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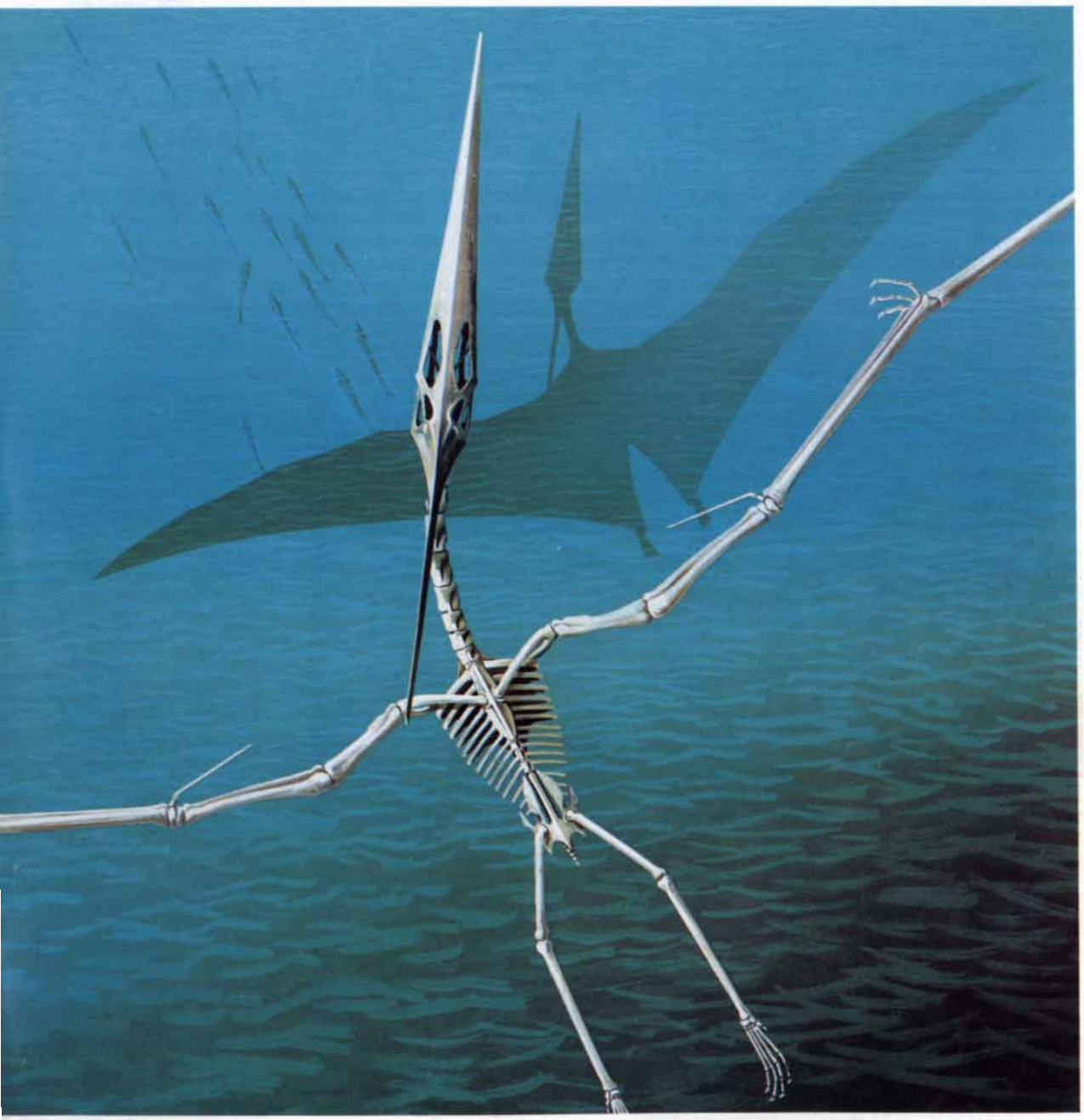

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	EST. HWY.	EPA EST. MPG
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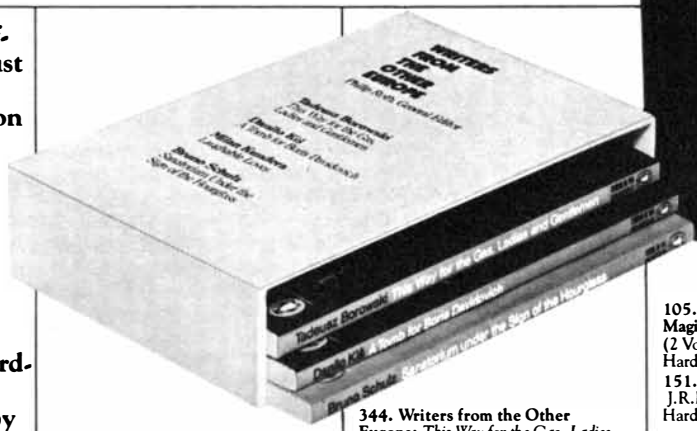

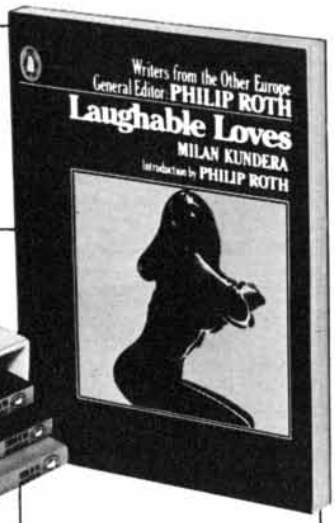

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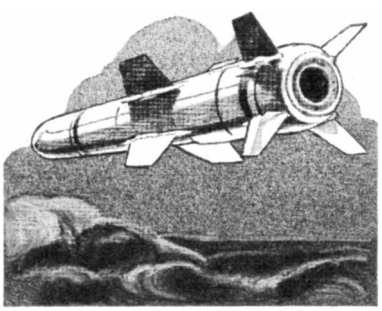

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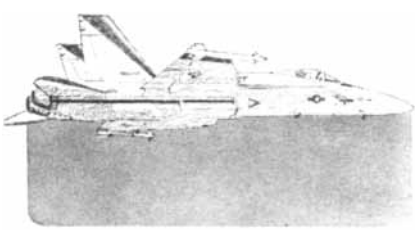

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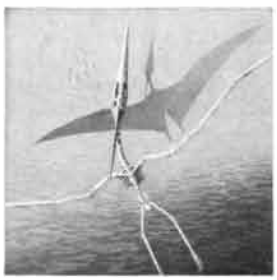
Established 1845 **SCIENTIFIC AMERICAN** February 1981 Volume 244 Number 2

ARTICLES

DEPARTMENTS

SCIENTIFIC AMERICAN (ISSN 0036-8733), PUBLISHED MONTHLY BY SCIENTIFIC AMERICAN, INC., 415 MADISON AVENUE, NEW YORK, N.Y. 10017.



THE COVER

The painting on the cover shows the skeleton of *Pteranodon,* a flying reptile of the Mesozoic era and one of the larger representatives of the extinct order Pterosauria (see "Pterosaurs," by Wann Langston, Jr., page 122). The holes in the bone of the skull exemplify the tendency for the weight of the animal to be kept at a minimum. The bones themselves were thin and hollow. The most dramatic evolutionary adaptation of the animal for flight was the greatly elongated fourth finger of the forelimb, which became the principal strut for the wing. The other three fingers on each hand were characteristically reptilian: each one had a claw at the end. The surface of the water below the skeleton suggests a wind of about 10 miles per hour. It is nearly the strongest breeze in which *Pteranodon* could maintain control of its slow and often gliding flight as it searched the water for fish. Its brain was highly developed for vision.

THE ILLUSTRATIONS

Cover painting by Ted Lodigensky

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39	Lockheed Corporation (*top*), U.S. Navy (*bottom*)
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45	Ilil Arbel (*top*), Jon Brenneis (*bottom*)
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53	Susan Stallman and Zacheus Cande, University of California at Berkeley (*top*); Joseph G. Gall, Yale University (*middle*); George Lefevre, California State University at Northridge (*bottom*)
54	George V. Kelvin (*top and bottom right*), Roger D. Kornberg (*bottom*)
55	George V. Kelvin (*top*), Ada L. Olins and Donald E. Olins (*bottom*)
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165	Bernard E. B. Fagg (*top*), Detroit Institute of Arts (*bottom*)
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170–175	Michael Goodman

Jeffrey of Arabia

Quick, describe Saudi Arabia!

Most people think of sand dunes, camels, oil wells in the desert. Oil prices, too.

Few would think of Little League baseball or 11-year-old Jeff Jaszczak of the Dhahran Steelers. But to people who work for us, Little League is an ordinary part of Saudi Arabian life.

We're Aramco, the Arabian American Oil Company. There are 13,000 North Americans in Saudi Arabia with us. And even though you hear a lot of news about Saudi Arabia, there are things that might surprise you about our lives there.

1. We're doing something important. Aramco produces more oil than any other company. Badly needed oil. Including about 15 percent of the oil America imports.
2. The Saudi Government and Aramco are working together on some *incredibly* large energy projects. And on huge communication networks, electric utilities, and more.
3. Our people are glad to be in Saudi Arabia with Aramco. They came for excellent pay and professional challenge.
4. After 46 years in Saudi Arabia, Aramco is still growing fast. So is the number of interesting and rewarding job opportunities.
5. Jeff made the all-star team.

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We are indeed living in cautious times.

Even those fortunate enough to have a large amount of what economists call "disposable income" are disposing of it as prudently as possible.

And so one could find considerable irony in the fact that, even during the dog days of last year's crunch, the demand for BMW exceeded even the most optimistic predictions.

One could, that is, if it were not for the fact that the BMW is as appealing to those who know money as it is to those who know cars.

ENGINE TECHNOLOGY, A DECADE AHEAD OF THE COMPETITION.

In a desperate attempt to cope with the realities of the 80's, many automakers have been forced to drastically rethink their engine technology. Cutting cylinders, resorting to diesel fuel, tinkering with all manner of electronic devices.

Now, as any automotive expert can tell you, evolution is always preferable to revolution. So the fact that the engineers at BMW recognized the wisdom of such formerly exotic concepts as four and six-cylinder engines, sensible piston displacements and impressive power-to-weight ratios, literally decades ago, puts the BMW —and its owner—at a decided advantage.

In truth, the legendary performance capabilities of the BMW power plant are the result of years of careful evolutionary development—millions of miles of testing and refinement—on and off the great racecourses of the world.

STATE-OF-THE-ART ELECTRONICS.

At the turn of the ignition key, a computerized engine monitoring system (first installed by BMW in 1975) goes into operation.

With every engine revolution a computer receives and assesses signals from electronic sensors within the 6-cylinder engine itself. Then instantly determines the precise air/fuel mixture to be injected into the cylinder ports—optimizing emissions, fuel consumption and power development to a degree once considered merely within the realm of academic theory.*

THE OPTIMAL SYNTHESIS OF MAN AND MACHINE.

When you drive a BMW for the first time, you will experience a unique sensation: a total oneness with the car.

A standard five-speed transmission (automatic is available) affords the unaccountably unique opportunity to pick and choose one's own gears.

Its suspension system—independent on all four wheels—has a singular capacity for removing the drama from even the most unnerving road conditions.

Vital controls are within easy reach. The tachometer, speedometer and ancillary instruments are large, well-marked and totally visible.

RESALE: THE ACID TEST.

When all of the hyperbole has been expended, there is one brutally reliable way of determining a car's true value: how much of its original price it retains on the used-car market.

Seen in this revealing light no car in its category—not Mercedes 280E, not Jaguar XJ6, not Cadillac—equals the BMW.

According to the National Automobile Dealers Association's own 1980 used-car guide, for example, over the past 5 years the BMW 528i retained an astonishing 77.9% of its original price.

If you find the notion of owning a BMW more than a little intriguing, we suggest you phone your nearest BMW dealer and arrange a thorough test drive at your convenience.

THE ULTIMATE DRIVING MACHINE.

BMW, MUNICH, GERMANY.

*For example, the BMW 320i (with 5-speed standard transmission) delivers 25 EPA estimated mpg, 36 estimated highway mileage and, based on these figures, an estimated mpg range of 383 miles and a highway range of 551 mi. (Naturally our fuel efficiency figures are for comparison purposes only. Your actual mileage and range may vary, depending on speed, weather and trip length. Your actual highway mileage and highway range will most likely be lower.)

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LETTERS

Sirs:

Timothy Whitcombe has curiously misunderstood Otto Neugebauer and A. Sachs's discussion of Yale Babylonian Collection Tablet No. 7289 in *Mathematical Cuneiform Texts* ["Letters," SCIENTIFIC AMERICAN, November, 1980]. Three points are worth noting:

1. Whether or not YBC 7289 shows evidence of knowledge of the Pythagorean theorem can be disputed, perhaps, but there is no disputing Plimpton 322, also covered in the Neugebauer and Sachs work, which gives dozens of integer solutions to $A^2 + B^2 = C^2$, arranged to form a sort of "trigonometric table," that is, in order of increasing tangent. The Babylonians thus had a much better notion of this theorem than did Pythagoras himself, who could only find integer solutions of the type $C = B + 1$, and they had at least equaled the level of skill represented by Lemma 1 of Proposition 28 in Book X of Euclid's *Elements*.

2. YBC 7289 displays a result; the question is how that result was reached. Neugebauer and Sachs cite another tablet, VAT 6598, which shows the procedure for obtaining the square root of $28\frac{1}{3}$. Application of the VAT 6598 procedure to the problem of $\sqrt{2}$ produces the result of YBC 7289. Neugebauer and Sachs start the reconstruction with the guess $\sqrt{2} = 1.5$, but they could as easily have started with $\sqrt{2} = 1$, which yields 1.5 on the next pass. Moreover, Archimedes used the same procedure, and a variant crops up in Diophantus.

3. Although Newton, in reinventing the procedure, employed differentiation, the discovery does not require this. It is simply a systematization of guessing. One can obtain a root on a four-function calculator by guessing, squaring the guess and trying again, higher or lower, depending on whether the squared guess was low or high. The next step in sophistication is to divide the number by the guess to obtain a compensating "counterguess" and to use guess and counterguess as outer limits for the next guess. From this to *averaging* guess and counterguess to give an automatic new estimate is a trifling effort, and yet this simple improvement gives the algorithm.

The real question is not whether the Babylonians were capable of developing such a method but why the method was not widespread in classical times. This is easy to answer. With the exception of Archimedes, always the maverick, the Greeks were still in the grip of the Pythagorean tradition: they had a horror of division, fractions and irrational numbers. Since unity, the monad, equaled divinity itself in their equation, it was impermissible to divide it (see Book X of Plato's *Republic*). Fractions were perforce translated into ratios or into line segments. As for the irrationality of $\sqrt{2}$, this uncomfortable fact was kept secret for more than a century, until Aristotle, after breaking with Plato, revealed it. The implicit problem, therefore, is not "How could the Babylonians be so clever?" but rather "How could the Greeks be so stupid?"

But when we speak of "the Greeks" in the sense of their greatest mathematicians, we are speaking of perhaps 20 people, according to J. B. S. Haldane's estimate. That some 19 of these shared a common obsession that prevented them from using a fairly obvious calculational technique is hardly to be wondered at.

EUGENE DU FRESNE

Jet Propulsion Laboratory
California Institute of Technology
Pasadena

Sirs:

On using your excellent issue on economic development [SCIENTIFIC AMERICAN, September, 1980] for geographic research on China, I discovered an unusual error that you may wish to bring to the attention of readers. In the article "The Economic Development of China" a panoramic view of the Pan Zhihua iron and steel plant, one of China's newest industrial centers, is spread across the bottom of two pages. The caption identifies the plant, which is not mentioned in the article, as being in southern Yunnan Province, near Wenshan. This puts the site as much as 260 miles from its actual location. There is indeed a village called Pan Zhihua near Wenshan, but that is not where the steel plant is. It is not unusual in China for more than one place to have the same name. The Pan Zhihua iron and steel plant, named for a mine that is not identified on most maps, is actually in the new city of Dukou, which is shown in the panoramic view. This industrial center is situated in southernmost Sichuan Province, on the upper reaches of the Chang Jiang (Yangtze River), whose estuary is strikingly illustrated in a Landsat image elsewhere in the article. The ore deposit was discovered in the early 1960's and, because of the value of its vanadium-bearing titaniferous magnetite, was selected as the site of an iron and steel project. Construction began in 1965, and the No. 1 blast furnace was blown in five years later. The plant now produces 1.5 million tons of steel, or more than 4 percent of China's annual output. The city of Dukou (the name means "ferry" in Chinese) arose around the plant in the 1970's and now has a population of 330,000. That makes it a new urban center far larger than any in Yunnan's isolated Wenshan tribal area, where your picture caption placed it.

THEODORE SHABAD

Columbia University
New York, N.Y.

Sirs:

A recent letter from J. Richard Gott III ["Letters," SCIENTIFIC AMERICAN, October, 1980] noted that in "Flatland" both electromagnetism and gravity would be interestingly different from what we have in our actual world with three spatial dimensions ("Fatland"). I believe Gott may have inadvertently overstated his point, however, in saying that *gravity* would not exist as a long-range force à la Newton. What was intended, I think, was to note that *Einstein's theory* would not work that way in Flatland. There still remains a possible version of gravity mediated by a scalar gravitational field, as originally proposed by Nordström. This type of theory is not popular in Fatland because, contrary to observation, light rays would not be bent and the perihelion of Mercury would regress, not advance, if it were correct. Nevertheless, a creator of Flatland might be willing to endow it with scalar gravity rather than have its inhabitants drift about aimlessly, even at the risk of Einstein's disapproval.

F. CURTIS MICHEL

Rice University
Houston, Tex.

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

FEBRUARY, 1931: "The most trustworthy measurement of the velocity of light is the one obtained by A. A. Michelson in his famous experiment at the Mount Wilson Observatory in 1924. At that time he reflected a beam of light from Mount Wilson to Mount San Antonio, a distance of 22 miles, and back. The velocity determined was 186,359 miles per second. Dr. Michelson desired to increase the accuracy of this measurement and set up a second series of experiments between Mount Wilson and Mount San Jacinto, a distance of 88 miles. The attempt was not a success because of atmospheric conditions. He then proposed the idea of measuring the velocity of light in a vacuum, a condition that would give perfect seeing and direct accuracy in measuring the distance over which the light beam would travel. (Light travels slightly faster in a vacuum than it does in air.) The vacuum tube has now been built by the Mount Wilson Observatory on the Irvine Ranch near Santa Ana. It is slightly more than a mile long. Evacuation is accomplished by two Kinney vacuum pumps with a capacity totaling 400 cubic feet of air per minute. If the apparatus is ready in time, Dr. Einstein may co-operate with Dr. Michelson on the vacuum experiment."

