unlikely that any significant proportion of the birds in this category would reach the Caribbean or South America if they persisted in poorly oriented flight at low speed. The last category consists of birds that are apparently trying to move in a direction other than toward the Caribbean.

We could not discern a statistically significant tendency for these four types of behavior to be grouped in any area of the Atlantic we studied. We therefore concluded that some factor other than geography must have been determining the categories of behavior we observed from the ships. If one plots the same data on a diagram of the predominant weather patterns at a given time, a clearer picture emerges.

A typical weather system for which we made such a plot consisted of a low-pressure center or hurricane, a moving cold front, a stationary front and two high-pressure air masses, one subtropical and the other (northwest of the frontal system) representing air that had just moved off the North American continent [*see bottom illustration on opposite page*]. The migratory patterns differed according to the weather. In the area around the subtropical high we found only migrants with headings to the south or southeast; they were making effective progress toward the Caribbean. Groups of birds with scattered headings were found only northwest of frontal systems or south and east of low-pressure centers. A common factor in both cases is that the disoriented birds have recently experienced strong offshore winds. It is in these areas also that we found most of the birds with an average airspeed of less than 20 kilometers per hour.

Based on this analysis we can tentatively classify birds observed over the Atlantic as true migrants if they have penetrated the frontal system that initiated their departure and as unsuccessful migrants if they are observed in a high-pressure center northwest of a frontal system or in a low-pressure system. (Some true migrants will occasionally turn up in the second category, usually because the observation was made near the North American coast when the birds had not yet penetrated the frontal system.) It is probable that the unsuccessful migrants are birds that would normally migrate over land but have been blown out to sea.

A heading that is generally southeast is typical of the true migrants, regardless of whether the radar that detects them is coastal, island-based or on a ship. Nevertheless, it is not always easy to identify the true migrants because of the frequent simultaneous occurrence of two or more patterns of migratory behavior, particularly at the large coastal or island-based radars. Therefore at each site we separated groups of birds on the basis of track direction and then computed the average heading of each group. Although the average heading of all migrants at Cape Cod, Wallops Island, Miami and Bermuda was to the southeast, the analysis at Antigua is probably the most important one. There we divided the birds into two groups: those that were moving along the Antilles to the southeast and those that were arriving from the Atlantic moving southwest. In spite of this arbitrary division the average heading of both groups was to the southeast; the difference in track direction was due to the fact that the birds were flying in different wind conditions.

The analysis of headings suggests that a remarkably simple guidance system is adequate for this 3,000-kilometer flight. Once birds leave the coast of North America they maintain a constant compass heading to the southeast until they reach the coast of South America. It apparently is not necessary for them to change this heading; the shift from a southeast track to a southwest one is accomplished for them when they encounter the northeast trade winds in the area of the Sargasso Sea. A substantial body of experimental evidence supports the notion that a bird can establish and maintain a compass heading on the basis of the sun, the stars or the magnetic field of the earth.

Although radar has many advantages

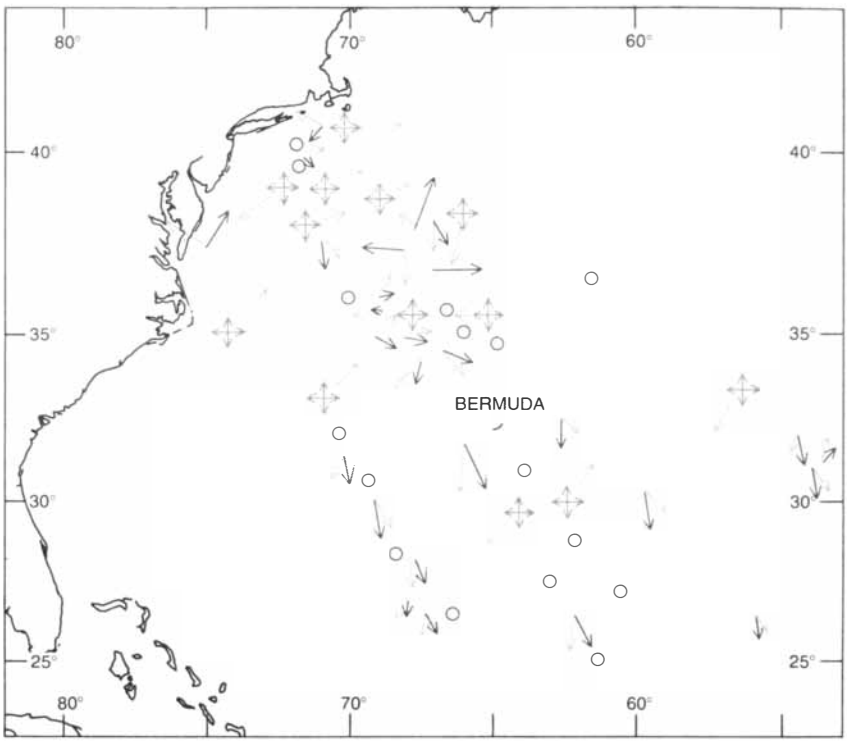
for studying the migration of birds, it does not enable us to identify the birds that are detected on the radar screen. We have gone at the question indirectly by determining the airspeed of the 4,600 or more birds we have detected by radar. At coastal sites the range of airspeeds is quite broad, but in the Caribbean it is mainly between 30 and 60 kilometers per hour. Even though airspeed is not a precise means of identifying birds, most of the birds flying at less than 45 kilometers per hour are probably small songbirds. Shorebirds and waterfowl fly faster.

Much better identifications can be made of birds that are seen passing or landing on ships. During the last two years of our shipboard observations Carol P. McClintock of the State University of New York at Buffalo undertook to obtain as many specimens as possible. Since firearms are not allowed on the ships, she resorted to live traps or a slingshot for which green grapes served as the ammunition. Her findings, together with careful observations made with binoculars, reveal that small songbirds were by far the most abundant species seen from ships in all the areas of the Atlantic we investigated.

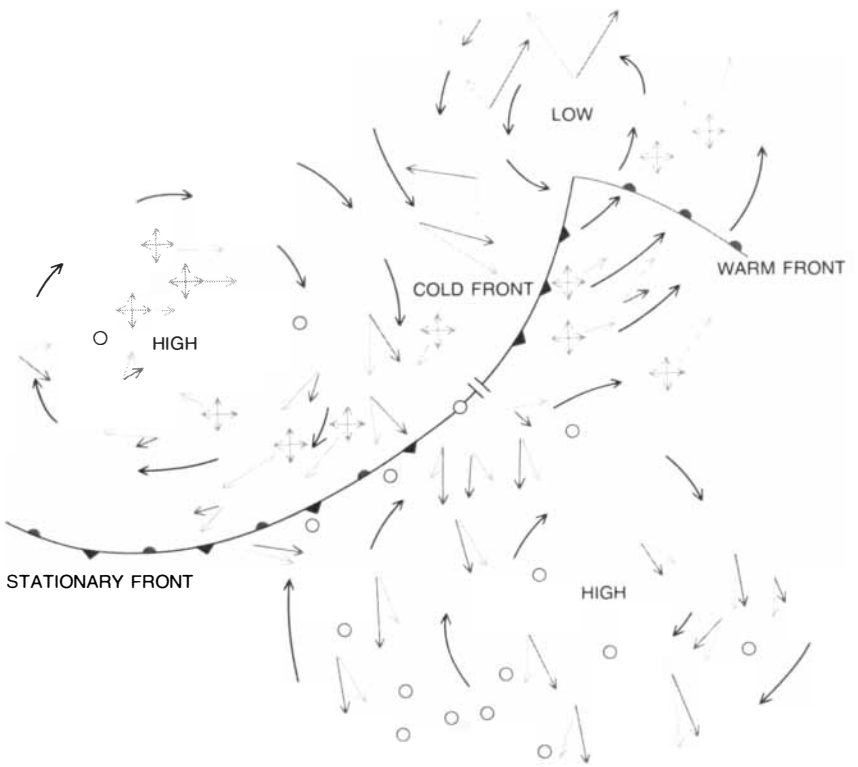
The variations in the observed distribution of songbirds appeared to reflect behavioral differences rather than physical ones. For example, warblers, sparrows and juncos are about the same size and weight, yet all but one of our observations of sparrows and juncos were confined to the area between the coast and Bermuda, and warblers were seen as far south and east as the ships traveled. We believe many of the birds we have defined as true migrants are warblers, whereas many of the birds seen wandering behind frontal systems or south of low-pressure areas (the unsuccessful migrants) are such species as sparrows and juncos, which do not migrate to the Caribbean or South America.

The Atlantic is not a hospitable place for small songbirds. During storms at sea hundreds or thousands of small birds have been seen flying around a ship, entering cabins and hitting masts or wires. At such times it seemed unlikely that many of the birds could survive for more than a few hours. Our belief that large numbers of these birds perish at sea is supported by reports from oceanographers that bird feathers are often found in the stomachs of deep-sea Atlantic fishes.

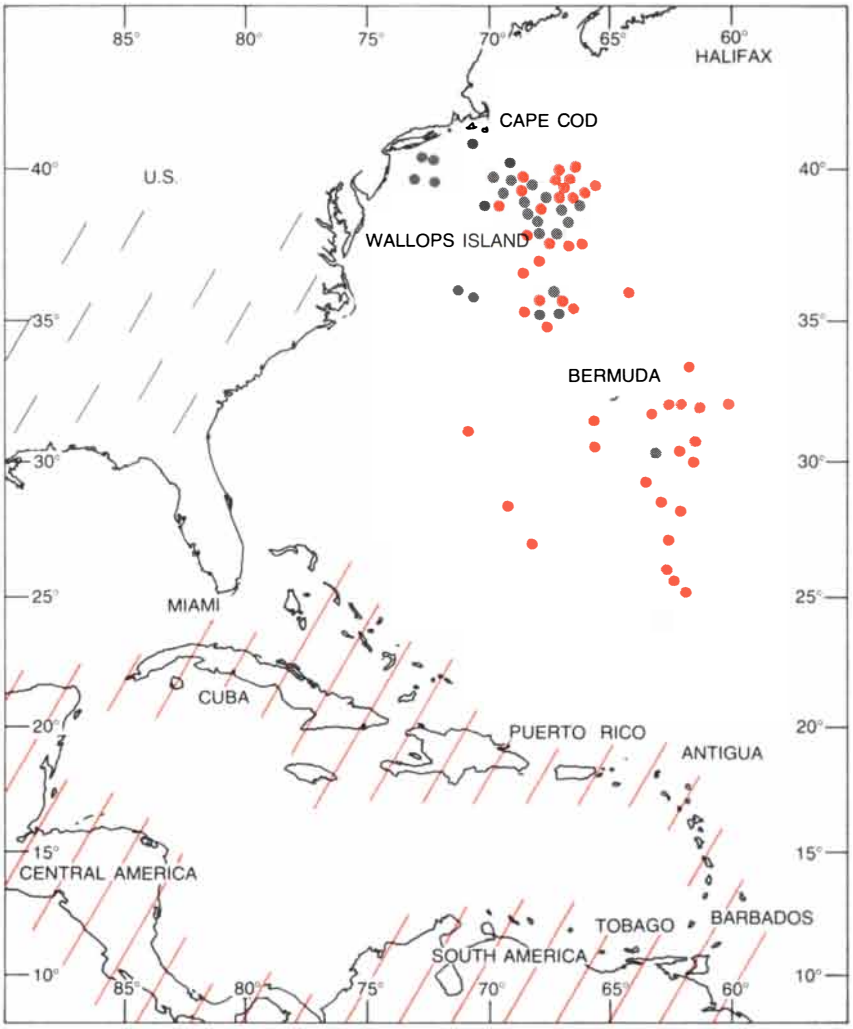
Our radar data indicate, however, that such losses arise primarily among birds that lack the behavioral adaptations for flying over the ocean. For the true migrants a relatively simple migratory strategy takes advantage of a surprisingly predictable series of weather conditions along the route. First the migrants wait on the east coast of North America until a strong cold front passes



MIGRATORY BEHAVIOR of birds over the ocean was observed by means of shipborne radar. The dark gray arrows indicate the average heading of the birds and, by the length of the arrow, the relative airspeed; the longer the arrow, the higher the average airspeed. The light gray arrows similarly indicate the average track of the birds and their average speed in relation to the ground. The open circles represent areas where no migrating land birds were seen.



EFFECT OF WEATHER on migratory behavior is indicated by plotting the data from the illustration at the top of the page on a diagram of typical weather conditions. Weather patterns are much more important than geography in influencing the behavior of migrating birds.



BIRD SIGHTINGS from ships in the western Atlantic reveal a difference between the migratory patterns of small songbirds that winter in the southern U.S. and those that winter in the Caribbean and South America. The first group, represented by gray dots and gray hatching in the wintering area, includes three types of sparrow and the slate-colored junco. The second group includes eight species of wood warbler and is represented by colored dots and hatching. Some species of warbler winter in Central and South America rather than the West Indies.

southeast over the coast and out into the Atlantic. This weather pattern not only ensures the birds favorable northwest winds during the first part of their flight but also is a remarkably good indicator of fair weather between the coast and the Sargasso Sea. Tropical storms or hurricanes approaching the North American coast usually halt the southeastward movement of cold fronts. On 93 days or nights we observed moderate or heavy movement of birds along the North American coast or at Bermuda, and on only two of those occasions did we see birds apparently flying into the path of an approaching storm.

Once the migrants have left the coast they have only to fly constantly to the southeast until they reach the Caribbean or South America; their actual track will be first to the southeast to the Sargasso Sea and then, as they encounter the trade winds, southwest until they reach their destination. As soon as they have penetrated the frontal systems near Bermuda their flight will be for the most part under clear skies with either light and variable winds or moderate, steady northeast ones.

The ocean route from Halifax to Antigua is about 2,800 kilometers (47 percent) shorter than a route by way of Florida. Moreover, birds on the ocean route take advantage of both northwest offshore winds and the northeast trade winds as tailwinds, and the route presumably is without predators. The trip does, however, require a degree of exertion that is not matched by any other vertebrate. For a man the metabolic equivalent would be to run four-minute miles for 80 hours. The avian respiratory and muscular systems show many adaptations that make such an output possible. If a blackpoll warbler were burning gasoline instead of its reserves of body fat, it could boast of getting 720,000 miles to the gallon!

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THE AMATEUR SCIENTIST

Some whispering galleries are simply sound reflectors, but others are more mysterious

by Jearl Walker

Whispering galleries, which are usually a domed room, are an attraction for visitors the world over. Their distinctive feature is that they carry a sound as soft as a whisper over distances the whisper would not traverse without acoustic aid from the structure. At first the listener finds the effect startling, particularly when he can see the whisperer and so can recognize the improbability of the sound's carrying over such a distance.