"In 1925 skillfully made arrow points of a new type were found in association with the bones of a large prehistoric species of bison near Folsom in the northeastern corner of New Mexico. Since that date much work has been done in an attempt to learn more about the remarkable race that was responsible for these evidences, a race that must have antedated the cliff dwellers and pueblo builders and other American Indians yet was far more skilled than they in the art of flint chipping. At a new location in Yuma County in northeastern Colorado more than 100 very well made Folsom points have now been found in association with fossil bison and mammoth bone. One of the bison species appears to be identical with *Bison taylori,* found with the original Folsom artifacts in New Mexico. This evidence appears to tie up the two areas as being nearly contemporaneous and helps to date the original Folsom discovery."

"Again this year there is a strong trend toward eight-cylinder cars to replace sixes. Buick has entirely abandoned the six-cylinder engine in favor of the eight. Marmon is producing a 16-cylinder car for the first time and Cadillac a 12 to supplement its eights and its line of 16's announced last year. With the increased number of cylinders has come increased horsepower. Piston displacements of the larger Packard and of the Chrysler Imperial closely approach 400 cubic inches. In line with the increases in horsepower and displacement many cars have longer wheel bases. The Cadillac V-16 leads in this respect with a wheel base of 148 inches."

FEBRUARY, 1881: "M. Pasteur has at last made known the method by which he claims that the virus of fowl cholera can be modified to produce a morbid disease with the same protective power against the original disease that vaccinia has against smallpox. M. Pasteur's communication on the subject is of extreme interest, on account of the bearing the alleged discovery has on all infectious diseases. The special poison of the disease, according to Toussaint and Pasteur, is an oval micro-organism about a forty-thousandth of an inch in diameter. This organism can be easily cultivated in certain media, such as a decoction of muscle, and it was by cultivating it in these media that Pasteur obtained the results he now announces. It was found that if these micro-organisms were subjected to numerous cultivations immediately succeeding each other, the virulence was not at all diminished, but if the intervals between the cultivations were prolonged, a gradual diminution in virulence did take place. If the time between the successive cultivations is extended to six, eight or 10 months, the virulence of the poison continues to become weaker, until it finally causes simply a mild disease that does not injure the fowl but protects it from the effects of any further inoculations even with the freshest and most virulent organisms. M. Toussaint states that he has been able to modify the poison of anthrax, so that after its inoculation in healthy animals a morbid action is produced removing the susceptibility to the original poison."

"Two years ago the whole photographic world was startled by the announcement that Mr. C. Bennett could obtain pictures in the camera in but a fraction of the time necessary with any process extant up to that time. The process he used was founded on that of Dr. Maddox, in which bromide of silver emulsified in liquid gelatine is coated on a glass plate and allowed to dry. In the recent photographic exhibition in Pall Mall in London we saw examples of the rapidity of which the gelatine process is capable. A train going 60 miles per hour was fairly expressed on the photographic plate, there being a sharpness of image that was truly marvelous. The 150th part of a second is a short interval of time, yet in such a time the picture was taken. Drawing-room photography by amateurs now becomes a possibility and a practicability that before it was not, and in one remarkable picture we have the dark interior of a room and the portrait of a charming model secured on one plate in 25 seconds."

"We are now approaching the period when frequent and large sun spots may be expected. The evidence is quite conclusive that they return with tolerable regularity at intervals of about 10 or 11 years. Through a long course of years it has been shown that the periods of magnetic variation coincide with the period of sun spots. Auroras were noted, even in southern latitudes. Telegraphic lines refused to work, and shocks were given to the operators. It is not difficult to explain a connection between earth currents of electricity, auroral displays and magnetic disturbances, but how these are caused by sun-spot prevalency, or how a common cause produces all, is a problem that has not been satisfactorily solved. It is well to heap up the records, to keep a close watch on the sun and note the size and character of his dark and bright spots, to look out for auroras and record their appearance and duration, and to observe any especial disturbances in telegraphic currents and any odd freaks of the magnetic needle."

"It has been known for years, if not for centuries, that combustible gases escape from the earth at Baku in the Caucasus, yet no one seems to have suspected that Baku was destined to become as famous for its oil springs as our own Pennsylvania. Recently, however, the production of Caucasian petroleum has been such as to interfere with the sale of American petroleum in Russia. Two of the foremost chemists of St. Petersburg, Messrs. Beilstein and Kurbatow, have subjected this oil to a critical examination, which is given in full in the *Berichte* of the German Chemical Society. The peculiarity of the petroleum from Baku consists in its high specific gravity as compared with American petroleum of the same boiling point. For a long time this fact caused Russian consumers to be mistrustful of their own oil. Wilm and Biel, however, proved that the Russian oil gave 10 per cent more light than the American, and Biel also found that the illuminating oil of even this high gravity was drawn up the wick to the flame more easily than the American oil. Since that time the public prejudice has disappeared, and the importation of American oil into Russia has as good as ceased entirely."

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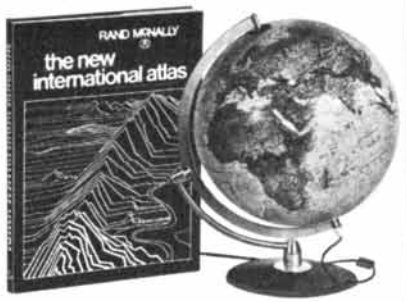

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THE AUTHORS

JOEL S. WIT ("Advances in Antisubmarine Warfare") is a research fellow with the Congressional Research Service. A graduate of Bucknell University, where he majored in international affairs, he received a master's degree at the Columbia University School of International Affairs in 1979. He has done research work for several groups engaged in the study of issues related to arms control and disarmament, including the Foreign Policy Association, the International Peace Academy and the World without War Council. His article is adapted from a paper he prepared under the auspices of the World without War Council.

J. NEIL RUTGER and D. MARLIN BRANDON ("California Rice Culture") are agricultural experimenters with a common interest in the improvement of rice. Rutger is research leader of the U.S. Department of Agriculture's Rice and Oilseeds Genetics and Breeding Station at the University of California at Davis. He studied agricultural science as an undergraduate at the University of Nebraska before going to Davis, where he earned an M.S. in agronomy in 1962 and a Ph.D. in genetics in 1964. Rutger taught at Cornell University for six years before returning to the Davis campus in 1970. Brandon is associate professor at the Louisiana State University Rice Experiment Station. After majoring in general agriculture as an undergraduate at the University of Tennessee he went on to get an M.S. in soil microbiology at Iowa State University in 1965 and a Ph.D. in soil science from Davis in 1977. Before moving to Louisiana in 1979 Brandon was the University of California Extension rice agronomist, serving as a liaison officer with the California rice industry.

ROGER D. KORNBERG and AARON KLUG ("The Nucleosome") have both made important contributions to the understanding of the structure of chromatin, the chromosomal material of all higher organisms. Kornberg is professor of structural biology at the Sherman Fairchild Center of the Stanford University School of Medicine. He received a B.S. in chemistry at Harvard University and a Ph.D., also in chemistry, from Stanford. From 1972 to 1975 he was at the Medical Research Council Laboratory of Molecular Biology in Cambridge, England. He returned to the U.S. to teach biological chemistry at Harvard, and he joined the Stanford faculty in 1978. Klug is joint head of the division of structural studies in the MRC Laboratory of Molecular Biology. A native of South Africa, he got his bachelor's degree at the University of Witwatersrand, his master's degree at the University of Cape Town and his Ph.D. from the University of Cambridge. He was at Birkbeck College of the University of London from 1954 to 1962, when he joined the MRC Laboratory of Molecular Biology.

NOEL R. ROSE ("Autoimmune Diseases") is professor and chairman of the department of immunology and microbiology at the Wayne State University School of Medicine. He has a B.S. from Yale University, a Ph.D. from the University of Pennsylvania and an M.D. from the State University of New York at Buffalo. "While at Buffalo," he writes, "I came under the influence of Ernest Witebsky, one of the giants who fashioned the discipline of immunology. It was he who sparked my interest in autoimmune disease. I remained on the faculty at Buffalo for 22 years, eventually succeeding Witebsky as director of the Center for Immunology. In 1973 I moved to Wayne State University, where I undertook the development of a department of immunology and microbiology. The present article was written while I was on a sabbatical leave at the Walter and Eliza Hall Institute of Medical Research in Australia."

OLIN C. WILSON, ARTHUR H. VAUGHAN and DIMITRI MIHALAS ("The Activity Cycles of Stars") are astronomers. Wilson, who was educated at the University of California at Berkeley and the California Institute of Technology, spent his entire professional career at the Mount Wilson Observatory. Since his retirement in 1975 he has continued to work as an astronomical observer, specializing in various aspects of stellar chromospheres. Vaughan is a staff astronomer at both Mount Wilson and the Las Campanas Observatory in Chile. He studied engineering physics as an undergraduate at Cornell University and went on to get his Ph.D. in physics and astronomy in 1964 from the University of Rochester. He was awarded a postdoctoral fellowship at Mount Wilson the same year and joined its staff in 1967. Mihalas is at the Sacramento Peak Observatory in New Mexico. His degrees are from the University of California at Los Angeles (A.B., 1959) and Cal Tech (M.S., 1960; Ph.D., 1964). He has taught at a number of universities in the U.S. and Britain, and he continues to hold the position of professor adjoint in the department of astro-geophysics at the University of Colorado at Boulder, where he was senior scientist at the High Altitude Observatory from 1971 to 1979.

WANN LANGSTON, JR. ("Pterosaurs"), is director of the vertebrate paleontology laboratory at the Texas Memorial Museum, a division of the University of Texas at Austin, where he is also professor of geological sciences. He writes: "As director of the museum's laboratory of vertebrate paleontology I have charge of the *Quetzalcoatlus* specimens from the Big Bend National Park (which were collected under the authority of the U.S. Department of the Interior Antiquities Act), and I have been actively involved in the reconstruction of the big pterosaurs ever since their discovery in 1971." Langston would like to acknowledge the assistance of Douglas A. Lawson, Kevin Padian, James Brower, Peter Wellnhofer and John McMasters in the preparation of his article.

JOHN G. LEARNED and DAVID EICHLER ("A Deep-Sea Neutrino Telescope") are physicists involved in the planning of the experiment named DUMAND: deep underwater muon and neutrino detector. Learned is currently visiting associate professor of physics at the University of Hawaii, on leave from the University of Wisconsin. His degrees are from Columbia University (A.B., 1961), the University of Pennsylvania (M.S., 1963) and the University of Washington (Ph.D., 1968). Eichler is assistant professor of astronomy at the University of Maryland in College Park, where he holds an Alfred P. Sloan Fellowship. He was educated at the Massachusetts Institute of Technology, which awarded him a Ph.D. in physics in 1976. After spending two postdoctoral years at the University of Chicago he joined the Maryland faculty in 1978.

THURSTAN SHAW ("The Nok Sculptures of Nigeria") is professor of archaeology at the University of Cambridge. Born in Devon, he read archaeology and anthropology at Cambridge, achieving first-class honors in 1936. Following a postgraduate course in colonial education at the University of London, he joined the staff of Achimota College in the Gold Coast (now Ghana) in 1937 and served as curator of the anthropology museum there until 1945, when he returned to Cambridge. In 1958 he was invited by the director of the Nigerian Federal Antiquities Department to excavate the site of Igbo-Ukwu in eastern Nigeria, which he did in 1959–60 and again in 1964, after being appointed research professor of archaeology at the University of Ibadan. Shaw reached retirement age at the University of Ibadan in 1974 but thereafter returned for three seasons of field work (1976–78) under the auspices of Ahmadu Bello University. He was awarded a Ph.D. by Cambridge in 1967 on the basis of his published works. Shaw would like to thank Bernard E. B. Fagg and Joseph Jemkur for their help in the preparation of his article.

WHAT'S NEWS IN PATENTS?

A continuing series on progress by GE inventors.

Last year, General Electric inventors were awarded over 700 patents, adding to GE's unsurpassed total of over fifty thousand U.S. patents, past and present. Here, GE reports on some recent patents—and on the inventors who won them.

Victor Mark: The firefighter.

GE's Victor Mark has learned how to fight fire, not with fire, but with sulfonic acid salts.

Those salts are the key to his

latest patent (Number 4,197,232—"Composition of a Flame-retardant Glass-reinforced Polycarbonate Resin").

Mark's discovery was that adding small amounts of sulfonic acid salts made a dramatic improvement in the flame-retardant properties of polycarbonates. The salts are thermally stable during processing and do not affect the performance characteristics of the polycarbonate resin.

The result is Lexan® 940 polycarbonate—a glass-reinforced version of one of the most popular GE engineering plastics. Its ability to retard flame is helping many manufacturers build increased safety into their products.

Mark's work in organic and polymer chemistry has won him over one hundred patents. And he has some fifty patents pending.

Beltran, Schilling and Muth: Taking the heat off turbine nozzles.

Raising the operating temperature of a gas turbine from 2000°F to 3000°F can raise the efficiency of a power-generating system by no less than 12 percent.

But turbine temperatures of 3000°F throw a chill into materials engineers. At 3000°F, the nozzles that

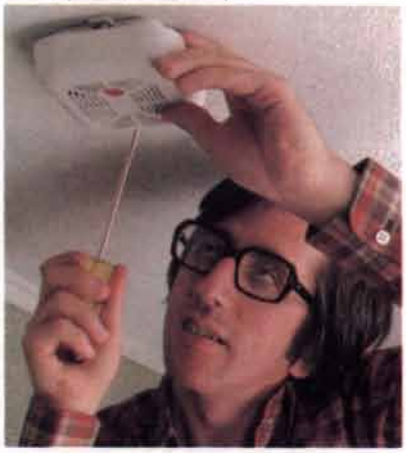
direct the hot gases at the turbine buckets must be liquid-cooled to keep them from disintegrating. A trio of GE engineers has now come up with a remarkable way to fabricate such nozzles. For their work, Adrian Beltran, Myron Muth and Bill Schilling have received patent number 4,183,456—"Method of Fabricating Liquid-cooled Gas Turbine Components."

Their method uses diffusion bonding with hot isostatic pressure to produce a nozzle with a copper core and stainless steel reinforcing, clad with a superalloy. A manifold system of tubing is built in for the liquid coolant.

The new nozzle is a crucial step along the way to more efficient turbine systems. Progress indeed.

Mike Byrne: Farewell to false alarms.

GE physicist Mike Byrne has truly built a better mousetrap with his work on home smoke detectors.



In the typical detector, alpha particles generate an ionization current between electrodes. When smoke particles enter the detector, current drops between the electrodes, and the alarm goes off.

Trouble was, even moderate currents of nonsmoky air could sweep out ionized particles, causing a false alarm.

Byrne's invention is patent number 4,185,196—"Ionization Smoke Detector Having Improved Stability and Sensitivity." It consists of a new electrode configuration that establishes a high-intensity field at the perimeter of the detector chamber; a low-intensity field at its center. The high speed of the ions at the perimeter stabilizes the device, while the reservoir of ions in the center increases the sensitivity.

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MATHEMATICAL GAMES

Gauss's congruence theory was mod as early as 1801

by Martin Gardner

There was a young fellow named Ben
Who could only count modulo ten.
He said, "When I go
Past my last little toe,
I shall have to start over again."

Congruence theory (sometimes called modular arithmetic) is based on principles as old as arithmetic, but it was the German "prince of mathematicians," Karl Friedrich Gauss (he has been called the greatest mathematician who ever lived), who pulled them all together and unified them with a notation so compact and powerful that it is hard to imagine how number theory could have advanced without it. The son of an uneducated bricklayer, Gauss was a child prodigy whose most influential book, *Disquisitiones arithmeticae,* was published by himself in 1801 when he was 24. He had written it four years earlier. It was this book that introduced the concept of number congruence.

Gauss defined two integers a and b to be congruent for a modulus m (modulus is from the Latin for a small measure) if their difference is divisible by a nonzero integer m. To say the same thing another way, two integers are congruent modulo m if they have the same remainder when they are divided by m. Gauss symbolized congruence by three short parallel lines, a symbol still used today: $a \equiv b \pmod{m}$. Incongruence is indicated like this: $a \not\equiv b \pmod{m}$.

For example, 17 and 52 are congruent modulo 7 because each has a remainder of 3 when it is divided by 7. Expressed the other way, $52 - 17 = 35$, which is 7×5. If we call the multiplier k (in this instance k is 5) and let a be the larger integer, then $b = a + km$, where m is the modulus and k is some integer. Many of the rules of ordinary arithmetic and algebra (such as addition, subtraction and multiplication) apply to the manipulation of congruences.

Remainders are called residues, and for every modulus m there are m "residue classes." The smallest modulus, 2, distinguishes even and odd numbers. All even numbers are congruent to 0 (mod 2) and have the infinite residue class $\ldots -4, -2, 0, 2, 4, \ldots$ All odd numbers are congruent to 1 (mod 2) and have the infinite residue class $\ldots -3, -1, 1, 3, 5, \ldots$ For $m = 3$ the residues are 0, 1 and 2. There are three infinite classes (mod 3) and so on for higher values of m.

As Gauss made clear, his congruence algebra provided simple proofs for various rules that determine whether a number is divisible by a given number. (From here on "number" will mean "integer.") Thus n is divisible by 3 if and only if the sum of its digits is congruent to 0 (mod 3). Similarly n is congruent to 0 (mod 9) if and only if the sum of its digits is congruent to 0 (mod 9). A number n is congruent to 0 (mod 4) if and only if its last two digits form a number congruent to 0 (mod 4), and n is congruent to 0 (mod 8) if and only if its last three digits form a number congruent to 0 (mod 8). A number is congruent to 0 (mod 11) if and only if the difference between the sum of its digits in even positions and the sum of its digits in odd positions is congruent to 0 (mod 11).

Congruence algebra led to important theorems about prime numbers and also simplified proving them. For example, Fermat's "little theorem," which is useful in testing for primality, states that if a number a is raised to the power of $(p - 1)$, where p is a prime that does not divide a, then when the result is divided by p, the remainder is always 1. In Gauss's terminology, $a^{(p-1)}$ is congruent to 1 (mod p). Thus a number can be raised to the power of one less than a prime so large that the result can have billions of digits and be far beyond the ability of computers to calculate, yet we know that if we subtract 1 from this unprintable monster, we shall have a number that is a multiple of the prime.