The effect occurs mainly in two types of structure. In the simpler type the inside surface of the room is a section of a sphere or an ellipsoid. When a speaker stands at the center of curvature of the sphere, the spreading sound waves are reflected and focused back to him with surprising loudness. If an ellipsoid is involved, the speaker is at one focus and the listener is at the other. Again the curved surface reflects the spreading sound waves and focuses them, this time to the second focal point. In both types of structure a sound can travel through a large volume of air and still remain audible because of simple reflection and focusing.

The second type of whispering gallery is also curved but is more difficult to analyze because it involves no focusing. When a speaker whispers along one of these circular walls, the sound is somehow held in a layer adjacent to the wall; it travels along the wall and can be heard by a listener anywhere on the circumference. Why the sound clings to the wall in this manner and how you can demonstrate the effect for yourself are my subjects for this month, although I should make it clear at the outset that I do not understand all the features of the demonstration.

The most famous whispering gallery of the second type is at the base of the dome of St. Paul's Cathedral in London. The gallery is a walkway about 40 meters above the main floor. The walkway is six feet wide and forms a circle with a diameter of 108 feet. The wall along the side of the walkway is inclined slightly inward. About 40 meters above the walkway is the top of the dome.

Long ago it was noticed that someone whispering along the gallery wall could be heard by anyone who was close to the wall at any point around the walkway. If the speaker whispered directly across the diameter of the circular gallery, however, the spreading of the sound waves made the sound inaudible to a listener on the far side.

The anomalous audibility in the gallery was first brought to scientific attention by Sir John Herschel, who is largely noted for his contributions to optics and astronomy in the first half of the 19th century. Later (in 1871) Sir George Airy, the astronomer royal, explained the effect in terms of simple reflection and focusing of sound waves by the dome. In 1878, however, Lord Rayleigh pointed out that such an explanation could not possibly be correct because it would require the listener to be on the opposite side of the gallery from the speaker. Since the listener could actually be anywhere along the circular walkway, the effect was clearly not due to reflections from the dome.

Rayleigh's first explanation appeared in his *Theory of Sound* (Volume II, Section 287, published in 1878), in which he drew on his earlier work on the diffraction of sound as it leaves a person's mouth. In general, when sound waves pass through an aperture that has a width comparable to their wavelength, they interfere with one another and create a diffraction pattern. The most intense sound is at the center of the pattern; angled off from the center are alternating regions of destructive interference (corresponding to less intense sound) and constructive interference (corresponding to more intense sound, although not quite as intense as the sound in the central region). A similar diffraction occurs when sound waves pass an edge or move around an object of a size comparable to the wavelength.

When someone speaks, the sound coming from his mouth forms the pattern because the sound diffracts first through the opening of the mouth and then backward around the head. It is more difficult to determine the pattern than it would be if the sound went through a single aperture in an otherwise solid surface, but for the moment we can simplify the pattern by concentrating on the central peak of intensity in an idealized experiment with a single aperture. The angular width of the central region depends in part on the wavelength of the sound: the longer the wavelength (the lower the frequency), the more spread the central region. If you are to hear a person making sounds primarily of shorter wavelengths (higher frequencies), the person should be facing you, otherwise you will not be in the central region of the diffraction pattern. If the voice of the person speaking consists primarily of longer wavelengths, you can still hear the sound well even if he is partly turned away from you, because diffraction makes the central region wide enough so that a significant amount of sound is sent to the side of the speaker and even to the rear.

Rayleigh pointed out that to demonstrate the whispering-gallery effect on St. Paul's walkway a person had to whisper along the wall. Since whispering consists only of high frequencies, most of the sound emerged in a fairly narrow cone along the wall. For the sake of simplicity let us consider the cone as having two dimensions rather than three and as lying horizontally, so that we can ignore the vertical spread of the sound.

The sound leaves the wall in a cone of rays forming a maximum angle of θ with a tangent to the wall. The rays reflect from the curved wall at various points along the circumference in such a way that with each reflection the angle of reflection equals the angle of incidence. Because the rays began in a cone of angle θ they remain in a region bounded on the outside by the wall and on the inside by an imaginary wall with a radius that is the radius of the real wall multiplied by the cosine of θ. The rays are therefore trapped in a layer along the wall and can be heard by a listener in that layer but not by someone outside it. In this model the thickness of the layer is determined by the radius of curvature of the gallery and by the maximum angle at which the sound leaves the wall when the speaker whispers along it. That angle is in turn determined primarily by the diffraction of the sound coming from the speaker. The higher the frequency, the smaller the diffraction pattern; the smaller the maximum angle is, the more closely the sound is confined to the wall.

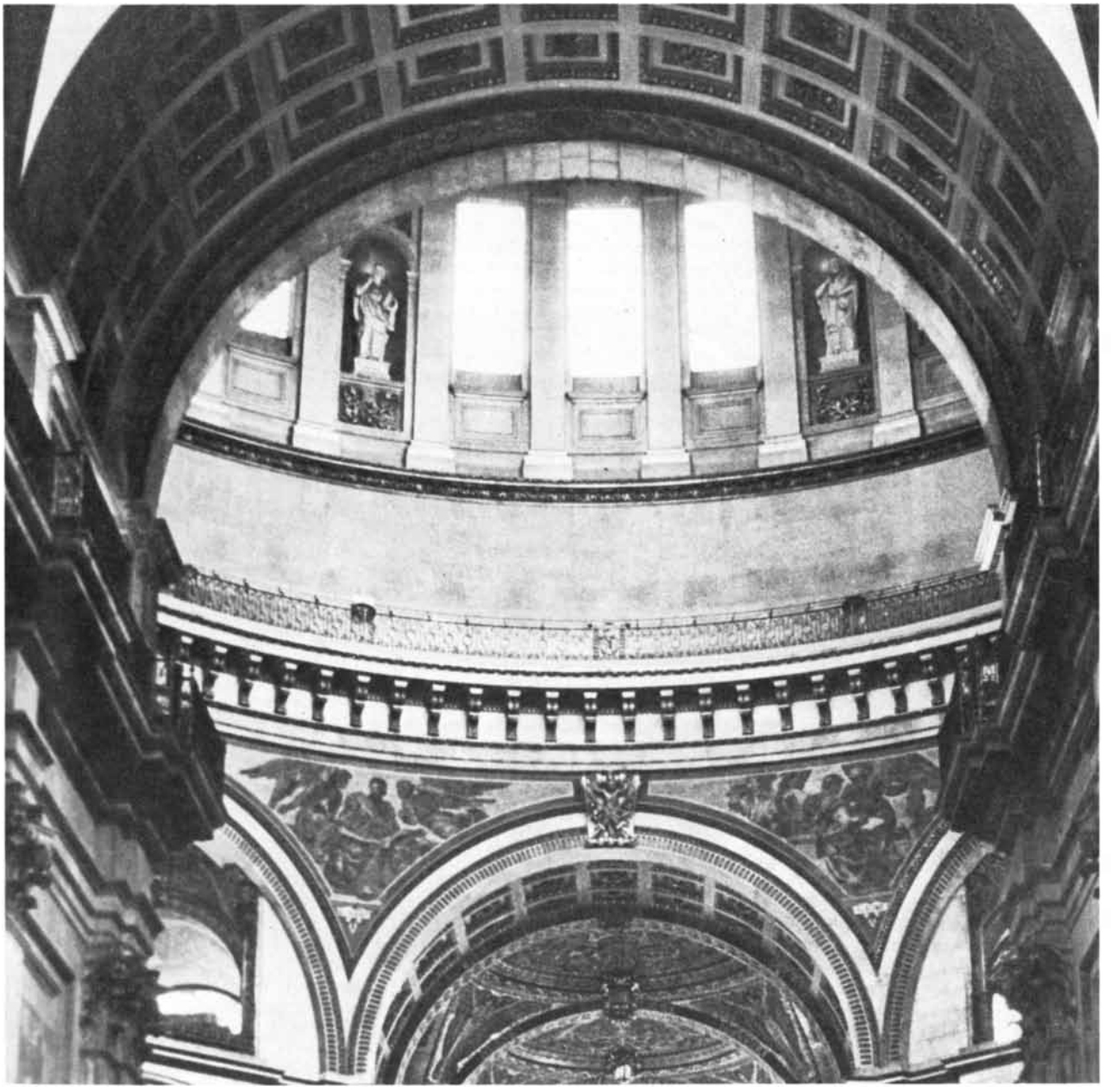
When sound from a small source spreads out in a plane in free space, its intensity drops off as the inverse of the square of the distance from the source. With the multiple reflections in Rayleigh's model for St. Paul's gallery, however, the intensity diminishes only as the inverse of the first power of the distance. Hence the sound remains stronger as it travels around the wall than it would

if it were sent directly across the gallery. The sounds of lower frequency in normal speech do not contribute as noticeable a layer of clinging waves because their diffraction from the speaker's mouth spreads them over such a thick layer that a listener somewhere around the wall will intercept a smaller fraction of the original intensity. Rayleigh's model was appealing because of its simplicity; as we shall see, however, its simplicity is somewhat misleading.

In 1904 Rayleigh returned to the whispering-gallery effect, working with a laboratory model consisting of a long strip of zinc (12 by two feet) bent into a semicircle. Inside one end of the strip Rayleigh placed a birdcall whistle and at the other end a flame that was sensitive to the pressure variations produced by sound. When the whistle was blown, it emitted a high-frequency sound at a wavelength of about two centimeters and caused the flame at the far end of the semicircular wall to oscillate. If Rayleigh placed a narrow barrier (about two inches wide) anywhere along the inside wall of the zinc strip, however, the flame was not disturbed by sounds from the whistle. This result indicated to Rayleigh that sound waves were indeed traveling along the surface of the curved strip rather than passing directly across the semicircle. In a like manner surface waves were traveling along the wall in St. Paul's gallery.

In spite of the success of his model Rayleigh was not satisfied with it. He finally published a wave model of the effect in 1910. He then likened the excitation of the air enclosed by the circular gallery of St. Paul's to an excitation of a circular membrane on a drumhead. In an ideal case the membrane would oscillate in a wave pattern with zero amplitude along the rim (because the membrane is fastened in place there) and amplitudes changing toward the center of the membrane according to an equation involving Bessel functions, which are also known as cylinder functions (from the type of problem in which they are helpful).

In a circular gallery a voice or any other noise makes the molecules of air oscillate, causing the air pressure to oscillate. The oscillations of air pressure



The whispering gallery of St. Paul's Cathedral in London **(below windows at top)**

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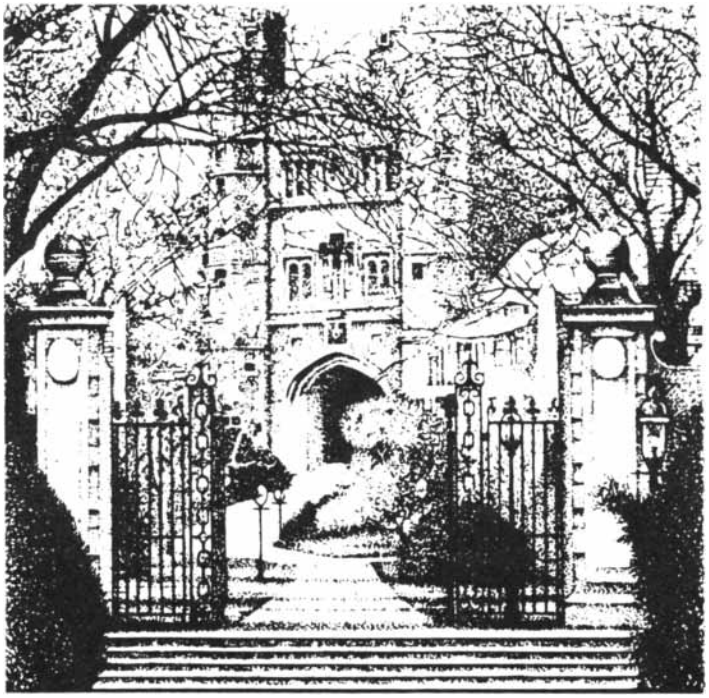