Another famous result related to Fermat's little theorem is known as Wilson's theorem. If you multiply consecutive numbers starting with 1 and stop at any number immediately preceding a prime, the product obviously is divisible by any number up to p but not by p itself. If you add 1 to the product, however, lo and behold the result becomes a multiple of p. For example, 1 times 2 times 3 times 4 is equal to 24, which is not divisible by the next number, 5, a prime. But 24 plus 1 is equal to 25, which *is* a multiple of 5. Using factorial and congruence signs, Wilson's theorem is $(p - 1)! + 1 \equiv 0 \pmod{p}$.

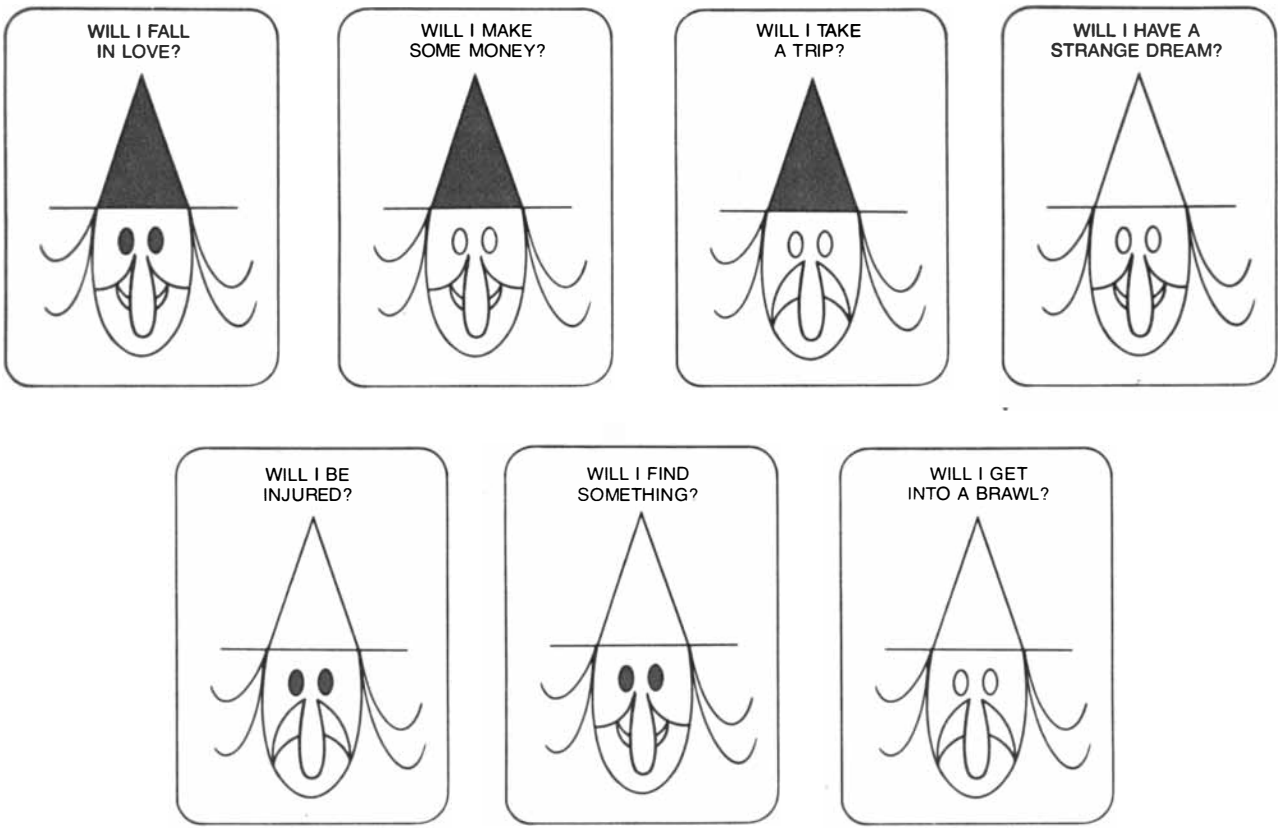
The theorem was known to Leibniz but was rediscovered by a British scholar named John Wilson. Someone credited it to him in an algebra book and remarked that the theorem would never be proved because mathematicians had no good notation for primes. When Gauss was told this, he proved the theorem in five minutes without sitting down, and he commented that for such proofs one needs not *notationes* (notations) but *notiones* (notions). Wilson's theorem is a marvelous criterion for primality, but unfortunately it is of no use in computer searches for big primes.

Thousands of basic theorems in number theory are compactly expressed and their proofs made easy and elegant by modular theory, and endless puzzles have been based on such theorems. For example, suppose a manufacturer of dice ships his product to wholesalers in large cubical boxes. A wholesaler removes one row of dice from the cubical array to test them for possible flaws, and during the tests these dice are destroyed. The remaining dice are packed into small boxes, six to a box. How many dice are left over? Surprisingly, regardless of the size of the original box none are left over. This follows from the congruence theorem $n^3 - n \equiv 0 \pmod{6}$.

Here is a problem that demonstrates

1. Call the year *Y*. Subtract 1900 from *Y* and call the difference *N*.
2. Divide *N* by 19. Call the remainder *A*.
3. Divide $(7A + 1)$ by 19. Ignore the remainder and call the quotient *B*.
4. Divide $(11A + 4 - B)$ by 29. Call the remainder *M*.
5. Divide *N* by 4. Ignore the remainder and call the quotient *Q*.
6. Divide $(N + Q + 31 - M)$ by 7. Call the remainder *W*.
7. The date of Easter is $25 - M - W$. If the result is positive, the month is April. If it is negative, the month is March (interpreting 0 as March 31, -1 as March 30, -2 as March 29 and so on to -9 for March 22.

How to calculate Easter for any year from 1900 to 2099 inclusive



The Wicked Witch of the West's magic precognition cards

the power of congruence algebra to provide solutions. (I found it in Allan Gottlieb's "Puzzle Corner" in *Technology Review* for May, 1978.) You want to prove the curious theorem that every integer n has some multiple that consists of a string of 1's followed by a string of 0's. How can you go about it? One way is to list n "rep unit" numbers starting with 1, 11, 111, 1111 up through n such numbers. The number of possible remainders when any number is divisible by n is obviously n. To our list of n rep-unit numbers we add one more. On the pigeonhole principle at least two numbers on this list must have the same remainder and therefore be congruent modulo n. Now, the difference between any two numbers that are congruent modulo n is congruent to 0 (mod n), which means that the difference is a multiple of n. Therefore we subtract the smaller of the pair of congruent rep-unit numbers from the larger, and the result will be a number of the form we seek.

To see better how this works, let us find a number of the form 111...0... that is a multiple of 7. The first eight rep-unit numbers are 1, 11, 111, 1111, 11111, 111111, 1111111 and 11111111. Their residues (mod 7) are respectively 1, 4, 6, 5, 2, 0, 1 and 4. Since there are eight numbers, we must have at least two numbers with the same residues (mod 7). In this instance there are two such pairs. The smallest pair is 1 and 1111111. The difference is 1111110, or 7×158730. It is the smallest number of the form we seek.

Measurements of time in most cultures are made in modular systems. We measure hours by a mod-12 arithmetic. If it is 3:00 now and we want to know what time it will be 1,000 hours from now, we simply add 1,000 to 3, then divide 1,003 by 12. The residue, 7:00, is our answer. The clock is such a familiar model of a modular system that when schoolteachers introduce number congruences, they like to call it "clock arithmetic." The U.S. armed forces use a mod-24 clock. Days of the week conform to mod-7 arithmetic, the months of the year to mod 12 and the years of the century to mod 100.

Many problems about the calendar yield readily to congruence formulas. Gauss himself gave algorithms for determining the day of the week when one is given the year and the day of the month, and also algorithms for calculating the date of Easter. According to the Gospels, the resurrection of Jesus took place on a Sunday morning during the Jewish Passover week, celebrated after the first full moon of spring. The early Christians wanted to keep the symbolic connection between the Passover sacrifice and the sacrifice of Christ, and so it was decided at the First Council of Nicaea (A.D. 325) that Easter would be the first Sunday after the first full moon after the vernal equinox. Unfortunately the old Julian calendar made the year slightly longer than it actually is, so that the vernal equinox kept creeping closer to winter. By 1582 it was getting dangerously near February. When Pope Gregory XIII introduced the present calendar in 1582, he did so mainly to restore Easter to spring. It is a sad commentary on mathematics in the Middle Ages that calculating the exact dates of Easter was then one of the most important of all applications of mathematics to nature.

Gauss's algorithms for determining Easter dates in both the Julian and the Gregorian calendars are complicated, and they have to be patched by special rules to take care of exceptions. If we limit our concern to the years from 1900 to 2099 inclusive, however, there is a straightforward procedure, with no exceptions, that was devised by Thomas H. O'Beirne of Glasgow and first published in his paper "The Regularity of Easter" (*Bulletin of the Institute of Mathematics and Its Applications,* Vol. 2, No. 2, pages 46–49; April, 1966). O'Beirne found he could memorize his procedure and as a party stunt give the date of Easter for any year during the relevant period by making all the calculations mentally.

O'Beirne's algorithm is summarized

in the illustration on page 17. Easter always falls in March or April. The earliest possible date is March 22. It last happened in 1818 (when it fell on a full-moon day), and it will not happen again until 2285. The latest possible date is April 25. It last happened in 1943, and it will not happen again until 2038. You might like to test O'Beirne's procedure to see that it correctly gives April 6 for Easter in 1980, April 19 for 1981 and April 11 for 1982. April 19 is the most frequent of all Easter dates, with April 18 running a close second.

Countless magic tricks, particularly with numbers and playing cards, are based on congruences, and many have been described in previous columns by me. A trick I have not discussed earlier depends on the fact that the sum of all the values of the 52 cards in a deck is $364 \equiv 0 \pmod{13}$. (Jacks count as 11, queens as 12 and kings as 13.) Let someone shuffle the deck, then remove a card without anyone's seeing its face. After dealing just once through the deck of 51 cards, looking at the face of each card, you correctly name the card that was removed.

Magicians have devised many algorithms for this trick, but the following one seems to me the easiest. As you deal the cards keep in your head a running total of the values but cast out 13 as you go along. In other words, whenever the total goes above 13, subtract 13 and keep in mind only the difference. The task is greatly simplified by two rules:

1. Ignore all kings. Their value, 13, is congruent to 0 (mod 13); therefore they do not alter the number you keep in mind.

2. For 10's, jacks and queens, instead of adding 10, 11 and 12, subtract 3, 2 or 1 respectively. This reflects the fact that in the mod-13 system 10 is congruent to -3, 11 is congruent to -2 and 12 is congruent to -1.

After the last card is turned subtract the number in your head from 13 to get the value of the missing card. If the result is 0, the card is a king.

How do you know the suit? A good procedure is to use your feet for secret calculating in mod-2 arithmetic. Start with both feet flat on the floor. For each spade raise or lower your left heel. For each club raise or lower your right heel. For each heart alter the positions of both feet simultaneously. Ignore all diamonds. After the deal your feet indicate the suit of the missing card as follows:

If only the left heel is up, the card is a spade.

If only the right heel is up, the card is a club.

If both heels are up, it is a heart.

If both heels are down, it is a diamond.

After some practice it is surprising how quickly you can deal through the deck and name the missing card.

Robert Hummer, a magician, has

000 You will dream about a relative.
001 You will have an argument on the telephone.
002 You will dream about elephants.
003 You will exchange angry words with a plumber.
010 You will find a lost ring.
011 Something you say will harm you.
012 You will find the weather abominable.
013 Be alert for an injury to your foot.
020 You will dream about an old friend.
021 Yes, but it will be a fight *you* did not start.
022 You will dream about an airplane.
023 Not if you can control your temper.
030 You will find a coin on the street.
031 Only a slight nick while shaving your face or your legs.
032 You will find a lost object in the pocket of an old bathrobe.
033 No, but you will injure someone else.
100 No, because you know counterfeiting is illegal.
101 You will make a trip to the liquor store.
102 Just the usual amount.
103 You will make a short journey south.
110 You will fall in love with a cat.
111 Maybe.
112 You will fall in love with a stranger in a self-service laundry.
113 Absolutely not.
120 An unexpected check will come by mail.
121 You will trip over a beer can.
122 Not more than $1,000.
123 You will visit an out-of-town friend.
130 You will fall in love with a new car.
131 Positively yes.
132 You will fall in love with a real estate agent.
133 Foolish question.
200 You will dream you are a bird.
201 You *never* get in brawls.
202 A dream will wake you in the middle of the night.
203 You will have a falling-out with an old friend.
210 You will find a lost key.
211 No injury of any sort for the next seven days, but be careful on the eighth.
212 You will find something unpleasant in your bed.
213 Watch out for a punch on your nose.
220 You will dream of coconut pie.
221 Avoid arguments on a bus.
222 You will dream about a flying saucer.
223 Be careful not to antagonize anyone named Harvey.
230 You will find this trick puzzling.
231 It is a dangerous week to stand on stepladders.
232 You will find the news tomorrow disturbing.
233 Climbing stairways can be dangerous.
300 Yes, *lots* of money.
301 You will not leave your neighborhood all week.
302 On the contrary, you will *lose* some money.
303 You will take a marvelous trip in your imagination.
310 You will not fall in love with anyone for a change.
311 *You* can answer that as well as I can.
312 You will fall for someone in show business.
313 Whom do you think you are kidding?
320 Yes, but most of it will go for taxes.
321 Yes, but you will not enjoy the trip.
322 Some, but you will spend it immediately.
323 You will go on a long trip by plane.
330 You will fall in love *twice*.
331 I don't know.
332 You will fall *out* of love.
333 You should be ashamed to ask such a question.

The Wicked Witch's answers

been unusually productive in inventing mathematical tricks, and many of his creations are based on mod-2, or odd-even, principles. I give here for the first time a set of mysterious fortunetelling cards that is one of Hummer's most ingenious ideas.

First you must make a set of the seven cards shown in the illustration on page 18. Photocopy them, paste them on a sheet of cardboard and cut them out. Here is how they are used.

You are allowed to ask the Wicked Witch of the West only one question a day. Of course, you may experiment with more questions if you like, but the answers are not guaranteed to be trustworthy. Each answer applies only to a period of seven days following the day the question is asked. Select the card with the desired question and put it aside. Shuffle the remaining six cards and hold them face down in one hand. Wave your other hand over the packet and slowly pronounce the mystic precognitive mantra "Puthoffa Targu."

From the top of the packet remove the first pair of cards. If the colors of the hats match, put the cards aside to form a pile. Discard them if the hats fail to match. Repeat with the next pair. If the colors of the hats match, put the pair on top of the pile. Otherwise discard them. Check the remaining pair and repeat the procedure. Now count the number of matching pairs. The number will be 0, 1, 2 or 3. Write this down as the first digit of a three-digit number.

Assemble the six cards, shuffle, pronounce the mystic mantra and repeat the procedure, except this time look for matching eyes. Record the number of matching pairs as the second digit of your number.

Shuffle the six cards for the third and last time, say the mantra and go through the packet by pairs as before. This time look for matching expressions (smile or frown). The matching pairs are counted—remember, you count pairs, not single cards—to get the last digit of your number.

Find your number in the illustration on the preceding page and read the answer. Even though the digits of your number were randomly obtained, you will find a specific answer that applies only to the question asked.

If you want to ask the Wicked Witch a yes-no question that is not on any card, you may do so, but now you must use all seven cards. Follow the same procedure, looking first at the hats, then at the eyes and then at the expression. This time, however, you must form two piles, one of matching pairs and one of non-matching pairs. Ignore the last card. Subtract the number of pairs in the smaller pile from the number of pairs in the larger and record the number. After three trials you will have a three-digit number that gives the answer to your question.

Larger sets of cards can be designed for answering a larger number of questions. The number of cards must be one less than a power of 2. In 1980 Karl Fulves published *Bob Hummer's Collected Secrets,* a compilation of all known Hummer tricks. This gold mine of ideas for mathematical magic is available postpaid from Fulves for $20 sent to Box 433, Teaneck, N.J. 07666. Page 77 of the book describes a set of 15 fortunetelling cards, each with four features that may or may not match, to be used with a fortunetelling book (not provided!) of $8^4 = 4{,}096$ answers. I leave it to readers to puzzle out why the answers are always appropriate.

Having opened with an anonymous limerick about congruences, I shall close with one by John McClellan, an artist living in Woodstock, N.Y., whose work reflects a lifelong interest in recreational mathematics and wordplay:

A lady of 80 named Gertie
Had a boyfriend of 60 named Bertie.
She told him emphatically
That viewed mathematically
By modulo 50 she's 30.

Two questions about prime-number patterns were left unanswered in my December column. The first concerned a procedure that seems to generate only primes. Did you recognize this as a clever disguise of Euler's famous prime-generating formula $41 + x^2 + x$? Letting x have integral values starting with 0, the formula generates 40 primes. It fails for $n = 40$, which gives the composite number $1{,}681 = 41^2$.

Leo Moser's triangle pattern is based on the properties of a sequence known as Farey fractions. It produces a sequence with a prime number of numbers for the first nine rows, but it fails for $n = 10$, which gives a sequence of 33 numbers. If one counts digits instead of numbers, the 10th sequence has 37 digits, a prime, but the next sequence has $57 = 3 \times 19$ digits.

To obtain the k numbers for the nth row, add 1 to the sum of the Euler totients for numbers 1 through n. The Euler totient for a natural number n is the number of natural numbers not greater than n that have no common divisors with n other than 1. For 1 through 10 the Euler totients are 1, 1, 2, 2, 4, 2, 6, 4, 6 and 4. The sum of these numbers is 32. Adding 1 gives the composite number 33 for the 10th row. I do not know if Moser ever published this curiosity.

The largest pair of twin primes given in the December column has now been surpassed by an even larger pair discovered in 1980 by A. O. L. Atkin and Neil W. Rickert, the same two mathematicians at the University of Illinois at Chicago Circle who previously held the record. The new pair of twin primes, which has more than 1,000 digits, is $1024803\text{-}780 \times 2^{3424} \pm 1$.

Space Scape

A new painting by Mark Rickerson offers opportunity for JS&A customers in this exclusive print offering.

The painting above is by one of America's fastest rising American artists, Mark Rickerson. Rickerson's works represent some of the most popular space paintings ever created and they have been displayed at some of America's leading galleries and purchased by many space-age companies.

About one year ago, JS&A's president was traveling through Honolulu on a trip back from the Far East when he stopped by an art gallery to examine some paintings.

PRESIDENT'S IDEA

While in the gallery he saw one of Rickerson's works. Since JS&A markets space-age products, our president thought it would be a great idea to feature one of Rickerson's paintings on the next cover of JS&A's space-age catalog.

So he bought the painting and traveled to the Hawaiian Island of Maui, where he met with Rickerson in his studio to discuss reproduction rights. Rickerson refused. His paintings were growing in value and he did not want to commercialize his efforts at that stage of his career.

PROGRAM UNACCEPTABLE

Several months later however, our president received a call from Rickerson. The artist wanted to know if JS&A would be interested in offering limited edition prints exclusively to its customers, many of whom would appreciate the subject matter because of their interest in space-age electronics.

This time we refused. Rickerson wanted JS&A to offer 300 signed and numbered proofs for $200 each. A typical JS&A response, however, would far exceed the available prints and we would have to return too many orders. In addition, Rickerson had been getting $350 for his prints and we didn't understand why he would lower his price.

RICKERSON'S PLAN

But Rickerson had a plan. Those who would respond to our offer would have their name placed in a computer and at the end of our promotion, the computer would randomly select 300 people eligible to purchase the prints. All respondents however, would make up his personal mailing list.

In the future, whenever a new Rickerson print would be announced for $350 or more, those on his personal list would be eligible to purchase that print during the next three years at only $200 regardless of Rickerson's status, fame or the value of his paintings.

Rickerson looked to this promotion as a way of establishing himself and his art firmly as a major factor on the American art scene and at the same time establish a strong following. JS&A in turn has not only agreed to assist Rickerson in that goal, but will be actively promoting his art and his products during the next three years. This offer to participate in his print program will end on February 28, 1981 and only those who respond will be allowed to participate during the next three years.

26 SEPARATE PLATES

Rickerson's painting shown above is called 'Space Scape,' and is one of a series of four that will be offered in this program. Space Scape is a spectacular view of outer space and expresses mankind's relationship to space in a dazzling display of colors, planets and shapes.

The serigraph prints are as spectacular as the original. Limited to only 300 hand-signed and numbered proofs, there are 26 separate overlaid colors from 26 separate silk screens to reproduce every exact detail on 100% museum-quality PH-balanced paper. And they are large–a 30" x 40" image size delivered in a well-constructed and protected carton.

PAINTING OFFERED

Later the original painting will be offered to the general public for $10,000, or for $5,000 to anyone on Rickerson's list on a first-come first-served basis.

There is no obligation to enter and no money is required. Simply fill in the information requested on the coupon and mail it to: One JS&A Plaza, Northbrook, Illinois 60062.

Each participant will be sent an acknowledgment letter with a number. The program will officially close on February 28, 1981 and those selected to receive the print will be notified directly by a public accounting firm by March 15, 1981. There is a strict limit of one entry per person and our computer will automatically reject duplicate applications. If for any reason you are dissatisfied with your purchase, you may return your print anytime during the next three years for a full refund.

Participate and join with us in a great opportunity to own a print from one of America's fastest rising American artists and become part of a select group. Send in your free reservation today.

FREE PARTICIPATION COUPON

Please accept this coupon as my eligibility for participation in the random selection drawing for the print shown above. I understand that I am under absolutely no obligation and that I will be eligible in future programs whether I obtain the print or not.

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BOOKS

Nuclear nightmares, toxic plants, galaxies, processes of seeing and early man in China

by Philip Morrison

NUCLEAR NIGHTMARES: AN INVESTIGATION INTO POSSIBLE WARS, by Nigel Calder. The Viking Press ($10.95). "Relativity is almost as tricky as nuclear deterrence, but at least they don't roast your children alive if you flunk it." In this ironic vein, as an eyewitness and a probing interviewer in silos, with an infantry company, at Los Alamos, under Cheyenne Mountain, even aloft with the generals in a flying alternate command post of S.A.C., the gifted science writer Nigel Calder tries to evoke the precarious state of our roofs, our atmosphere and our conscience in these overarmed 1980's. It is possible nuclear wars, not reactor meltdowns or waste leakages, that he is focused on, nightmares of public health certainly two orders of magnitude more fearsome than all the world's nuclear-power plants.

Calder's report is hardly reassuring. Without gore, without long tables or puzzling jargon, without much illusion, it is up to date and analytic behind a scrim of urbane detachment. Serious readers can form from it a concrete view of how the enormous structure stands that we hear about so often in homely metaphors of superiority, sports or manly strength, all measures too blandly simple for so outrageously heavy a burden.

Perhaps the best introduction to the book is the aphorisms that abound in it, most of them well-worn coins of military and analytical discourse, passed among those who staff this explosives magazine in which we seek to fulfill our days. At Fulda, in the gap where Eastern European forces stand closest to the Rhine, an American captain reflects. "The air force don't die. Army die.... There won't be any rolling over through my sector." But the circle that enfolds what Calder terms "the German volcano" is one of "unbridled viciousness." It is no shallow cynicism but a coldly penetrating one that defines a tactical nuclear weapon as "'one that explodes in Germany.'" The chief defect of elaborate schemes for the nuclear redress of a perceived military imbalance in central Europe is one modern demographic parameter: "With legitimate hyperbole, 'German towns are only two kilotons apart.'"

From the Central Front we are led to look abroad, to lesser powers worldwide, from *la minitriade Française* to the supersonic-nozzle isotope-separation plant in Valindaba in the Republic of South Africa. Attention is paid to the rumored and the real capabilities of quite a few lands. Calder comes down on the Middle East as a credible host to a regional nuclear war, with the complication that there the fleets of the superpowers might stand in confrontation. Inhibitions against the use of nuclear weapons seem weaker at sea, against ships or submarines. "As naval officers put it: 'A nuclear weapon leaves no hole in the water.'"

Then we look at those elaborate systems that deploy, alert and command the silos in their thousands. There are redundant command posts both buried and aloft, and emergency communications satellites for a last-ditch launch. Yet no link is certain, and the fog of nuclear warfare soon gathers into total darkness, a night both transoceanic and radioactive. "'The built-in dynamics of command and control make it very likely that any low-level conflict between the United States and the Soviet Union will lead to all-out nuclear war.'" After a look at a strategy of attack on the Russian command and its links (which seems to have had a major influence on the new U.S. Presidential Directive 59) and a variety of other ploys of the missile duel, Calder concludes that the clever options may be irrelevant: "The victim superpower will simply 'launch on warning.'" Revelation offers an apropos forecast by one early war-gamer: "And the third part of trees was burnt up, and all green grass was burnt up."

Calder sees hope, but he is persuaded that only small, slow, prudent steps can carefully dismantle the house of cards. First we need a treaty against antisatellite systems, he says. Then we need a ban at long last on all weapons tests, and a verifiable quota on tests of the missiles themselves. That might slow down the improvement of weapons, and in the end even erode the generals' confidence in their own aging missiles.

Any reader is bound to be sobered by this taut yet melancholy book. One important criticism might be made. Calder had easy access to the thought and attitudes of the U.S. Air Force; that alert organization was open and helpful. The U.S. Navy, on the other hand, quietly stonewalled. Calder was not able to visit them at all. Yet it is precisely the USAF and its Russian counterpart that must view the apocalypse most urgently: silos are targetable, bombers are slow and perhaps vulnerable, alternate command planes are good only for some hours aloft. The Navy, with its hidden submarines, can afford to think deeper and act more prudently, as indeed they travel. The most urgent binds he outlines may thus be somewhat self-induced, merely the transient outcome of the special nature of certain weapons. All the same Calder's sketch is the most economical and thoughtful one of the cliff edge on which we all now dwell. Perhaps it is a profound moral restraint, as an internal mandate of survival, that best guards the brink: "The simple touchstone of morality about nuclear warfare is that it remains unthinkable." It is surely time not to expand our patently excessive powers but to contract them.

TOXIC PLANTS, A. Douglas Kinghorn, editor. Columbia University Press ($20). Hardly intended for the general scientific reader, this modest volume is nonetheless worthy of the attention of Sherlock Holmes. It reports a symposium held a few years ago for the Society for Economic (Diseconomic?) Botany at Coral Gables, Fla. Eight experts review recent research on toxic plants, not in an effort to provide a comprehensive guide or compendium but rather to set out their own findings in context. Toxic plants are of course nothing new, but we are taking a closer look now, mainly with the powerful tools of organic analysis and the insights into biochemical processes at the molecular level.

The editor's introductory piece itself is surprising. "Since the advent of the 'childproof' safety cap... poisonous plants have moved into first place" as a category of the human ingestion of poisons. Few of the cases result in hospitalization, fewer still in death, but physicians quite naturally "react to inadequate information by playing it safe." There is a deal of agony in all that panic, with painful gastric lavages by frustrated physicians, who are mostly unable to learn the accurate name of the plant ingested and whose "access to the literature is defeated before it has begun."

Labels on plants, like those on cans of drain cleaner, seem no sure answer. We could well label certain dangerous and exotic ornamentals, but what of the un-

labeled plants? Will they not be held safe? We need a rather stern folkloric rule against children eating anything not commonly recognized as wholesome. Certainly the current literature is inadequate, although a helpful new list of more than 100 household plants tested is found in one of these papers. The toxicity of a popular flowering shrub (*Daphne*) is rested by a standard compendium on sources that can be traced, reference by bookish reference, back to experiments on dogs done before 1800, which themselves added little to the report made by Dioscorides himself in Hellenistic times! The example is by no means singular.

Take the poisonous mushrooms. Every text warns quite correctly—so much is simple familiar observation—of the deadly toxins of *Amanita*. Indeed, this genus is responsible for nearly all fatalities from mushroom intoxication, two or three per year in the U.S. The handsome, delicious (on the report of survivors), greenish-white-capped mushroom is becoming commoner in the U.S., perhaps being steadily introduced as a root contaminant of imported plants. The toxin is now well known: it is a linked pair of eight-peptide protein chains. It seems that some five milligrams is fatal taken orally in man, the amount supplied by one fresh mushroom. The toxin kills by inducing acute liver damage, binding to one of the RNA polymerases in the nucleus of the active cells of the liver.

The treatment is supportive. Earlier claims for a sure antidote are not persuasive: "Thioctic acid is the Laetrile of mushroom intoxications." On the other hand, the alkaloid principle muscarine, first found in the colorful fly agaric mushroom, is not in fact present in it in significant concentration. The intoxication from this mushroom, rarely fatal, arises mainly from a quite different compound; it produces a delirious state, with visual and auditory disturbances much sought after among certain northern Asian cultures. There the intoxication was even passed from person to person by drinking the urine of a shaman or priest. It may have been the holy euphoriant Soma of the Rig-Veda. The medical texts often advise atropine as an antidote; it is indeed a specific against the absent muscarine, but it may enhance the effects of the actual hallucinogen, the alkaloid muscimol.

By now almost everyone knows how acute a poison are the hard, beadlike seeds of a widely grown tropical vine, *Abrus precatorius*. Their black-and-scarlet pattern accents many an inexpensive imported necklace. The story is not yet complete, but it is clear that the poison abrin is a small protein whose remarkable and dangerous property it is to agglutinate red blood cells in almost any species, at micro concentration and in minutes. An entire class of such seed proteins is known; their two small chains connive, one to bind to the cell surface, the other to inactivate the synthesis of protein within the cell, at the ribosome level. What is more remarkable is the fact that the toxin from the scarlet seed is similar in "structure, function and apparent mechanism" to the dread toxins of the bacteria of cholera, tetanus and diphtheria.

Finding such a bizarre kinship seems to illuminate the tangled bank of molecular evolution like a flash of lightning. No doubt the plants had to find some way of disposing of various unwanted products of metabolic chains, once they came ashore and could no longer excrete the stuff into the limitless waters of the ocean. They could learn to detoxify, to segregate the toxic material in quiet peripheral depots such as bark. Some instead turned the waste products to their advantage as poisons, mainly against the swarm of herbivorous insects that have coevolved with the land plants over the epochs.

Often a mammal is a not quite innocent bystander caught in the crossfire when a product lies by chance in the molecular neighborhood of a vital mammalian process. The strains of bacteria, of which some secrete the deadly plantlike diphtherial toxin, are also for the most part harmless parasites in the human throat, living and letting live. Once in a while a virulent strain appears, turning by some molecular misprint what was a mere nuisance to scavenging white cells into a life-taking poison. Children are the sufferers, once in the epidemics and now as occasional victims of the scarlet seed.

Poison ivy is one of a family of toxic plants (with not only poison oak and poison sumac but also the lacquer tree of Japan and the cashew) whose habit it is to secrete snakelike chains of a dozen or so carbons, the serpent molecule bearing a ring head. The principle works subtly; the first contact does not bring visible symptoms, but it induces a sensitized immunological state. On later exposure, even after 20 years, the sensitized individual may acquire after a few days the familiar reddened and blistered skin. Preventive immunization has had a limited trial, but perhaps one day it will solve the problem. Here too plants seem to utter the ancient molecular phrases of the microorganisms.

GALAXIES, by Timothy Ferris. Illustrated with 39 full-color and 106 black-and-white photographs and with drawings by Sarah Landry. Sierra Club Books, distributed by Charles Scribner's Sons ($75). It is a long trip from Big Sur or Bridal Veil Falls to the blue-white jet of the galaxy M87, and not even the most resolute backpacker will ever make it. Indeed, the glows of that active member of the Virgo cluster of galaxies are disclosed to us chiefly by giant camera-telescopes, exposed by rather bookish temporary residents of a few low peaks with easy automobile access in Texas or California. But the Sierra Club, as part of its manifold 20-year campaign to protect and celebrate the wilderness through public education, has added the Virgo cluster and regions well beyond it to its philosophical domain. This volume is one more elegantly made large-format, strikingly colorful book of photographs and text. Like the human mind, the author says, it is "strongly oriented around the visual sense." But the objects it celebrates, "part of—most of—the natural world," must be examined from afar, through a window that has been built for the eye by the mind.

A Brooklyn College professor of English, Ferris, who prepared the brief, clearheaded and evocative text, has here limited himself to the most popular end of the spectrum of writing on science for the nonspecialized reader. He does without graph or equation, using almost no numbers except for distances and ages and masses in solar units, plus a few maps and big diagrams of space-time geometry. With characteristic perceptiveness he observes that writers "who report on science solely in terms of its results are like hunters who shoot leopards solely for their skins." The window these grandly displayed photographs open on the galaxies is actually rather complex, depending as much on spectra, variations and not very explicit theory as it does on mirrors and emulsions.

Ferris has tried to make this window "so clear that we might occasionally forget that it is there." He remarks in his valuable few pages of introduction that the result is bound to be compromise. The burned-out centers of printed galaxy images always belie the gemlike brilliance of the nuclei. The colors of these beautiful color reproductions, although they are real enough, are sensitive to the assumptions of the observers working in the mountain darkroom, greening or reddening the gorgeous field somewhat according to taste. Additional judgments are made, very well for the most part, by the craftsmen-printers of the Dai Nippon company. Ferris has not put the reader even to the effort of looking at several photographs of the same galaxy at different exposures or in different printings. He and his editors have not been concerned with angular scale or consistent orientation, although they have cleverly prepared photographs in which the images of stars in our own galaxy have been retouched out, to display the galaxy subject "as in its natural habitat, floating in starless

"Ask me."

Funny, isn't it. Chances are you need life insurance. In fact, you probably have a policy or two tucked away in a drawer.

But life insurance isn't something you can file away and forget. If it is going to work for you and for your family, it must be the right kind of insurance. The right amount. And fit your changing needs.

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If you don't know the answers, don't feel bad about it. Lots of people don't.

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space." (Of course, the galaxies' likely habitat is not as dark as all that; it is probably studded with dwarf galaxies of the kind we see in our own Local Group.)

First the reader is taken on a journey to the center of our Milky Way galaxy. (The narrative device of a lighthearted personal starship trip is used engagingly in an introduction of a few pages to each of the regions, which is then surveyed by a more matter-of-fact description.) About a score of the color plates exhibit the familiar furniture of our galaxy, the glowing diffuse nebulas, the jeweled clusters, the Crab Nebula and a few other showpieces. This component is attractive, but it is not fresh for most readers, since similar photographs are found in many other publications. The big mosaic of the dusty galactic plane on a four-page gatefold is one distinctive feature in black and white. The Local Group comes next, with a gaudy view of the Clouds of Magellan and a good look at the Andromeda galaxy, this time enriched by several photographs at different scales and a radio map. Then we tour more distant galaxies, stopping to admire their several species. Edgewise NGC 4565 is a filigreed slash across an entire page in black and white. The color plates include the enigmatic active galaxies, such as Centaurus A, and M87 with its jet "like a bony finger."

The freshest and most interesting part of the book is a timely study of interacting galaxies. Here are color shots of M51 reaching out after its fleeing little partner, of bizarre M82, of the mottled form of NGC 4631, and the computer diagrams that seem to explain these wonderful anomalies. A couple of pages collect a dozen images made by Halton C. Arp of the Hale Observatories, showing more interacting galaxies: skewed, bridged, long-tailed. We come to suspect some connection between activity in the nucleus of a galaxy and the sudden inrush of gas captured or merely disturbed by off-center gravitational collision. "Might galaxies characteristically flare up when they encounter one another, their nuclear beacons flashing," like ships that pass in the night?

Then we see clusters of galaxies, an unusual color plate of the center of the cluster in Coma Berenices and a beautiful black-on-white sky negative of the cluster in Hercules, almost a full two-page spread with hundreds of galaxies to be easily made out. The book closes with cosmology, a good account of the key idea of look-back time and a clever discussion of the homogeneous universe, based on the Flatland conception. The sources of the photographs are identified, but a little less precisely than one might hope for. There is a useful set of categorized references at varying levels and a glossary.

The book is a beauty, even among its luxurious genre; one wishes it the success it merits. It is not cheap. Frugal readers who want to enjoy big, striking photographs of galaxies can seek out a floppy plastic-bound picture book, with 10 plates about as big as any in the Ferris book (although only in crisp black and white) and some 100 other excellent smaller photographs. It is *The Hubble Atlas of Galaxies,* edited by Allan Sandage, with his brilliant brief historical essay and a technical commentary on every galaxy shown, published first in 1961 by the Carnegie Institution of Washington (1530 P Street NW, Washington, D.C. 20005). Publication 618 is still to be had from them at near-1960's prices, under $20 postpaid.