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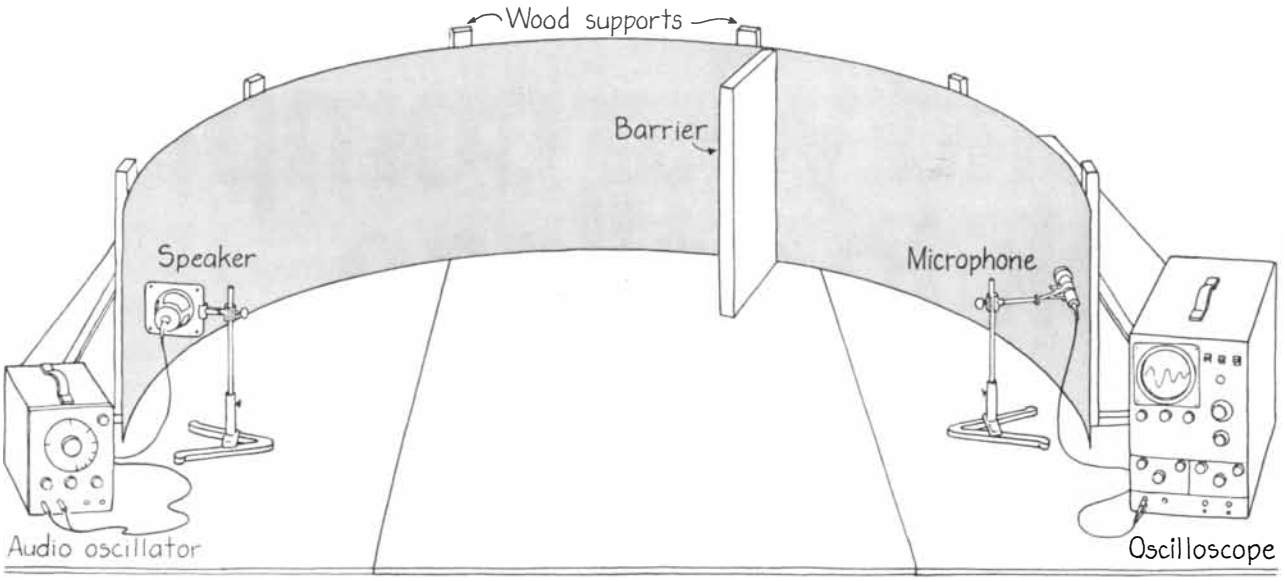
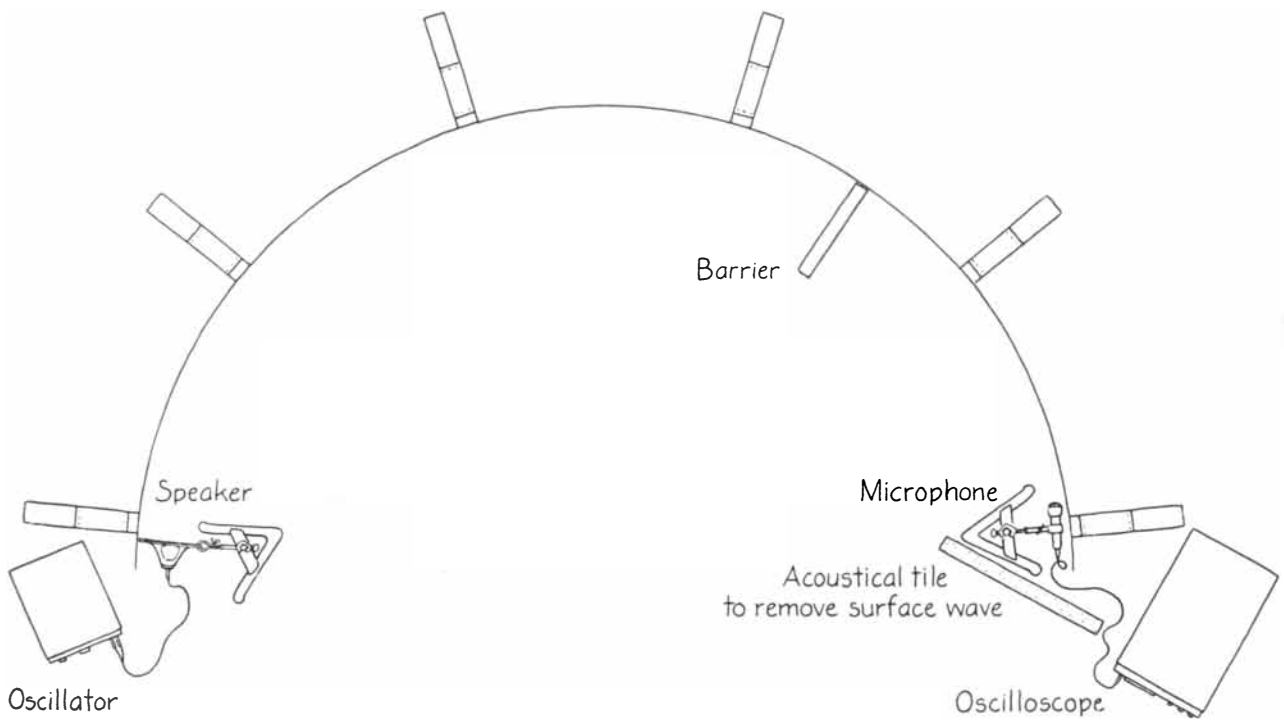


John S. Derov's setup for testing the St. Paul's effect

are what we call sound, since they cause the eardrum to oscillate. The molecules next to the wall cannot readily move (because the wall is in the way), but molecules farther out can. When the oscillating molecules farther out move toward the wall, they squeeze the molecules next to the wall and increase the air pressure. When the molecules move away from the wall, they leave the molecules next to the wall less dense and therefore decrease the pressure. Hence the pressure variations in the layer of air next to the wall are relatively large.

With a vibrating membrane on a drum the mathematical condition to be met at the rim is that the amplitude of the vibrations be zero. With air pressure the condition to be met at the wall is that the amplitude of the variations in air pressure be at a maximum. To a listener this result means that the sound has an intensity maximum at the wall. As the listener moves away from the wall the pressure variations and therefore the intensity of the sound die away according to a Bessel function of the listener's distance from the center of the gallery.

On a real drumhead and in a real circular gallery many of these patterns (the Bessel-function solutions) can exist simultaneously. For the sake of simplicity Rayleigh considered the oscillations in the gallery to be due to a single Bessel function of a high order, the high order being necessary so that the oscillations occurred only near the wall and then rather quickly died away with distance toward the center of the circle. (Lower-



Overhead view of Derov's arrangement

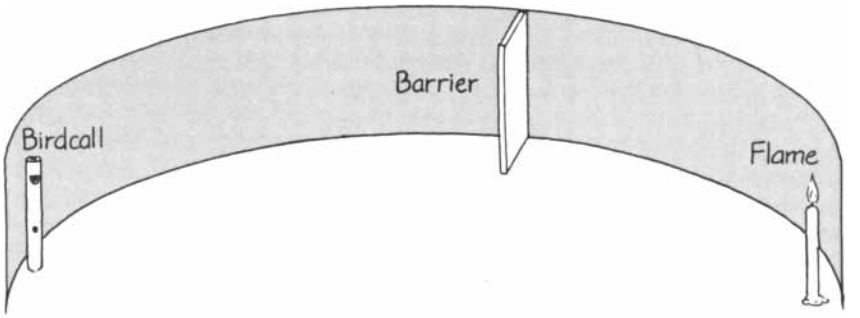
order Bessel functions would produce oscillations nearer the center.) Such excitation only along the wall was required because the speaker whispered close to the wall, hence creating little or no excitation away from the wall. Rayleigh was thus able to demonstrate that the pressure variations due to the surface waves would be at a maximum at the wall and essentially zero away from it. Moreover, he was able to write an equation that gave the amplitude of the pressure variations as a function of radial distance from the center of the gallery. Once again, however, the simplicity of his results can be somewhat misleading.

John S. Derov, a physics student at Cleveland State University, has performed a series of experiments with surface waves on a curved surface similar to Rayleigh's. The results cannot be as clearly interpreted as Rayleigh's work implied. This means that you can do a lot more work on the experiment if you would like to pursue it.

Derov fashioned a semicircular wall by joining two pieces of sheet metal eight feet long and two feet wide to get one sheet 15 feet long. At the overlap the sheets were attached with pop rivets. The gauge of the metal is not particularly important, except that with a heavier gauge the structure would be sturdier. To support the metal wall in a semicircle on the top of a large table Derov erected eight wood braces behind the wall about two feet apart. To increase the mass and rigidity of the wall he glued some concrete slabs to the outside of it and also stuck on some large slabs of Play-Doh.

Reflections from the room and its contents can tremendously complicate the behavior of sound, and so Derov suspended a tent of blankets over the top and across the front of the semicircle. He replaced Rayleigh's birdcall whistle and sensitive flame with several things. In one set of trials he used a two-inch paper loudspeaker for the sound source and a microphone for the detector. In another set he worked with two three-inch piezoelectric oscillators, one as the source and the other as the detector. He also briefly tried a pair of tiny earphones of the type supplied with some television sets, but their frequency range was quite narrow. In each case the source was driven by a sine wave from an audio oscillator with a controllable volume and frequency, and the signal from the detector was read on an oscilloscope.

A variety of equipment is available if you would like to do this experiment yourself. Primarily you need a source capable of emitting frequencies from about one kilohertz to at least 25 kilohertz, or as close to that range as you can get. The detector need not be anything more than a volume meter of the kind found in some tape recorders. Avoid putting large objects into the experimental setup because the reflections of the sound waves from them can complicate your data. Piezoelectric transducers are often sold in electronic and audio surplus shops as tweeters for stereo systems; they cost about $8 each and are good over the frequency range from seven to 25 kilohertz.