SEEING: ILLUSION, BRAIN AND MIND, by John P. Frisby. Oxford University Press ($16.95). "I started out to write the General Reader's Fun Book of Visual Illusions, with extended captions," writes this Sheffield psychology professor disarmingly. What came out was something else: a richly illustrated and tightly argued text, still meant for the general reader but at the stiff upper limit for such writing. The crisp and informal text is made workable by some 200 diagrams and drawings. There are still plenty of amusing visual fields that present illusions, to be peered at "often in disbelief" that the eye can get it all so wrong. But most of the illustrations are sequences of idealized diagrams, rather like those found in *Scientific American,* careful pedagogical paths along a line of argument from philosophy through neurophysiology to computer-realized logic of forms, seeking to explain how far we now understand the visual descriptions in our heads.

A template scheme recognizes the specially controlled numbers printed on our bank checks, but that is a caricature of seeing. Seeing means not merely a retinal image, somehow electrochemically repeated there in the tangled fibers of the visual cortex, but its translation into an explicit set of symbols. Yet only a naively ideal scene is mappable one to one onto simple fixed symbols; even the letter *T* is graspable over a wild set of variations, much more general and flexible than any plausible set of templates.

What is surprising is that the neurophysiologist, working with monkeys or cats to study what kind of visual stimulus would fire a single neuron in the layers of the optic tract, did find a kind of simple template—a feature detector—for edges, corners and so on. Those features, however, cannot act alone to sort edgeness out of, for example, a complex painting. Three stages beyond that are recognized today or at least can be supported by the evidence so far. A feature detector must be applied, of course, over all parts of the visual field. Its report is then deeply ambiguous; there is some effect almost everywhere. Each part of the image must be studied further by a patch of interacting cells (they seem to have been found) called a hypercolumn. In such a structure an entire set of related feature-detector outputs is examined. Each detector is of the same general kind but is smoothly transformed, say in orientation, over the sequence. A rule for comparison among the varied responses then allows overall judgment in context; we do not confuse an edge between black and white that is a little off vertical with a neatly vertical edge between grays. But a simple feature detector, made of cells that respond to light alone, positively and negatively, would be confused in just that way.

Here of course is the strength of illusion studies: the mechanism of discrimination can be judged from the nature of its failures. The next steps are known in computer programs but not yet within the brain. A plausible model, mainly due to David Marr, is outlined here for extracting a set of feature signals—say lines, edges and slits—and then looking within them for larger structure by continuity, by closure, by similarity in shape and size, the very *Gestalten* uncovered by the psychologists of the 1930's. To those groupings can be attached the symbols of recognition, which in language become words.

It is striking to see these ideas worked out fully in terms of the wonderful random-dot stereoscopic images of Bela Julesz, for which many examples are given, and also in terms of the cruder distinctions between light and darkness, again strikingly different from direct comparison of the physical value presented. (The black blotter on your desk under the lamp is brighter physically than the white paper away from the lamp, but the two colors are never confused.) No reader is likely to complain that these analytical chapters are without intellectual challenge; although they are nonmathematical, they are tough to get straight. The sense of progress is nonetheless strong and the aptness of the methods is impressive.

It is at the direct perceptual level, prior to conscious learning, closer to the retina, that these schemes seem most persuasive. The sense of unexaminable inner process that ends in the strong stereoscopic images out of random-dot patterns fits this kind of theory, and the computer programs simulate the visual results well. The argument separates data-driven processes from conceptually driven ones; those visual operations that demand an external input—some higher-level downflow that says "Look for rounded leaves"—are distinct from those that only elicit from higher centers the order "Move your gaze." The latter

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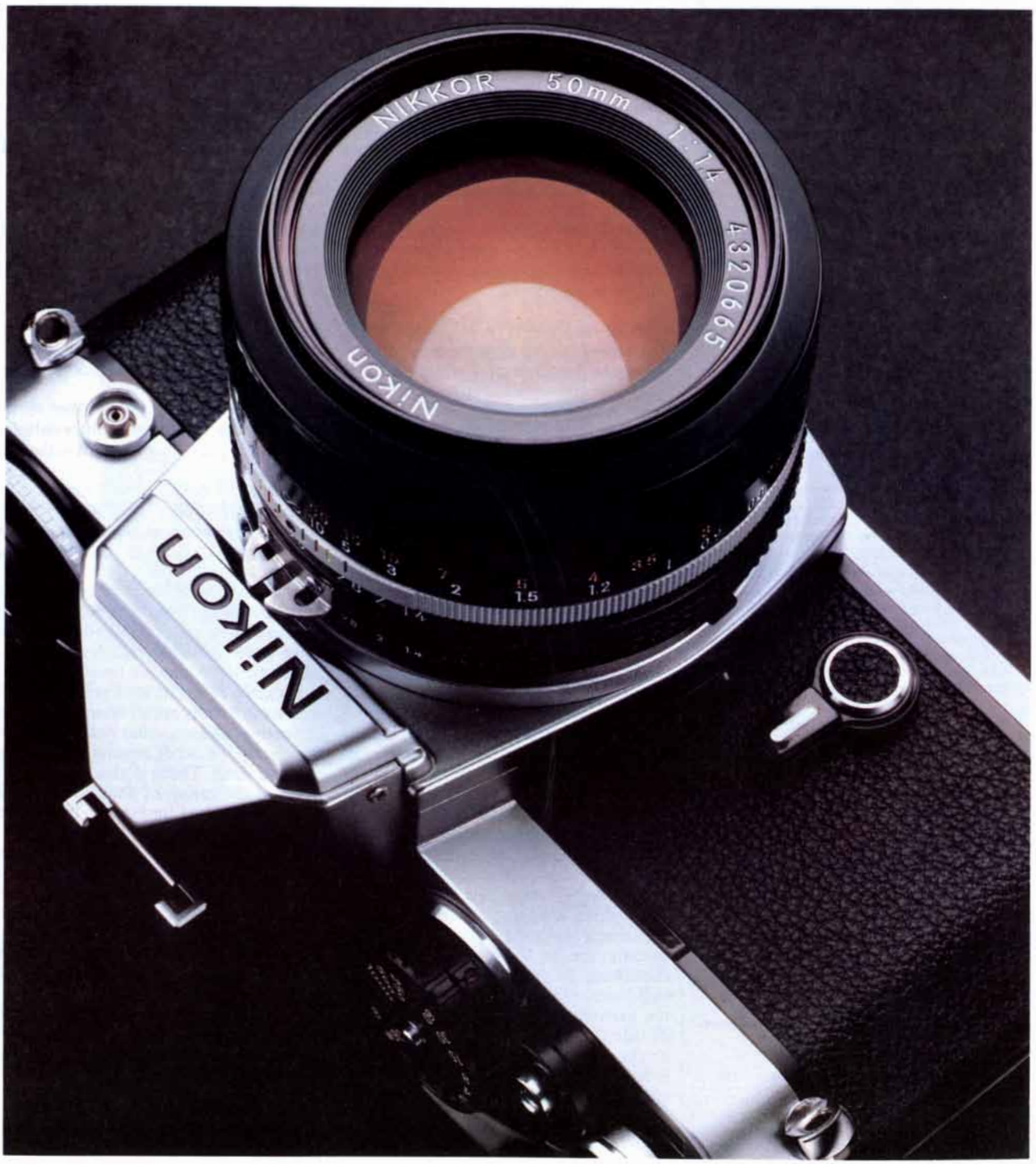

seem closer to initial understanding; the former are much less impressively exemplified, at least in today's computer programs.

Most of the work praised and explicated here has been done within the past four or five years. There is an undertone of triumph in the text: "a seeing machine built to match human visual performance" is foreseen within 50 years. The field is surely fascinating; it seems to challenge and decide profound issues in philosophy by simple concrete accomplishment. Truth and beauty may yet be found to arise from the details, those of a system developed over a very long time, now marshaling 10 billion complexly connected components. Maybe we shall follow to the end the hint that a single cell in the cerebral cortex of a monkey can receive signals from the entire field of view and yet will fire only "if a monkey's paw [is] present" somewhere in that field! (You can see in the book the shapes the cell rejected and the shape that works.) Pretty surely the notion of one cell, one concept is mere naiveté, but subtle programmers now hold the conceptual stage and the proof will be in the seeing.

ATLAS OF PRIMITIVE MAN IN CHINA, edited by the Compiling Group of the Atlas, Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences. Science Press, Beijing. Distributed by Van Nostrand Reinhold Company ($52.50). In what must be recognized as tea-table format, with large pages of striking color plates and a concise text mainly in the captions, a group of Chinese scholars seeks collectively to give readers "an overall view of the academic achievements of Chinese paleoanthropology up to the end of 1976" (with a few later notes). Page after page of this "scientific pictorial atlas" gleams with the color renderings of skulls and teeth and of stone tools, the objects shown with clarity and taste and sizes always noted. Here and there are striking reconstructions of groups of ape-people, of woolly rhinoceros or giant deer, sometimes sculptured, sometimes painted. The most telling of the plates show the sites themselves, again always carefully pinpointed on the land of China, the riverbanks and cliff caves that have yielded over the past 50 years fragments to hint at the story of the truly venerable ancestors.

Perhaps the most novel pages in the volume are at the beginning. In the southwest, in Yunnan Province, with bulldozers as well as with small brushes, the excavators have uncovered over a decade the oldest traces of our own genus known in China. The Protoanthropic find, called Yuanmou man, is dated by paleogeomagnetic means to 1.7 million years ago, with an uncertainty of only 100,000 years. The hominids lived there in a cool prairie-forest region among pines and alders; we have a few teeth but no skull parts to recall those who made the hand scrapers of stone. It is a long way from Olduvai and the Ethiopian lakeshores to the foothills of Yunnan.

Of course, the most extensive treatment is that of Peking man. Not far from the capital city proper "a community of ape-men inhabited a cave for a considerable period of time." By now, after 50 years of devoted study even under the blows of social upheaval and war, the scholars have found bones belonging to more than 40 individuals, male and female, young and old. Some 20,000 stone artifacts have also been recovered. We can see the wide vista of Dragon Bone Hill today, with the site and its fine new museum in the center. Everyone knows how the earliest finds were somehow lost during the chaotic months of Pearl Harbor. Casts remain, of course, and the searching spade has now found many more remains of the ancient hominids, shown here along with their stone projectile points and scrapers. Here too are photographs of ash and of charred bones and hackberry seeds, evidence of the early evolution of fire-bearing human culture by *Homo sapiens'* cousin *H. erectus* some half a million years ago. We see a hackberry tree still growing near the site.

Many other sites from Tibet to the Manchurian plains carry the evolution of humanity in China forward to the Upper Paleolithic. *Homo sapiens,* with its inventory of cunning tools and deft ornament, enters the record 400 centuries ago. It remains remarkable that the Upper Cave site, on the hill just above the Peking-man site, is still the source of the best collection of early remains of our own species in China. Carbon-14 dating places the age at about 18,500 years; the cave gave up 141 "articles of personal adornment." A pierced bone needle and a necklace of perforated pebbles, shells and teeth vividly recall their skillful and reflective makers, who were given to scattering red ocher around the remains of their dead. There is also a section on fossil apes, many of their sites in the stunning etched-limestone landscapes of southern China.

This is a first-rate evocation of the growing knowledge of human origins in China. The text is too concise to carry much detail; the absence of adequate citations and similar apparatus, along with a few other signs, reflects the turbulence of the last decade in Chinese science. The look and feel of the evidence are nonetheless here, very handsomely represented. The book has been well printed in Hong Kong. It is the first of a series of reference works we can expect from its copublishers in China and the U.S.

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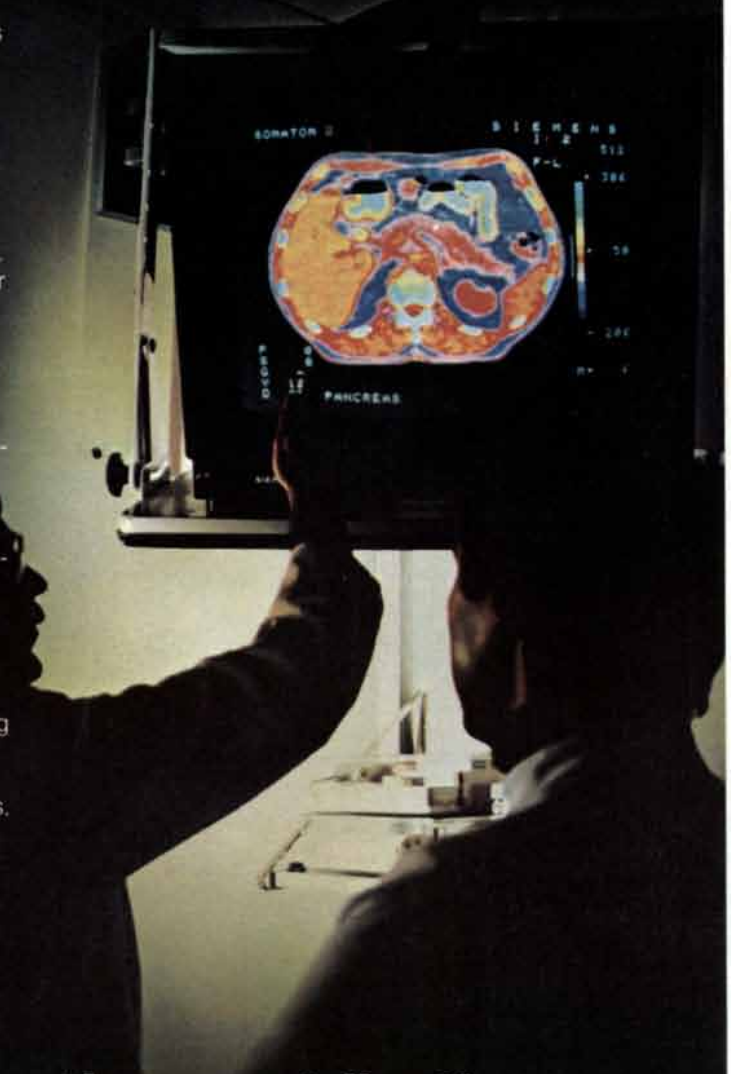

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Advances in Antisubmarine Warfare

Continuing improvements in U.S. antisubmarine forces are becoming an important factor in the overall strategic military balance. They could well play a major role in future strategic-arms-limitation talks

by Joel S. Wit

Over the past decade or so most American assessments of the balance of strategic military power between the U.S. and the U.S.S.R. have become increasingly negative. The usual methods of measuring the comparative strengths of the strategic nuclear forces on both sides, based on such static indicators as numbers of missiles or deliverable megatons, suggest that virtually all the discernible trends are in favor of the U.S.S.R. Moreover, efforts to venture outside of these strictly quantitative criteria have focused for the most part on seemingly threatening Russian activities in several fields, including civil defense, the development and deployment of antiaircraft and anti-ballistic-missile (ABM) systems and research on antisatellite weapons. The net result has been to reinforce the perception of a shifting strategic balance.

Such assessments tend to overlook a number of potentially important, if less obvious, factors without which any attempt to gauge the strategic balance is incomplete. One of these factors is the American antisubmarine-warfare program. For almost three decades the U.S. has conducted a vigorous antisubmarine-warfare effort costing billions of dollars and yielding slow but steady improvements in this country's ability to find and destroy enemy submarines. Although the U.S. antisubmarine force is directed primarily against threats to vital sea lines of communication and naval task forces, it has evolved to the point where it is becoming a potential threat to Russian ballistic-missile submarines.

This growing U.S. capability, which is unlikely to be matched by the U.S.S.R. in the foreseeable future, has accordingly acquired a strategic significance as well as a tactical one. I shall review here the current status of the U.S. antisubmarine-warfare program and the nature of the threat it presents to the ballistic-missile submarines of the U.S.S.R., with particular reference to those factors likely to contribute to Russian perceptions of that threat. In addition I shall examine the probable effect of the U.S. antisubmarine-warfare program on the stability of the strategic balance and on the prospects for nuclear-arms control.

Official public statements on the U.S. antisubmarine-warfare program have always stressed the program's tactical role. The success of such a mission depends on the achievement of four separate functions: (1) the detection of the submarine in question, (2) the identification of that contact as an enemy submarine, (3) the determination of the submarine's precise position and movements, a procedure known as localization, and (4) the destruction of the submarine. Although the emphasis has been on the tactical mission, the destruction of enemy ballistic-missile submarines for the purpose of limiting damage to the U.S. in the event of a nuclear war has been and remains an important priority of the U.S. antisubmarine-warfare effort.

The visibility of the strategic antisubmarine-warfare mission seems to have depended largely on the overall defense policy of the U.S. at any given time. Prior to 1963, when the declared policy of the Kennedy Administration emphasized a deterrent strategy aimed at destroying enemy military forces, the strategic mission of the U.S. antisubmarine-warfare program was a key objective of the U.S. defense effort. Following the shift to a retaliatory anti-city policy in the mid-1960's, the mission of destroying enemy ballistic-missile submarines became less visible, although the need to conduct such operations was and still is acknowledged by U.S. officials.

Most of the equipment procured by the U.S. Navy for antisubmarine warfare is specifically designed with the tactical mission in mind. Nevertheless, many of the systems intended for tactical operations can also be employed effectively in strategic ones. This overlap can be traced directly to the fact that in addition to employing local defense measures (such as surface ships) in the vicinity of individual convoys or task forces, the Navy plans to conduct a broader defense effort aimed at denying enemy submarines access to large parts of the open ocean through what are known in military terminology as "barrier and area search" operations.

The capabilities needed for this mission—undersea-surveillance systems, nuclear-powered attack submarines, land-based antisubmarine aircraft and antisubmarine mines—are also suited for locating and destroying enemy ballistic-missile submarines hidden in large ocean areas. Moreover, the Navy plans to conduct these operations even in waters adjacent to the main ballistic-missile-submarine bases of the U.S.S.R. Given this force-employment policy, the requisite capabilities and what seems to be the prevailing attitude that in war all submarines are fair game, Russian missile-carrying boats could be subject to attack at any time and at any place.

The U.S. has devoted substantial funds over the years to developing and procuring advanced systems for antisubmarine warfare. In the fiscal year 1980 alone the funds committed to antisubmarine-warfare activities came to $7 billion, or roughly 16 percent of the overall Navy budget. Moreover, an-

tisubmarine-warfare expenditures accounted for more than 20 percent of the Navy's 1980 budget for research and development. Much of this money is allocated to the continued improvement of systems potentially applicable to the role of strategic antisubmarine warfare.