Lord Rayleigh's experimental arrangement

For each set of experiments Derov placed both the source and the detector at equal heights (about halfway up the wall). The source was pointed along the wall; the detector also faced along the wall, although it was occasionally reoriented to test for sound being transmitted directly across the semicircle. As a first check Derov placed the source and the detector at opposite ends of the semicircle as Rayleigh did. Like Rayleigh, he found that the sound was more intense in the layer next to the wall. He also found as Rayleigh did that the sound was easily eliminated by a narrow board placed anywhere along the wall between the source and the detector. Thus both Rayleigh and Derov seem to have found that sound waves cling to the surface of the curved wall as they travel along it.

To systematically analyze the sound near the wall the detector was shifted in two ways. First it was moved along the circumference of the wall to see if the intensity was indeed at a maximum there. Then at various points along the circumference it was moved radially inward to see if the peak of intensity on the wall died out toward the center of curvature. We ran into trouble with the first set of measurements, because Derov immediately found that the intensity along the circumference varied considerably, alternating between the expected high values and some surprising values of near-silence.

Similar variations along the circumference had been observed by C. V. Raman and G. A. Sutherland in 1921 in the whispering gallery of St. Paul's. They placed a continuous, single-frequency source of sound near the gallery wall and then checked the level of the sound at various points along the walkway. Some had a proper loudness but others had near-silence. They attributed this variation to the interference of the waves that traveled around the circular walkway more than once and overlapped other waves. At some points the interference was constructive, yielding a noticeable sound, but at others the interference was destructive, yielding near-silence.

Something similar must have been happening in Derov's setup. It could not have been that waves were traveling more than once around a circular wall, because he had built only a semicircle. The explanation presumably was that some of the waves were coming off the end of the wall opposite the source, reflecting from apparatus, the blankets or even Derov himself and then traveling back along the wall in the opposite direction to interfere with the oncoming waves.

To check this possibility Derov put a large piece of acoustic tile (removed from our ceiling) at the end of the wall, angling it to help reflect waves out of the setup. He found that the regions of near-silence were either eliminated or greatly reduced, yielding an almost constant level of volume along the entire length of the wall. If you want to continue the experiment, you should take pains to eliminate the waves reflecting back along the wall.

More difficult for us to explain were Derov's measurements along a radial line. We expected to find that once the troublesome reflected waves were eliminated a detector moved outward in a direction perpendicular to the wall would show a single intensity peak at the wall and zero intensity a short distance away. Instead we always recorded at least two peaks, the largest peak at the wall as expected and one or two more away from the wall.

At first we found these extra peaks dismaying, but on further thought we realized we should probably have expected them for two reasons. First, the sound from the source was not emerging in a narrow cone running along the wall; rather it was diffracting out of the source and then spreading. As a result more than one of Rayleigh's Bessel-function solutions was being excited, creating a net pattern that has both a

strong Bessel-function peak at the wall and other Bessel-function peaks away from the wall. Derov was measuring the more complicated composite pattern. Second, reflections of the emerging sound from the tabletop, the apparatus and even the blankets were inevitable and would complicate the data by creating interference patterns whose peaks Derov was apparently observing.

By going to higher frequencies we expected to narrow the diffraction out of the source and thereby to decrease the distance from the wall at which the multiple peaks occurred. Derov's data might have confirmed this expectation to some extent, but the scatter in the data points was too large to make the argument convincing. If Derov had been able to go to even higher frequencies (and therefore shorter wavelengths) with his apparatus, he probably would have come closer to having a single layer of sound along the wall, as Rayleigh did. Nevertheless, the assumption of a single layer of sound is not particularly good even in St. Paul's whispering gallery because Raman and Sutherland also found multiple layers of sound there as they moved their detector radially away from the wall.

You could do a good deal of work with this experiment. First, you could improve on the design by eliminating more of the reflected sounds. For example, instead of mounting the wall on a table you might place it on Styrofoam to absorb the sound. To totally eliminate any reflected signals I suppose you could hang the semicircle outdoors, facing upward in a large open space. You might also want to build a larger semicircle or use an existing architectural structure that has a large radius of curvature. If you do not have access to a larger structure, you probably should try higher frequencies, so that the wavelengths are significantly smaller than the radius of curvature.

In addition to taking data such as Derov's you might want to see how the intensity of the surface waves changes with height along the wall and how the intensity pattern changes if the source and the detector are not halfway up the wall. One of the interesting features of the St. Paul's gallery is that the wall leans slightly inward. Some investigators have suggested that this slanting aids in maintaining the surface waves. By building a wall with a slight lean you might be able to confirm this suggestion. The whispering-gallery effect is supposed to work even with nonrigid structures (although the mathematical modeling is more complicated), and so you could also run the experiment with thin walls for a comparison.

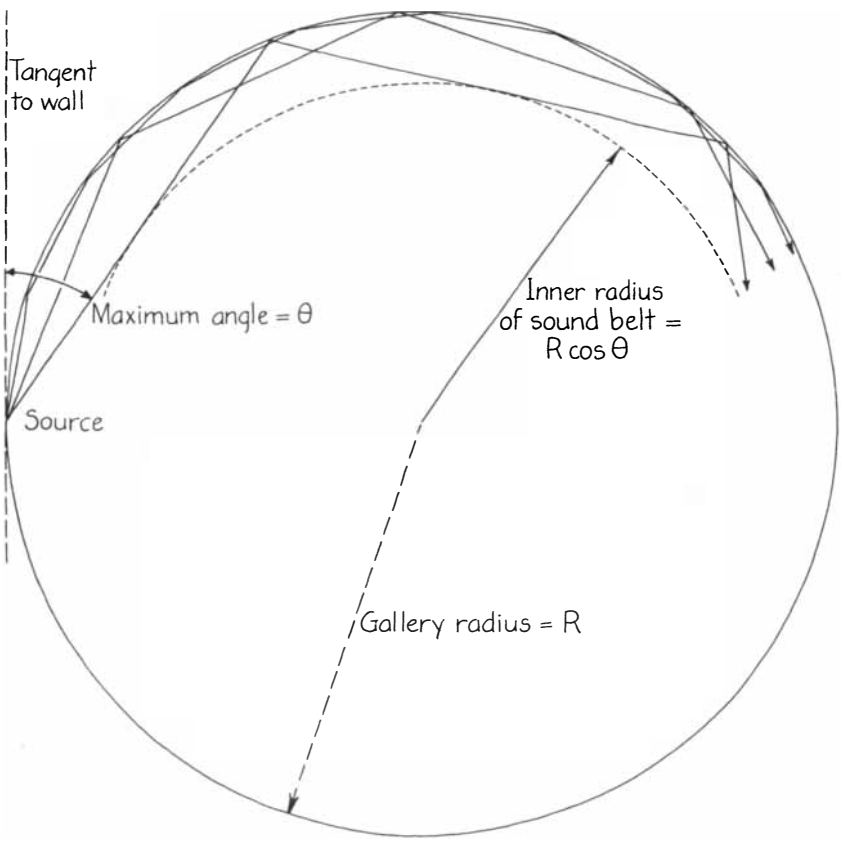
If you are good at electronics, you might want to measure the speed of the surface waves in the normal setup. They travel a bit slower than sound traveling in a straight line, and it would be interesting to see how much slower they are. You could find out by using an oscillator that emits a short pulse of sound (make it as close to a single frequency as you can) and also triggers an oscilloscope. Have the detector plugged into the oscilloscope. The time needed for the pulse to reach the detector starts when the trace begins on the oscilloscope and ends when the oscillation pattern begins.

If you visit London, you should try the whispering gallery of St. Paul's Cathedral for yourself. Although I knew what to expect, I found its acoustics amazing. A friend of mine stood on the opposite side of the walkway from me and spoke facing the wall. I could hear her whispers and normal speech in spite of the great amount of noise made by tourists on the walkway and far below in the pews. (It is best to visit the gallery in the winter, when fewer tourists are there.)

The effects seemed most pronounced when my friend and I stood next to the wall, but in normal speech the effect was still present when either or both of us moved toward the railing along the inside of the walkway. Following a suggestion by Robert S. Shankland, an expert on architectural acoustics, I spoke to my friend using words chosen because they result in sounds of either high or low frequency. As I expected, the words dominated by high frequencies were the easiest to understand.

While I was in the gallery I noticed that its wall not only tilts inward but also has a significant lip at the top. Shankland believes these two features must be largely responsible for the gallery's unique acoustics. The many other circular walkways in the world that lack these features do not display the same remarkable acoustics.

Whispering galleries of the simple reflection type can be found in a variety of places. Some, such as the old hall of the House of Representatives in the Capitol Building in Washington, have been famed for their ability to transmit even slight whispers. In 1851 the hall was made into the Hall of Statues and became, as the acoustic expert Wallace C. Sabine once noted, "one of the most perfect of whispering galleries." The ceiling was a portion of a sphere whose center of curvature was almost at head level. When someone stood at the center and whispered, the sound echoed back to the center, focused by the spherical surface. Sometimes guides would place one person on one side of the center and another person on the opposite side at about the same distance from the center, whereupon a whisper from one of them would be reflected and partially focused on the other. In 1901 a fire elsewhere in the building led to a refurbishing of the hall,



Rayleigh's ray model of the whispering-gallery effect

and the smooth wood ceiling was replaced by steel and plaster along with recessed panels and reliefs of moldings and ribs. The resulting roughness of the surface greatly reduced the simple reflection and focusing, and the hall was no longer as good a whispering gallery.

The Mormon Tabernacle in Salt Lake City is almost an example of an ellipsoidal whispering gallery, although the interior shape is not a perfect ellipsoid. Sounds created at the reader's desk in front carry by way of reflection and focusing to the rear of the room, making the sounds audible at the front of the rear balcony.

According to Herschel, a similar focusing in an ellipsoidal interior caused considerable embarrassment to parishioners at the old cathedral of Girgenti in Sicily not long after it was built. Although the details of the interior were later disputed by Sabine, Herschel maintained that one of the interior foci was unwittingly chosen as the place for the confessional, and so anyone standing at the other focus had access to even the faintest confessions. "The focus was discovered by accident," Herschel wrote, "and for some time the person who discovered it took pleasure in hearing, and in bringing his friends to hear, utterances intended for the priest alone. One day, it is said, his own wife occupied the penitential stool, and both he and his friends were thus made acquainted with secrets which were the reverse of amusing to one of the party."

Whispering galleries of both general kinds are thought to exist below the smooth, curved arches of some bridges. In 1948 several such arches were separately analyzed by Herbert Grove Dorsey and Arthur Taber Jones to determine if the acoustic properties were due to Rayleigh surface waves. For example, Dorsey investigated the arch under the Massachusetts Avenue bridge over Rock Creek in Washington, D.C. This circular arch has a diameter of 148 feet and a width of 74 feet. Both ends terminate on a base of smooth concrete that provided sharp echoes, supposedly of Rayleigh surface waves bouncing back and forth from end to end on the arch as they clung to the inside surface. "If one stands close to the arch wall in early-morning quiet," Dorsey wrote, "one can hear two distinct echoes from a faint whisper or from a pin dropped a half-inch into a little pasteboard box." A handclap produced from five to 10 echoes.

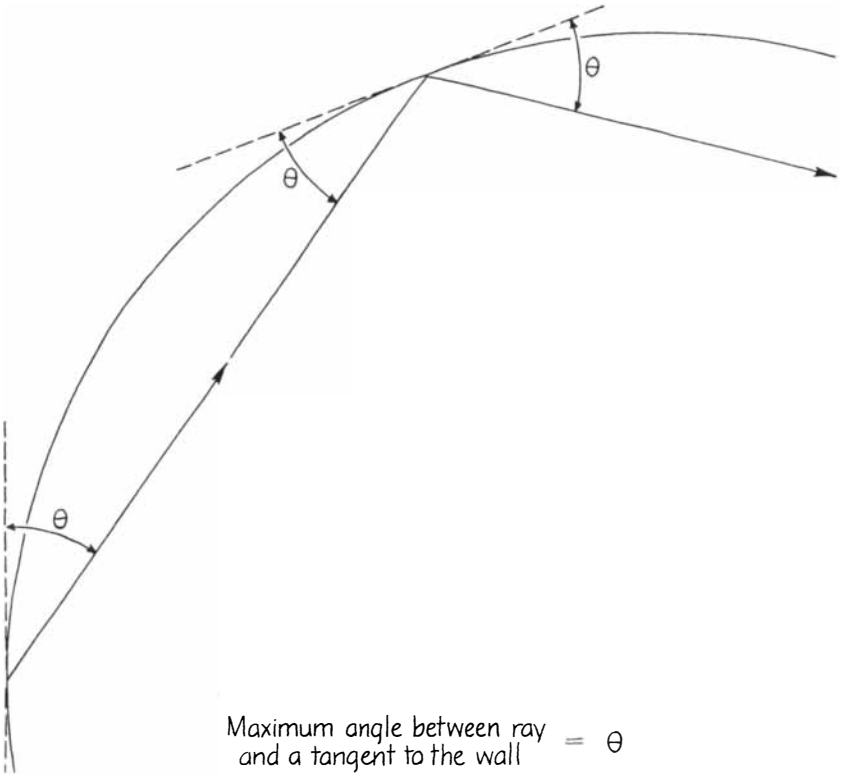
Later Jones investigated a similar bridge at Newton Upper Falls, Mass., but was unable to confirm Dorsey's hypothesis that the sound traveled along such an arch as a Rayleigh surface wave does. If surface waves were involved, Jones contended, an observer at the center point under the arch would not hear the echoes generated when another person clapped hands at one end of the arch, since the sound would be confined to a relatively narrow belt just below the surface of the arch. Stationing an observer under the bridge, Jones discovered that the echoes were seemingly as abundant there as at the ends of the arch. Hence the contribution of surface waves to the multiple echoes was left undecided.

Certain natural formations have noticeable whispering-gallery properties. The Ear of Dionysius, a grotto in an old quarry near Syracuse in Sicily, is such a natural formation. The grotto is in the shape of a horizontal backward *S*, with a total floor length of 67 meters and a height of 22 meters. Along the floor the width of the grotto is about 10 meters, but the *S* narrows toward the top until the width is only one or two meters. At the end of the *S* opposite the quarry, near the top of the grotto, a small opening leads to a short passageway, which in turn leads to a stone stairway to the top of the rock formation. When one stands on the floor of the grotto, the echoes from speech are so numerous that the speech is difficult to understand. If one listens at the small opening at the back of the grotto, however, one can hear even whispers from others standing on the grotto floor. Although the grotto is not strictly a whispering gallery of the kind I have been discussing, its design does somehow funnel the sound from the floor to a listener who is strategically placed in the small back opening.

The reason for the name Ear of Dionysius is that the grotto was used as a prison by Dionysius, the infamous builder of Syracuse. According to legend, he had a prison designed in such a way that he could hear even the faint whispers of the prisoners and so could thwart any attempt at revolt.