Undersea-surveillance systems are particularly important in this context because they provide Navy commanders with timely and accurate information on all hostile or potentially hostile submarines, including missile-carrying ones, in large ocean areas. The backbone of the U.S. undersea-surveillance capability is the Sound Surveillance System (code-named SOSUS). Utilizing passive hydrophone arrays deployed in selected areas of the continental shelf in both the Atlantic and the Pacific, SOSUS is capable of fixing the position of an enemy submarine to within a radius of 50 nautical miles or less. Two such arrays, one deployed parallel to the Kamchatka Peninsula and the other extending between Bear Island and Norway at the edge of the Barents Sea, are of particular importance to the surveillance of Russian ballistic-missile submarines, because of their proximity not only to the Russian bases for these submarines but also to their probable deployment areas.

In the next decade the U.S. undersea-surveillance program will concentrate on overcoming certain inherent drawbacks associated with the current SOSUS arrays. One problem with fixed installations of this type is that they are potentially vulnerable both to peacetime countermeasures and to direct attack in wartime. Another problem is that the restriction to continental-shelf basing makes it difficult to achieve good coverage of some mid-ocean areas. Two solutions to these problems are under development. One, called the Surveillance Towed Array System, or SURTASS, consists of arrays of hydrophones towed behind civilian-manned ships dedicated to the undersea-surveillance mission. SURTASS will give the Navy a mobile, long-range passive surveillance capability, which is expected to greatly increase the effectiveness of the current surveillance system by providing better localization of enemy submarines.

Although the focus of peacetime operations is likely to be the deep-ocean basins, the towed-array system could also be useful in improving the surveillance of waters adjacent to the U.S.S.R. In wartime the towed-array system would not be very effective in hostile environments, and therefore it would probably be deployed only in the deep-ocean basins with supporting forces.

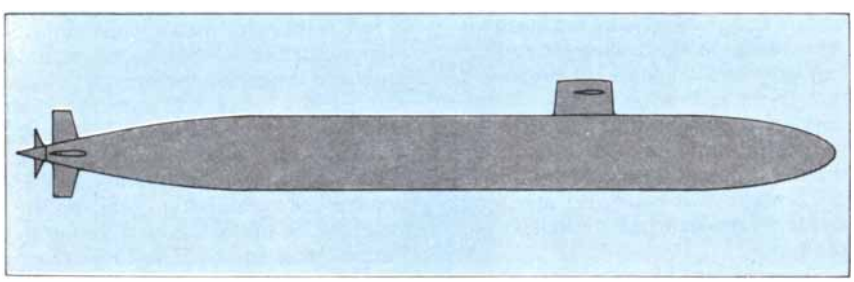
Another advanced undersea-surveillance system developed to overcome the disadvantages of the fixed-array approach is the Rapidly Deployable Surveillance System, or RDSS. It is based on the deployment, by either aircraft or submarines, of command-actuated sonobuoys, which are designed to moor themselves automatically to the ocean bottom. The sonobuoy "fields" would constitute a semipermanent acoustic surveillance system capable of detecting, classifying, localizing and tracking enemy submarines. In addition to providing a valuable backup capability for the fixed surveillance systems the rapidly deployable sonobuoy system could be deployed in wartime in waters near the U.S.S.R., where it could provide target data on Russian submarines for short periods.

Nuclear-powered attack submarines are by far the most effective weapons platforms for antisubmarine warfare, particularly against deep-diving nuclear-powered submarines, including missile-carrying ones. U.S. nuclear-powered attack submarines are particularly well suited for either tactical or strategic antisubmarine warfare. Extremely quiet and equipped with sensitive passive sonar, they are designed to operate in waters near the U.S.S.R., where the Russians are likely to control both the air and the surface spheres of operation and where an increasing number of Russian missile-carrying submarines are likely to be deployed. At present the attack-submarine force of the U.S. numbers 73 boats, including 10 new *Los Angeles*-class nuclear-powered ones. Over the next decade the force should grow to about 90 boats and perhaps more, depending on procurement choices to be made in the next few years.

Because of fiscal constraints it seems unlikely the Navy will continue to buy the highly expensive *Los Angeles*-class boats. As a result the fiscal-year 1981 budget provides for a transition by 1984 to a less expensive, somewhat slower nuclear-powered attack submarine, which could enable the Navy to exceed the 90-boat level by the early 1990's. In addition the Navy is said to be examining designs for another attack submarine for the 1990's that would be significantly smaller and would have greater capabilities than can be achieved with current technology.

American nuclear-powered attack submarines are generally acknowledged to be superior to their Russian counterparts in the two performance criteria considered crucial to victory in undersea encounters: sensor range and quietness. Future qualitative advances will probably capitalize on continuing programs not only to maintain and perhaps increase this margin of advantage but also to add new capabilities to the U.S. submarine fleet. These development programs include new towed sonar arrays and externally mounted, wide-aperture sonars capable of higher search rates and longer detection and localization ranges; a long-range, high-search-rate active sonar to counter quiet diesel-powered submarines and future classes of nuclear-powered submarines; new antisubmarine weapons, such as the Mark 48 "advanced capability" (ADCAP) torpedo and a new "standoff" weapon, a hybrid of the Mark 46 torpedo and the Harpoon cruise missile, to complement improved information-gathering sensors; new steel and titanium hull materials enabling submarines to operate at greater depths (a capability that, besides enhancing acoustic surveillance, would enable boats to avoid detection and incoming weapons more easily), and quieter performance through improvements in various mechanical, propulsive and structural components. The ability of these boats to deal with the threats likely to be encountered in hazardous waters will be improved as they are equipped with new weapons such as the Harpoon antiship cruise missile and the Self-Initiated Attack Missile (SIAM), which is designed to defend submarines against both fixed-wing antisubmarine aircraft and antisubmarine helicopters.

Land-based antisubmarine aircraft are equipped to detect, identify, track and destroy enemy submarines. If such aircraft are to most effectively find and destroy a submarine, they will need at least some prior knowledge of the general location of the target, through information supplied by undersea-surveillance systems or other sources. The American inventory of land-based antisubmarine aircraft consists entirely of



TWO KINDS of modern nuclear-powered submarine are drawn to scale in the profile views on these two pages. At the left is a U.S. attack submarine of the *Los Angeles* class, which is currently considered the most effective weapons platform for antisubmarine warfare in the U.S.

the Lockheed P-3 *Orion,* which according to the Navy "remains unsurpassed in its antisubmarine-warfare and ocean-surveillance capabilities." Of the 24 active squadrons and 216 aircraft (nine planes to a squadron) 15 squadrons consist of the P-3C, the most recent version of this aircraft, which is being procured at an average rate of 12 aircraft per year. The transition to an active force consisting entirely of P-3C's is expected in 1987. In addition the U.S. reserve force has 117 less sophisticated P-3A's and P-3B's organized into 13 squadrons. A worldwide basing network enables American land-based antisubmarine aircraft to cover an area of about 51.5 million square kilometers, including all the likely deployment areas for Russian missile-carrying submarines.

The U.S. Navy's force of land-based antisubmarine aircraft will continue to undergo significant qualitative improvements designed to counter future generations of Russian submarines by correcting current equipment limitations. Information-gathering systems will be improved through the procurement of several items: an upgraded magnetic-anomaly detector, which will double the range at which geomagnetic disturbances generated by a submarine's hull can be detected, an infrared detection system with the ability to detect submarines when they are on the surface by day or by night and a new system of sonobuoys designed to provide faster and more accurate localization of submarines.

The processing of acoustic signals will be improved during the early 1980's through the introduction of the Proteus signal processor, which will supply instantaneous, real-time analysis of data for the location and tracking of submarines. New lightweight antisubmarine torpedoes, the Mark 46 Neartip and the Advanced Lightweight Torpedo (ALWT), will improve target-acquisition and kill capabilities. The Neartip is designed to counter the Russian submarine threat of the mid-1980's; the ALWT is designed to be effective against third-generation missile-carrying submarines as well as all other enemy boats until the year 2000. All aircraft will also be equipped with Harpoon antiship missiles, providing them with an effective weapon against submarines on the surface or near it and against surface ships. Finally, the Navy is studying different concepts for a new aircraft for the 1990's capable of remaining on patrol for longer periods and of covering larger ocean areas. These aircraft might also be equipped with improved antiship and antiaircraft weapons, which would improve their ability to survive in difficult battle conditions.

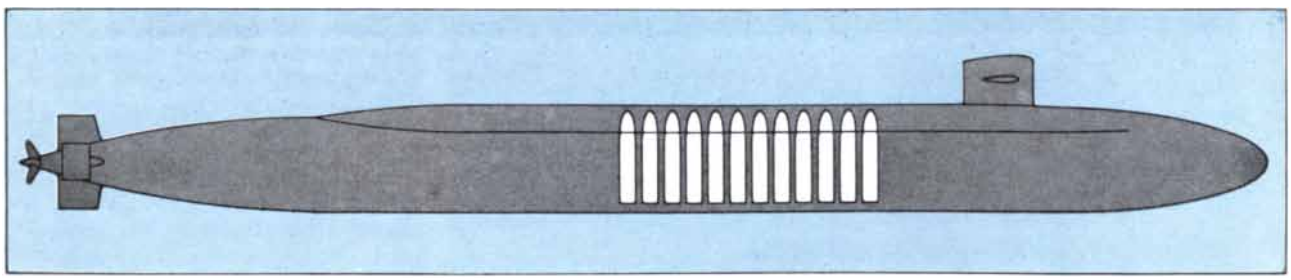
Traditionally mines have been considered as playing an important role in tactical naval warfare. Recent developments in mine technology, however, indicate they can also be useful in strategic antisubmarine operations. The "encapsulated torpedo" (CAPTOR) is the first U.S. Navy mine designed to detect and attack submarines in waters as deep as 760 meters.

These mines could form an important deep-water component of tactical antisubmarine-warfare barriers established at geographical "choke points" such as the gap between Greenland and Britain. Their use in this role, although primarily directed against attack submarines, could free friendly boats from patrolling these waters for other missions, including attacks on Russian missile-carrying submarines. The mines themselves could destroy enemy ballistic-missile submarines trying to reach the deep-ocean basins. The deliberate use of CAPTOR in a strategic role (for example the planting of minefields near ballistic-missile-submarine bases or in potential deployment areas) is possible, although the means of delivery to particularly well-defended waters are currently limited. Future developments, including the submarine-launched mobile mine, with its "standoff" mine-laying capability, and a submarine mine-delivery system enabling boats to carry mines in addition to a full torpedo load, could help to solve the problem.

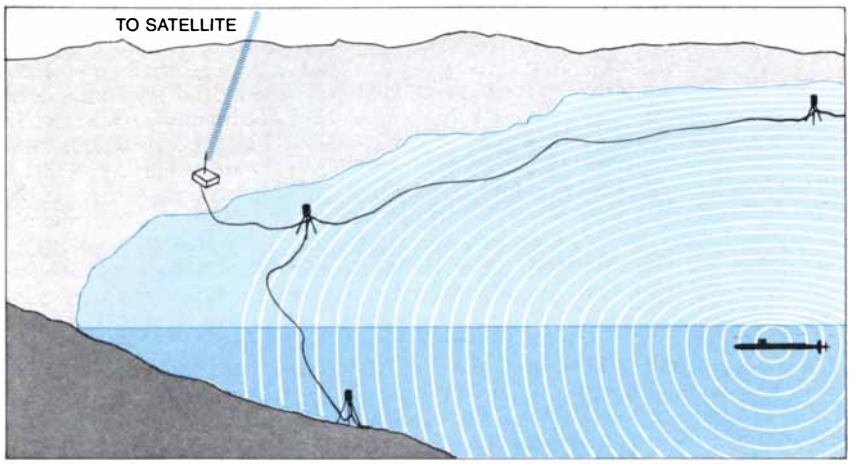
One of the best indicators of long-term technological trends in research and development in this area is the work conducted by the Defense Advanced Research Projects Agency (DARPA). According to Stephen J. Lukasik, a former director of the agency, DARPA's emphasis has been primarily on the undersea deterrent and the associated question of antisubmarine warfare. In this context Lukasik has stated: "Improved systems are required to address the threat which we postulate will be posed by quieter Soviet ballistic missile submarines." The goal of these efforts and related Navy antisubmarine-warfare programs is "not only to detect submarines but also to localize and track them in real time."

The DARPA acoustic antisubmarine-warfare program explores new technologies potentially applicable to the surveillance of both current and projected strategic and tactical submarine forces. Particularly important are the agency's efforts in the field of advanced signal processing. Future progress in finding submarines will require the development of special data-processing computers with abilities far exceeding those currently in service. The agency's program emphasizes technologies that could greatly reduce the number of aircraft flights required to conduct follow-up operations against Russian ballistic-missile submarines. The ultimate goal is a detection accuracy that would allow localization by a single aircraft. Since 1975 DARPA has employed in this role one of the world's most powerful computers, *Illiac 4.* Experiments are reported to have yielded a "substantial increase" over current submarine-detection capabilities. The results of this work have been handed over to the Navy, which is said to be building a new antisubmarine-warfare data-processing facility at the Moffett Field Naval Air Station in California.

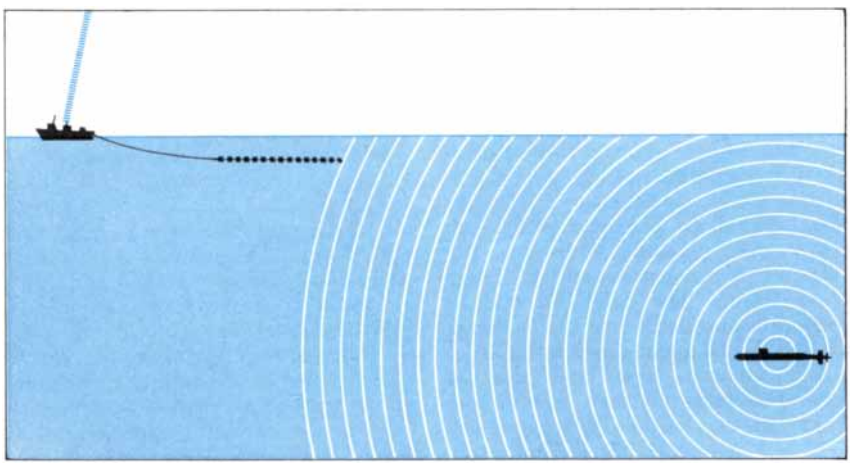
A second important component of DARPA's work in acoustics is research on both passive and active submarine detection. Under its Ocean Measurements and Array Technology (OMAT) program the agency has already done a number of experiments whose results indicate the ocean is a far more tractable underwater sound environment than had been thought. As a result improved detection ranges appear to be attainable. Linear sonar arrays 10 times longer than



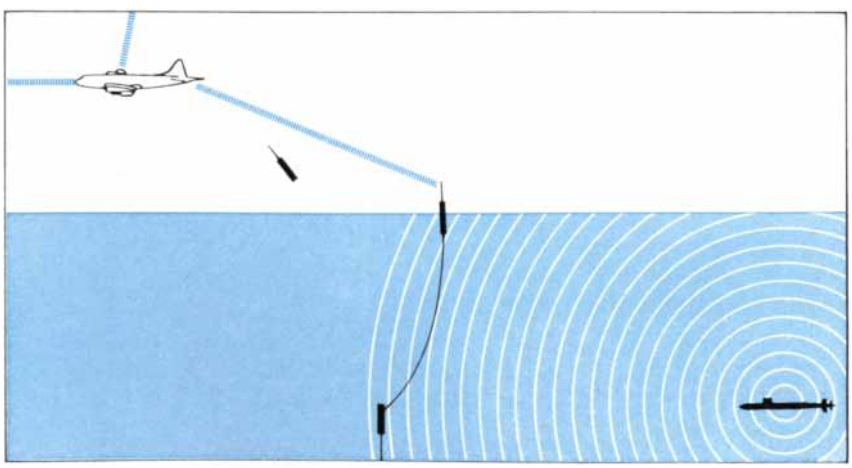
arsenal. At the right is a Trident ballistic-missile submarine of the *Ohio* class. Armed with 24 long-range Trident I missiles, each carrying eight independently targetable nuclear warheads, it is designed to serve as a major component of the U.S. undersea-based strategic deterrent force; eventually it could carry longer-range, more accurate Trident II missiles. At 560 feet it is the world's longest submarine.



SOUND SURVEILLANCE SYSTEM (designated SOSUS) plays a key role in the U.S. undersea-surveillance program. The fixed-installation acoustic system is based on the deployment of passive hydrophone arrays along selected sections of the continental shelf in both the Atlantic and the Pacific. SOSUS is capable of fixing the position of a submarine to within a radius of 50 nautical miles or less. Data are relayed by satellite back to the U.S. for analysis.



SURVEILLANCE TOWED ARRAY SYSTEM (designated SURTASS) is one of two systems currently being developed to overcome certain disadvantages of the fixed SOSUS arrays. The SURTASS approach, which consists of hydrophones towed behind civilian-manned ships, is designed to provide the U.S. with a mobile, long-range passive surveillance capability.



RAPIDLY DEPLOYABLE SURVEILLANCE SYSTEM (RDSS) is a semipermanent acoustic submarine-surveillance system that is designed to supplement the fixed surveillance systems of the U.S. Navy through the remote deployment (by either aircraft or submarines) of command-actuated sonobuoys, which would moor themselves automatically to the ocean bottom.

had been considered possible have been developed, and work is continuing on still longer arrays and on the evaluation of acoustic frequencies suited for moderate- to long-range detection. According to the director of DARPA, Robert R. Fossum, recent experiments involving this technology have yielded "spectacular" results, making it possible to track a quiet submarine continuously at long range. DARPA is also working on the development of a long-range acoustic surveillance system.

DARPA's nonacoustic antisubmarine-warfare research program is devoted to the examination of technologies not now being exploited by U.S. antisubmarine forces. The focus of this research seems to be on the wake effects produced by the passage of a submarine through water. As a result of tests conducted in 1978 and 1979 the presence and detectability of waves generated by submerged submarines were confirmed and quantified for the first time. Sensors resulting from this effort and others might eventually be mounted on satellites able to scan large ocean areas. Work on the development of more sensitive infrared early-warning systems for detecting missiles by satellite and on the refinement of other satellite-based surveillance technologies is potentially applicable to the detection of submarine-generated thermal anomalies. The detection of submarines by laser interferometry from the air has already been successfully demonstrated. Lasers mounted on satellites might also be useful someday in an antisubmarine role. In addition DARPA is exploring the application of "over the horizon" radar in detecting submarines. In this connection it has been reported that the SEASAT series of global ocean-monitoring satellites have the potential of detecting the distinctive hydrodynamic radar "signatures" of submarines.