You might want to search for whispering galleries. You could check any obvious sections of spheres or ellipsoids in buildings and natural shapes such as domes in cave ceilings. You might also want to check smooth archways (such as those under bridges), the interior of silos and other large structures with a circular cross section. Once a whispering gallery is discovered you ought to check for Rayleigh surface waves by an appropriate set of experiments such as placing a relatively narrow barrier on the curved surface to block any surface waves.

In the months since an experiment involving the creation of multiple-order rainbows in the laboratory was described in this department for July, 1977, several people have written to me about having seen more than two natural rainbows simultaneously in the sky. The primary rainbow arises from a single reflection of light inside a falling raindrop. The occasional secondary rainbow arises from two internal reflections. In the experiment you can see the next dozen or so rainbows, which arise



Detail of the model

from a progressively larger number of internal reflections from single water drops suspended on a thin wire.

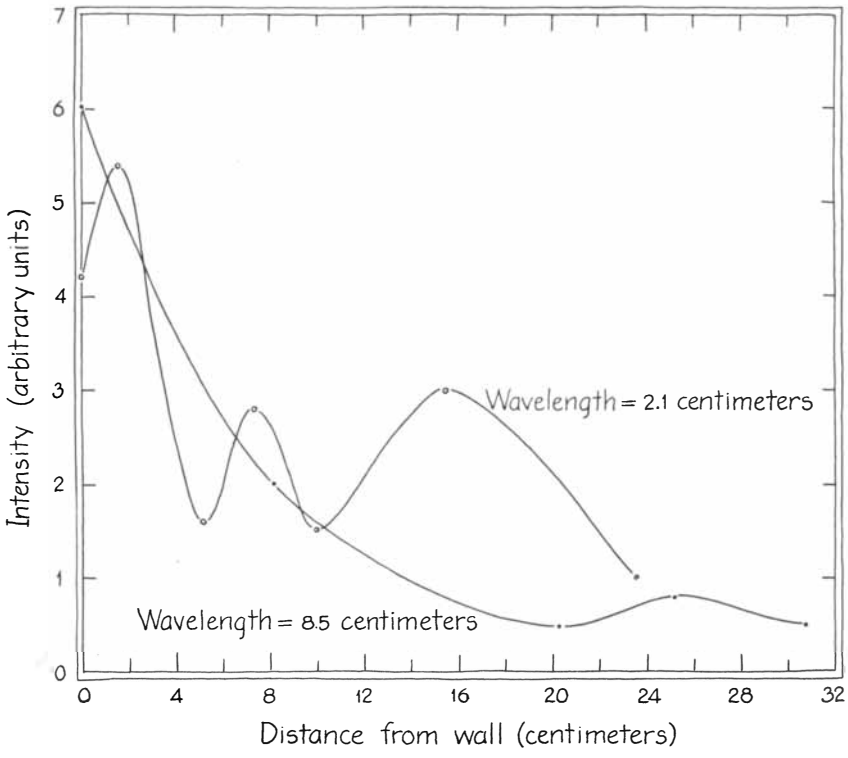
I had believed observing any natural rainbows beyond the first two was impossible because the colors of rainbows of higher order become so faint that they would be masked by the glare from the sky, from the light reflected from the outside surface of the drops and from light transmitted through the drops with no internal reflections. Still, perhaps under some circumstances rainbows of higher order might be visible.

M. L. Herr of the University of New Orleans recalled seeing more than two simultaneous rainbows, maybe even four, in Malaysia, which often has brief thundershowers brightly illuminated with direct sunlight. Other places such as Ireland are said to be good for brilliant rainbow displays, possibly with more than the first two rainbows, because many showers are lighted by direct sunlight. Such observations would be improbable in places where a thunderstorm usually means that the entire sky is clouded before and after the rain.

J. R. Prescott of the University of Adelaide described seeing what might have been the third-order rainbow under an unusual circumstance. As was demonstrated in my rainbow experiment, the third-order rainbow lies in the portion of the sky near the sun and so is normally lost in glare. Just before sunset Prescott saw colors arching through rain falling from very dark clouds that were high enough in the southwestern sky for the sun to be visible below the clouds. The colors were therefore seen against a dark background while the rain was well illuminated by the low sun. If this sighting was indeed of a third-order rainbow, it means that the rainbow becomes visible when the background is dark enough to keep the background light of the sky from masking the rainbow's colors.

You might want to watch carefully for such a fortunate arrangement of clouds, rain and sun. If you photograph the colored arc, measurements of its width would verify that the arc was truly a rainbow rather than a colored halo or some other atmospheric optical effect caused by ice crystals [see "Atmospheric Halos," by David K. Lynch; SCIENTIFIC AMERICAN, April]. You should also be careful not to confuse rainbows of the fifth and sixth orders, which lie near the first two rainbows, with well-developed supernumerary bows of the primary and secondary rainbows. If you do manage to photograph an authentic higher-order rainbow, it will be the first known photograph of any order except the common first two.

Several groups have worked with the suspended-drop rainbows described in my article. Steve Lai, a student of Fred Brace's in a high school in Portland, Ore., observed quite a few of the higher-order rainbows. To see rainbows of the 10th and 14th orders, which requires looking almost along the incident beam,



Derov's results at two wavelengths

Lai cleverly aimed a dentist's small mirror to reflect an image of the drops and the rainbows, thereby keeping his head out of the incident beam.

At this year's International Science and Engineering Fair, Joseph E. Becker of Spokane, Wash., showed me his work on experimentally determining a function by which the angle of a rainbow of any order can be determined for a fluid of any given refractive index. Three other exhibits at the fair were also extensions of topics taken up in this department. The Leidenfrost phenomenon (August, 1977) of fluid drops floating on a thin vapor layer over a hot plate was investigated by Jerry Ritter, Jr., of Cloudcroft, N.M., and by Stuart A. Travis of Akron, Colo. Ritter was interested in how the Leidenfrost point changes when the water is contaminated with various substances and how a measurement of the Leidenfrost point might serve to indicate the extent of the contamination. Travis measured the Leidenfrost points of distilled water (400 degrees Fahrenheit) and acetone (330 degrees F.) and had good luck photographing the floating drops with a 55-millimeter lens and a 6*x* extender.

Peter Rathmann of Brookfield, Wis., made an impressive analysis of a salt oscillator (October, 1977) in which he determined the oscillator's frequency as a function of hole size, running time, difference in densities between the salt water and fresh water and other factors. He found that for the range of holes small enough to allow the system to oscillate the oscillation frequency increased almost linearly with hole size. He also demonstrated that the frequency decreased with the running time of the experiment, a result he interpreted as indicating that as the experiment ran, the difference in density between the two fluids in the oscillator decreased because of mixing and therefore the force driving the oscillations weakened.

Rathmann and independently J. E. Schmidt of Charlestown, Ind., have properly pointed out that in my article I should have emphasized the pendulum-like nature of the salt oscillator. Once the fluid begins to flow it does not stop when the pressures at the hole are equalized, because the flow has momentum and the system overshoots its equilibrium state. Once the stream stops, the system again finds itself with unequal pressures around the hole and fluid begins to run in the opposite direction, again overshooting the equilibrium, slowing to a stop and reversing. The Rayleigh instability I discussed in that article is needed to keep the oscillator going because the viscosity of the fluids tends to decrease the momentum in the streams. Otherwise the pendulumlike oscillations of the system would die out relatively quickly.

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