Wide-ranging American research, development and procurement activities are producing steady incremental improvements in deployed antisubmarine systems and are exploring potentially useful new technologies for antisubmarine warfare. These improvements are largely the result of advances in computer technology, sensor performance and signal processing. Apart from a gradual increase in the number of deployed antisubmarine-weapons platforms there are a number of observable qualitative trends: increasing detection ranges; faster, more accurate identification and localization techniques, and longer-range weapons, which can be launched more rapidly and with higher kill probabilities. The overall result is an antisubmarine force able to conduct increasingly rapid and effective operations within an expanding three-dimensional undersea zone.

The growth of each platform's capa-

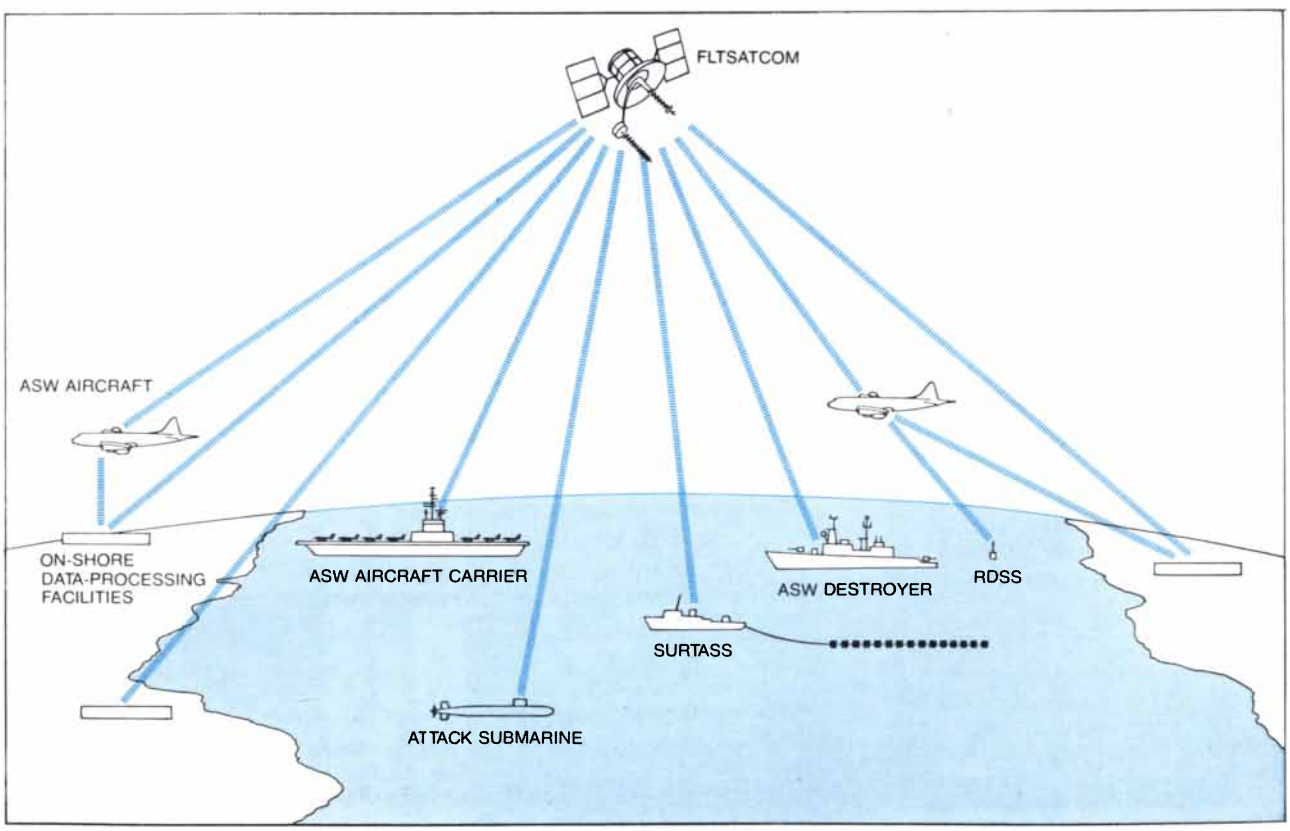
bilities is multiplied through the development of sophisticated command, control and communications networks. Each platform performs certain parts of the antisubmarine operation better than others; therefore in order to achieve the maximum synergistic effects of the different systems better command, control and communications networks must be developed and refined. For example, the "vectored intercept" method of dispatching land-based antisubmarine aircraft after the detection of an enemy submarine by an undersea-surveillance system involves each system's unique capabilities. Surveillance systems can detect submarine contacts over large ocean areas; aircraft can localize them and if necessary initiate an attack. The demand for increasingly sophisticated command, control and communications networks is likely to continue, given current trends toward the wide dispersal of antisubmarine forces over large ocean areas.

American work on command, control and communications networks has led to the growing integration of different systems. According to former Secretary of the Navy W. Graham Claytor, "our ability to orchestrate the many components into an effective submarine hunter-killer force has enormously improved in recent years." Perhaps the most important development in this area is the increasing use of satellite communications to link systems at sea with data-processing facilities ashore. The Fleet Satellite Communications System (FLTSATCOM) will be able to transmit data from computer to computer, thus providing accurate undersea-surveillance information and combat direction instantaneously. Linking powerful shore-based data-processing facilities such as *Illiac 4* with at-sea capabilities, FLTSATCOM will be an important factor in achieving the timely dissemination of more accurate target data in real time on an ocean-wide basis. The importance of satellite communications was demonstrated in a major antisubmarine-warfare exercise held off the East Coast of the U.S. in 1975. The number of submarine contacts almost doubled when satellites were used to link on-shore and at-sea units. Four FLTSATCOM satellites are currently operational, and additional launches are planned for the 1980's.

These technological advances are not being made in isolation. Over the next decade Russian submarines, including those carrying ballistic missiles, are likely to become faster, quieter and able to operate at greater depths. The American antisubmarine-warfare program seems to take these trends into account and is designed to counteract them. In summarizing the outcome of this interaction between American antisubmarine-warfare technology and Russian submarine technology, former Secretary of Defense Harold Brown has stated that even though Russian submarines have become quieter and harder to detect, "our Navy has maintained and, in some cases, even widened our technological lead."

A qualitative advantage is certainly crucial in waging antisubmarine warfare, particularly in a strategic antisubmarine operation. Nevertheless, the identification of technological trends is in itself insufficient to determine the potential implications of American antisubmarine-warfare developments for the survivability of Russian ballistic-missile submarines. The effective application of technology toward a given operational goal, such as the destruction of enemy missile-carrying submarines, also depends on additional factors. For example, will operations be conducted in situations short of war or will they be conducted only in wartime, and where will they be conducted? Any valid operational assessment must include an examination of these and other important factors.

One conclusion that can be drawn from such an analysis is clear: Whereas American missile-carrying submarines at sea are generally thought to be invulnerable to large-scale preemptive attack, Russian sea-based forces do not enjoy the same degree of perceived in-



FLEET SATELLITE COMMUNICATIONS SYSTEM (FLTSATCOM) is planned to link various antisubmarine-warfare systems at sea with data-processing facilities ashore, thereby facilitating the timely dissemination of more accurate data on an ocean-wide basis.

vulnerability. In other words, the American antisubmarine-warfare program threatens the existence of deployed Russian missile-carrying submarines.

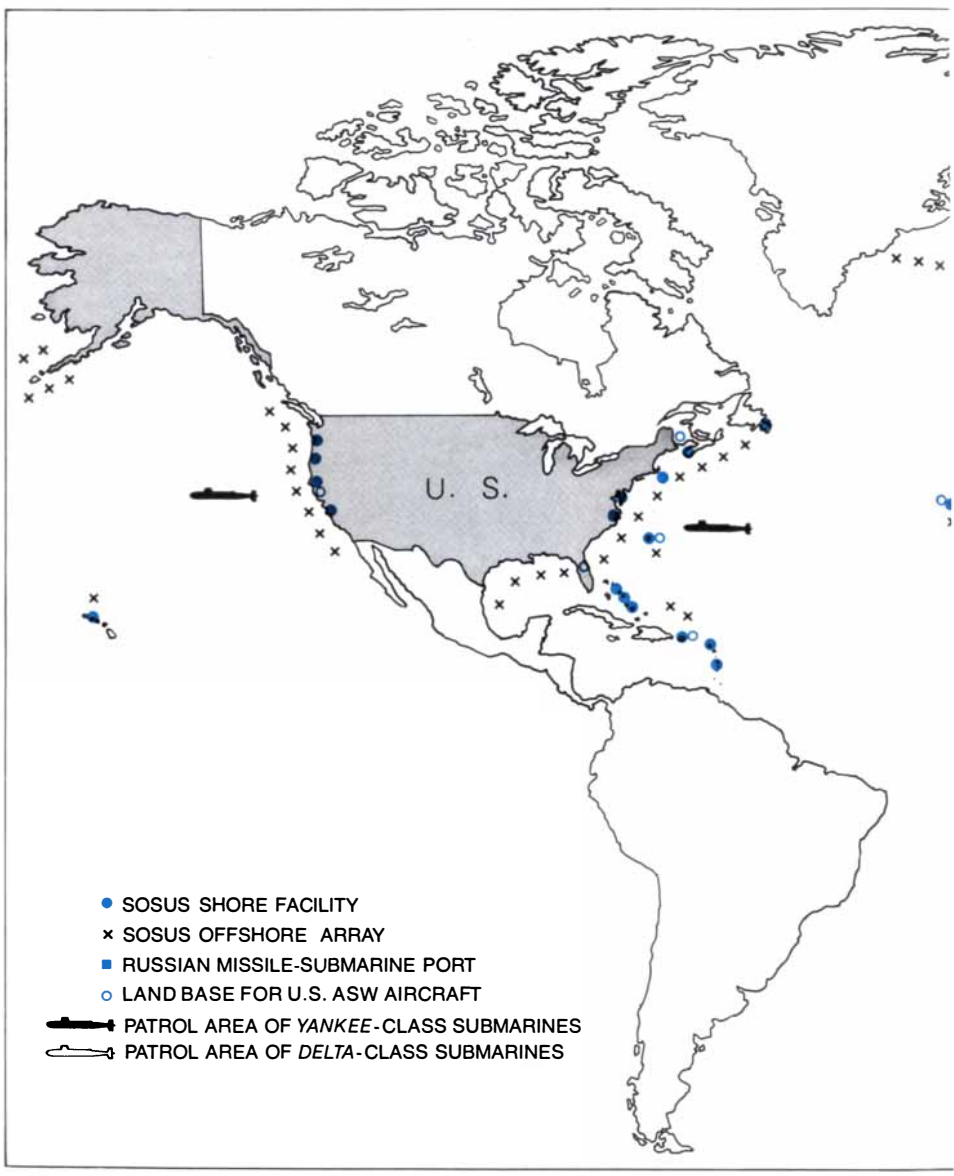
In the deep-ocean basins where the U.S., in conjunction with its allies, can mount large-scale antisubmarine operations, many of which are well suited for strategic missions, the erosion of Russian missile-submarine invulnerability is likely to be particularly rapid. Improved undersea-surveillance capabilities, including new mobile systems such as the Surveillance Towed Array System and the Rapidly Deployable Surveillance System, when they are linked to increasingly powerful data-processing facilities on shore by sophisticated command, control and communications arrangements, suggest that real-time tracking of enemy submarines on an ocean-wide basis will become increasingly feasible. Timely, accurate target information will then be available for individual antisubmarine weapons platforms, such as aircraft, attack submarines and surface ships, many of which will be able to track enemy contacts locally on a real-time basis and, if necessary, to execute a coordinated attack with growing rapidity and greater effectiveness. The overall result could be a perceived erosion of Russian missile-submarine survivability in these waters and a growing ability of the U.S. to launch a preemptive attack.

Although this trend is significant, it does not mean that all missile-carrying submarines deployed by the U.S.S.R. will become vulnerable to preemptive attack. Of the approximately 10 Russian submarines deployed at any one time only four or five patrol the deep-ocean basins in order to remain in range of targets in the continental U.S. New boats of the *Delta* class carrying long-range ballistic missiles are within range of targets in the U.S. while patrolling comparatively safe waters near the U.S.S.R., such as the Barents Sea and the Sea of Okhotsk. Moreover, if (as U.S. officials expect) the future peacetime deployment rate of Russian ballistic-missile submarines increases, the increase is likely to be accounted for by a larger number of *Delta*-class and perhaps new *Typhoon*-class boats operating in these waters. Therefore in the long run growing antisubmarine-warfare capabilities in the deep-ocean basins will probably have a diminishing preemptive utility for the U.S.

The significance of an expanding deep-ocean antisubmarine-warfare capability lies in the less obvious but potentially important implication it has for Russian perceptions of the survivability of the U.S.S.R.'s ballistic-missile submarine force. This capability has for all intents and purposes prevented the U.S.S.R. from using enormous tracts of the world's oceans as acceptable patrol areas. In all likelihood one of the driving forces behind the development by the Russians of long-range ballistic missiles for submarines was the need to deploy boats in safe patrol areas near the U.S.S.R. In effect expanding missile ranges have resulted in decreasing patrol areas and in confinement to comparatively restricted, albeit more secure, waters.

As a result there now exists a somewhat precarious state of affairs calling for a certain amount of peacetime unilateral restraint by the U.S. A conscious effort has been made to communicate to the Russians that the U.S. is not interested in pursuing a policy that might lead to a first-strike capability. This effort includes focusing the operational patterns of mobile antisubmarine forces and improvements in undersea-surveillance capabilities on areas of commonly perceived interest for potential tactical antisubmarine operations, such as the deep-ocean basins, rather than on those of strategic importance, such as the Barents Sea and the Sea of Okhotsk.

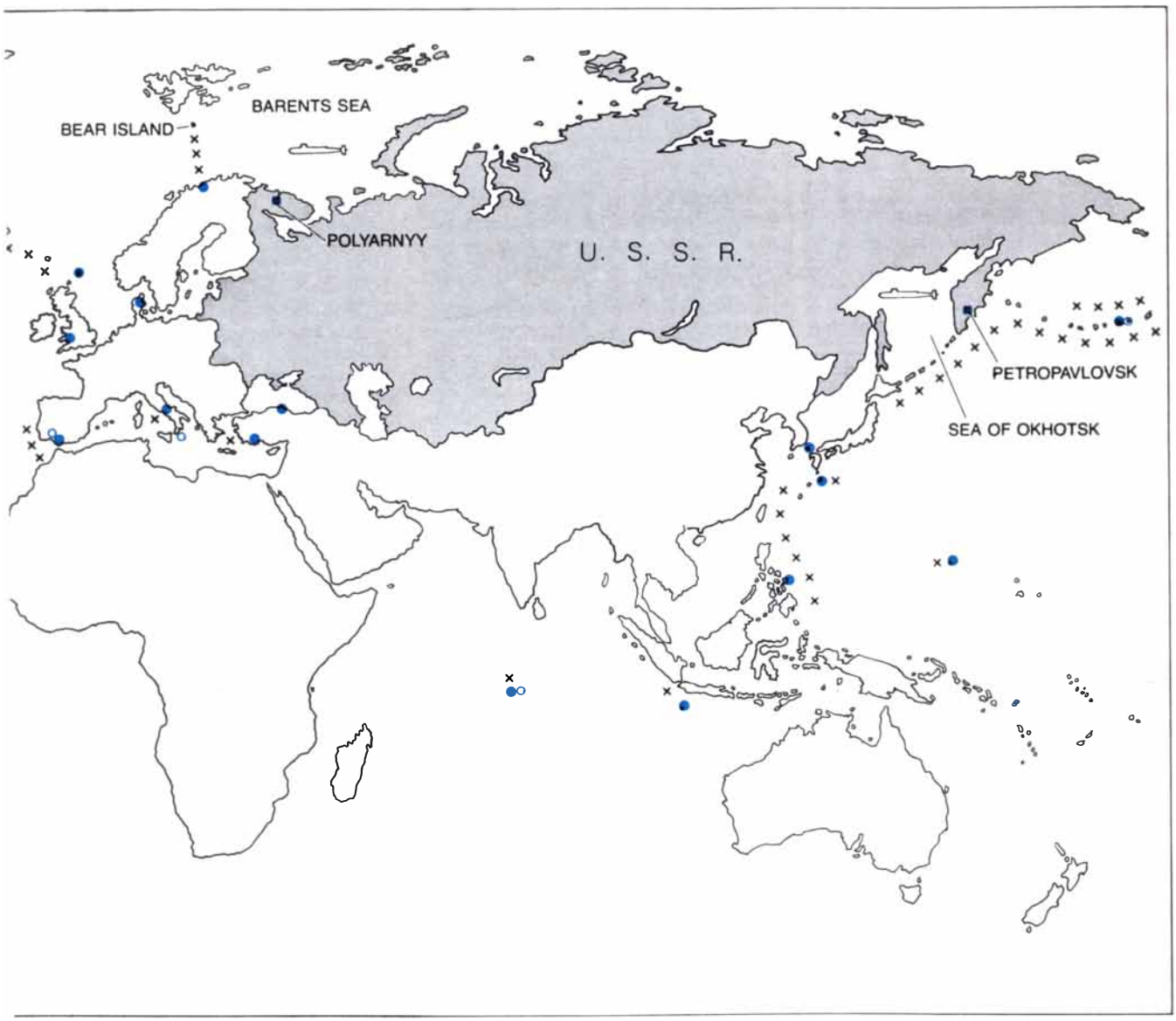
This does not mean that the U.S. has refrained from engaging in any activities related to the surveillance of Russian missile-carrying boats in waters adjacent to the U.S.S.R. Rear Admiral Donald P. Harvey, former director of U.S. Naval Intelligence, remarked in 1977 that "they [his superiors] expect me to tell them as soon as they [Russian



GEOGRAPHICAL FACTORS strongly favor the U.S. in the confrontation between its antisubmarine-warfare forces and the Russian fleet of ballistic-missile submarines. Although the U.S.S.R. has the world's longest coastline, it is actually all but landlocked as far as its submarine fleet is concerned. Its few available submarine ports (*colored squares*) are poorly situated and lack convenient outlets to the deep-ocean basins. For example, Russian *Yankee*-class ballistic-missile submarines stationed at Polyarnyy on the Kola Peninsula can gain access to patrol areas in the Atlantic only by passing through the gap between Greenland and Britain, where they

missile-carrying submarines] cast off the last line." Obviously the Navy is at the very least interested in maintaining surveillance of Russian ballistic-missile submarines in such waters. Identifiable activities include satellite surveillance of port facilities, limited monitoring of the Barents Sea with undersea-surveillance systems and occasional forays by American attack submarines into these waters to gather intelligence on Russian ballistic-missile submarines and area defenses. In the Pacific, Russian submarines based at Petropavlovsk are subject to surveillance while they are still in port, and they are also monitored on leaving port; at the same time, however, new patrol areas in the Sea of Okhotsk seem relatively free of surveillance. Efforts to improve monitoring capabilities in these waters could, according to one U.S. Government publication (a 1980 arms-control impact statement), "belie U.S. declarations that ASW [antisubmarine warfare] efforts are directed against attack and not ballistic missile submarines" and as a result could have "untoward political and strategic implications."

A final factor that is essential to any evaluation of the question of the survivability of Russian ballistic-missile submarines is their low rate of deployment. Currently on any normal day only 11 percent of the Russian force is at sea (compared with the American rate of 60 percent at sea); the remaining 89 percent of the Russian ballistic-missile submarines are in port without shelter. This low rate of deployment is largely due to a shortage of trained crews and to inadequate maintenance facilities. Moreover, even during periods of international crisis the Russians maintain the same deployment rate, unlike the U.S., which increases the number of boats at sea to almost 100 percent. Therefore in situations short of war almost 90 percent of the Russian force is potentially vulnerable to preemptive attack. Although this percentage could decrease if the Russians were to increase the rate of submarine deployment (as is expected), a substantial fraction of their forces would



are subject to surveillance by U.S. antisubmarine-warfare forces. Although the Russian ballistic-missile submarines stationed at Petropavlovsk on the Kamchatka Peninsula in the Pacific have direct access to the open sea, the proximity of the Aleutian Islands and Japan imposes serious limitations on their undetected movement. Indeed, the U.S. antisubmarine-warfare program is designed to exploit not only the geographical disadvantages of the U.S.S.R. but also the comparatively easy access to the open sea from U.S. ports and the strategic location of U.S. allies astride key geographical "choke points." Such geographical factors are presumably important in limiting the deployment of Russian long-range *Delta*-class ballistic-missile submarines to waters adjacent to the U.S.S.R., such as the Barents Sea and the Sea of Okhotsk. The key at the lower left indicates the various components of the antisubmarine confrontation on both sides.

probably still remain in port short of actual war.

The threat to Russian missile-carrying submarines deployed in the deep-ocean basins will probably increase steadily in the future. Although the possibility of scattered losses to American antisubmarine systems under conditions of actual war cannot be ruled out, such systems are likely to survive more or less intact. This assertion is based on the assumption that attempts to destroy these systems will be kept at a manageable level because the U.S. and its allies will have control of the air and the surface spheres of operation. Moreover, the backup capability provided by new mobile surveillance systems, possibly supplemented by new acoustic and nonacoustic systems, will facilitate continued coverage of the deep-ocean basins in spite of any damage done to the fixed SOSUS installations.

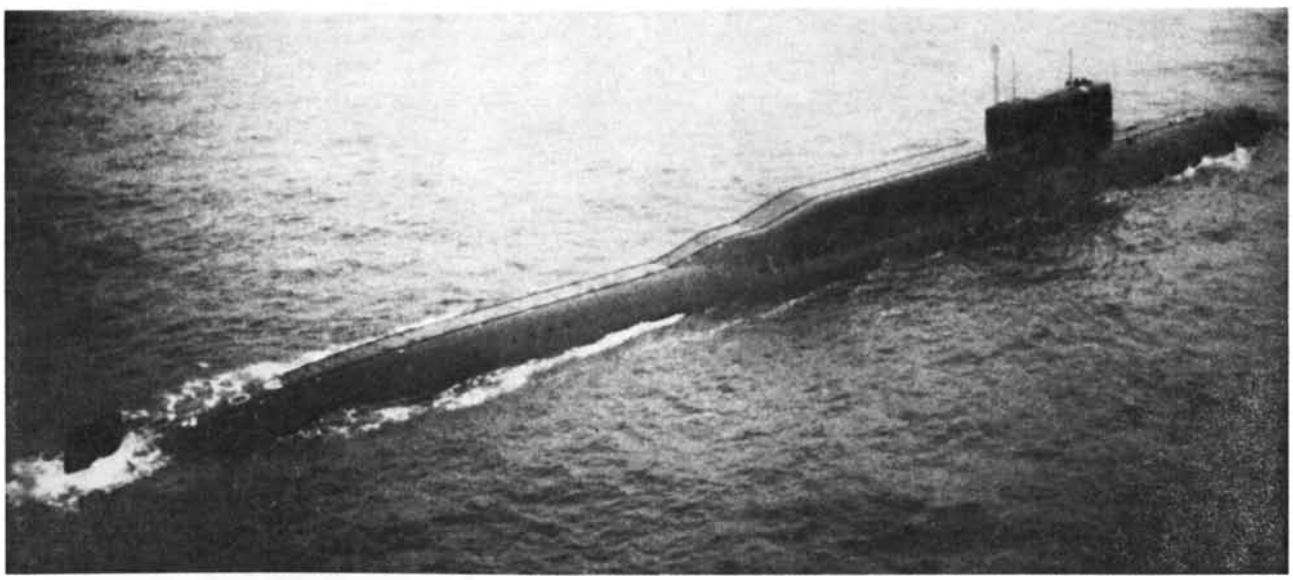
The availability of accurate target information combined with qualitative improvements in individual antisubmarine-warfare platforms could diminish the effect of any concerted attempt to protect missile-carrying submarines in these waters by attracting Allied antisubmarine forces to other tasks, such as the protection of sea lines of communication. It is conceivable that even a small number of platforms, particularly aircraft, could present a significant threat to those few Russian ballistic-missile submarines likely to be found in these areas. Of course, until an effort to attract antisubmarine forces away from strategic operations materializes, Russian submarines could be confronted with an almost overwhelming threat to their survival.

The mounting of deliberate strategic antisubmarine operations in these waters from the outbreak of hostilities could be perceived as an acceptable risk by the national-command authorities of the U.S. Complete target information on enemy submarines would probably be available at an outbreak of hostilities. Rather than exercise restraint until a later stage of the conflict when target information might be less complete, U.S. officials could order the immediate destruction of Russian missile-carrying boats. Russian commanders might then be confronted with the dilemma of having to use their nuclear weapons or lose them while the hostilities were still nonnuclear.

Allied naval predominance in the deep-ocean basins has a potential wartime strategic significance greater than the substantial threat it presents to deployed Russian ballistic-missile submarines. In addition to the boats already patrolling these waters, the U.S.S.R. also has 29 submarines of the *Yankee* class, which must reach the deep-ocean basins in order to strike targets in the U.S. Although the Russians may plan to devote substantial naval resources, such as ships, aircraft and attack submarines, to supporting these submarines in reaching and operating in the deep-ocean basins, adequate forces might not be available, owing to other pressing needs or wartime attrition, or they might be ineffective in the face of overwhelming Allied opposition. The Russians might therefore be forced to withhold these additional boats indefinitely or to risk sending the boats out into the deep-ocean basins with little or no support. In either case a significant number of Russian missile-carrying submarines might be unable to carry out their assigned strategic missions. In the long run some *Yankee*-class submarines will probably remain in the Russian inventory, although their number could decrease somewhat, particularly if a new SALT agreement is concluded and the procurement of new missile-carrying submarines continues.

The waters near the U.S.S.R., where the main concentrations of Russian missile-carrying submarines are likely to be found, should remain less hazardous for them than the deep-ocean basins, since the naval forces of the U.S.S.R. would presumably remain in control of the air and the surface spheres of operation. The presence of these forces probably would make antisubmarine operations extremely difficult, if not impossible, for most platforms. Even in these areas, however, the threat to the survival of the Russian ballistic-missile submarines presented by Allied nuclear-powered attack submarines could be significant, since the latter are designed to carry out effective operations in dangerous operating areas.

The success or failure of deliberate, sustained strategic antisubmarine operations would be closely related to tactical antisubmarine force requirements, the control of waters adjacent to submarine-deployment areas and communications links with nuclear-powered attack submarines. The Russians may well think, however, that the U.S. Navy has the capability, if not to contest the control of adjacent waters, at least to disrupt Russian control to the point of making the antisubmarine threat an extremely strong one. In addition to attack submarines P-3C aircraft armed with



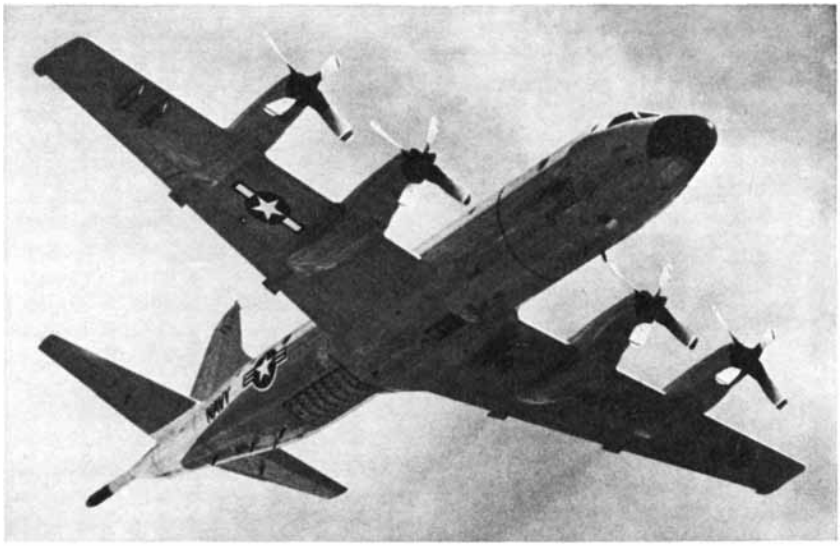
RUSSIAN BALLISTIC-MISSILE SUBMARINE, classified by the U.S. Navy as a *Delta I* nuclear-powered boat, was photographed in international waters. The submarine is believed to carry 12 SSN8 ballistic missiles with an estimated range of 4,200 nautical miles.

Harpoon antiship missiles and escorted by fighter aircraft, a possible new antisubmarine aircraft equipped with antiship and antiaircraft weapons and the Rapidly Deployable Surveillance System might have some utility in dangerous environments.

The ability to focus technologically sophisticated antisubmarine systems on the goal of destroying Russian ballistic-missile submarines in wartime depends to a significant degree on the nature of the conflict. The main interacting factors seem to be as follows: (1) tactical antisubmarine-warfare demands and other demands for forces potentially useful in strategic antisubmarine operations, (2) the balance of naval forces in specific geographical theaters of operation and (3) the survivability of the antisubmarine-warfare system itself. The most interesting element in this kind of analysis is the existence of close links among the survivability of Russian ballistic-missile submarines, general Russian naval strategy and Russian naval capabilities. The survivability of ballistic-missile submarines seems to depend to a large degree on the U.S.S.R.'s ability to occupy Allied antisubmarine forces with missions other than the strategic antisubmarine one and its ability to control key geographical areas such as the Norwegian Sea. Besides placing an additional burden on Russian naval operations, this link could be particularly significant because the failure of Russian non-nuclear naval operations could have important strategic consequences for the U.S.S.R. No such interlocking relation exists between American ballistic-missile-submarine survivability and American naval strategy or capabilities.

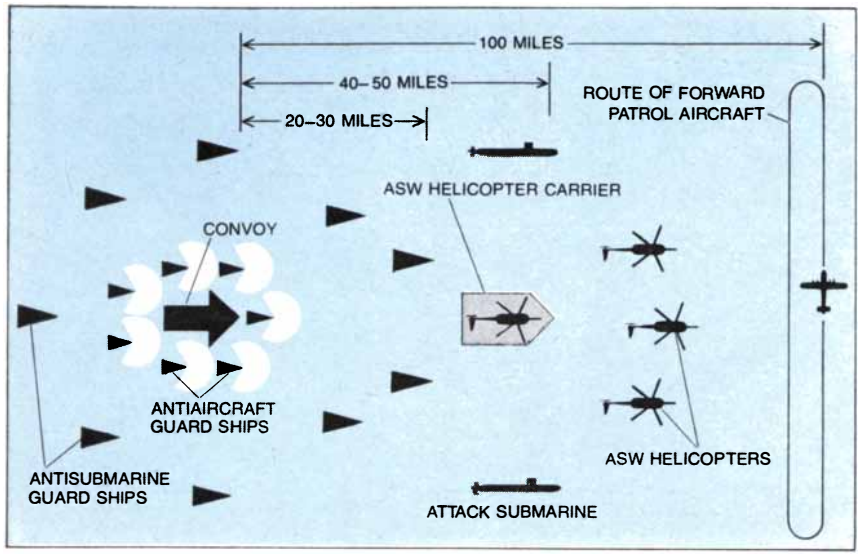
There can be no doubt, then, that American antisubmarine-warfare forces must be taken into account in gauging the strategic balance because of the potential threat they present to Russian missile-carrying submarines. In spite of this fact the subject of antisubmarine warfare has received scant public attention in the U.S. The reasons for this situation are diverse. To repeat, the commonest American methods of gauging the strategic balance focus on static numerical indicators, which allow no room for the inclusion of antisubmarine capabilities. Moreover, antisubmarine warfare is a complex subject involving many different equipment programs with important non-nuclear naval applications that obscure its strategic implications.

Although recognition in the U.S. of the potential threat presented by American antisubmarine forces is quite limited, the Russians have apparently been sensitive to perceived threats to the survivability of their ballistic-missile submarines. There are several manifesta-



ANTISUBMARINE AIRCRAFT, the four-engine turboprop Lockheed P-3C *Orion*, is the most advanced long-range, land-based warplane in the U.S. antisubmarine-warfare inventory. It carries an assortment of surveillance equipment, including a large number of sonobuoys, which are dropped into the ocean through the rectangular array of ejection tubes near the rear of the fuselage. The aircraft is also capable of carrying a formidable arsenal of antisubmarine weapons, including bombs, mines, depth charges (some of them nuclear), torpedoes and antiship missiles. The Navy is now procuring P-3C's at an average rate of 12 aircraft per year.

SENSOR STATION NO. 2 on a P-3C *Orion* antisubmarine patrol aircraft is said to contain the following control and display equipment: radar, electronic surveillance measures, magnetic-anomaly detector and infrared detector (the display part of which is not seen in this view). The photograph and accompanying information were released for publication by the Navy.



TACTICAL ANTISUBMARINE MISSION is exemplified by this schematic diagram of the deployment of a variety of protective systems around an Allied ship convoy. The systems employed for this purpose are primarily local in character, as the distance markers indicate.

tions of this sensitivity, including the institution of tight security measures in new submarine operating areas such as the Barents Sea and the Sea of Okhotsk. In addition Russian attack submarines periodically accompany their missile-carrying submarines in the deep-ocean basins as a precaution against being followed by American attack submarines. Another manifestation of this sensitivity is the development and deployment of new long-range ballistic missiles enabling Russian submarines to strike targets in the U.S. from more secure patrol areas near the U.S.S.R. The necessity of protecting ballistic-missile submarines against antisubmarine forces has a prominent place in Russian naval literature. Most analysts agree that in wartime the Russians would assign their most capable air, surface and subsurface forces to this mission.

The ability of American antisubmarine forces to present a potential threat to Russian ballistic-missile submarines becomes even more significant in view of the fact that the U.S.S.R. does not have a similar capability and is not likely to develop one soon. The American antisubmarine-warfare program therefore represents a potentially important means of limiting damage to the U.S. or of prosecuting a successful wartime strategy that the U.S.S.R. probably cannot match. The significance of this advantage could grow over the next decade as new American strategic-weapons systems mount an increasing threat to Russian intercontinental ballistic missiles (ICBM's).

The strategic forces of the U.S.S.R. have always been heavily concentrated on land-based missiles and are likely to remain so for some time. The U.S. already possesses a partial first-strike capability with respect to these missiles in its Minuteman III force, which could (in principle at least) destroy 43 percent of the Russian ICBM force, a capability that will probably improve with the procurement of new systems such as the Mark 12A warhead, the NS-20 guidance system, the MX missile and the Trident II missile. Add to this the potential threat new American air-launched cruise missiles present to Russian silo-based strategic forces and it seems likely the U.S.S.R. will face a perceived ICBM-vulnerability problem that is much more vexing than the problem now said to be facing the U.S.

A growing ICBM-vulnerability problem is only likely to make the Russians even more sensitive to perceived threats to their sea-based nuclear forces and to the U.S. advantage in antisubmarine forces. Of particular importance would be any American antisubmarine or other naval activities that deviate from accepted norms. For example, the increased procurement of land-based antisubmarine aircraft, of nuclear-powered attack submarines or even of other naval forces that might make the conduct of wartime operations in waters near the U.S.S.R. easier could stimulate Russian concern. Stepped-up peacetime intrusions into informal ballistic-missile-submarine "sanctuaries" might also have an adverse impact on Russian perceptions. Other developments, such as the possible use of satellites to scan waters adjacent to the U.S.S.R., could have the same effect. In any case American antisubmarine-warfare capabilities are likely to remain a factor in Russian calculations of the strategic balance for many years to come.

The potential implications of the American antisubmarine-warfare program for strategic-arms control also deserve consideration. One of the key concepts in American strategic planning is the criterion of stability, which is defined in two ways. Crisis stability refers to a situation in which neither side believes it can come out significantly ahead of the other after a limited nuclear exchange. Strategic stability refers in a broader sense to the nuclear-arms race and means that each side should avoid the development of weapons that would cause the opposing side to become concerned about the future viability of its own strategic force.

The question of whether the continued growth of American antisubmarine-warfare capabilities should be considered stabilizing or destabilizing is a difficult one to answer. In addition to strictly tactical applications of antisubmarine-warfare technology there are legitimate reasons for maintaining surveillance of Russian missile-carrying submarines. Monitoring their activities could provide warning of a possible preemptive attack on American strategic-bomber bases by submarine-launched ballistic missiles and also of any deviations from normal operating procedures, such as a suddenly increased submarine deployment, that could signal possible hostile action.

The ability to monitor Russian missile-carrying submarines could therefore be considered stabilizing in that it deters surprise attack and enhances the survivability of U.S. strategic forces. Nevertheless, in pursuing these legitimate objectives the U.S. could acquire a capability that could be perceived as threatening the survivability of Russian ballistic-missile submarines and therefore could be construed as destabilizing. If continued U.S. Navy efforts to monitor Russian submarines advance to the point where all deployed boats can be tracked from their pens to their operating areas and back again, it would be a significant first step toward the acquisition of a potentially destabilizing first-strike capability.

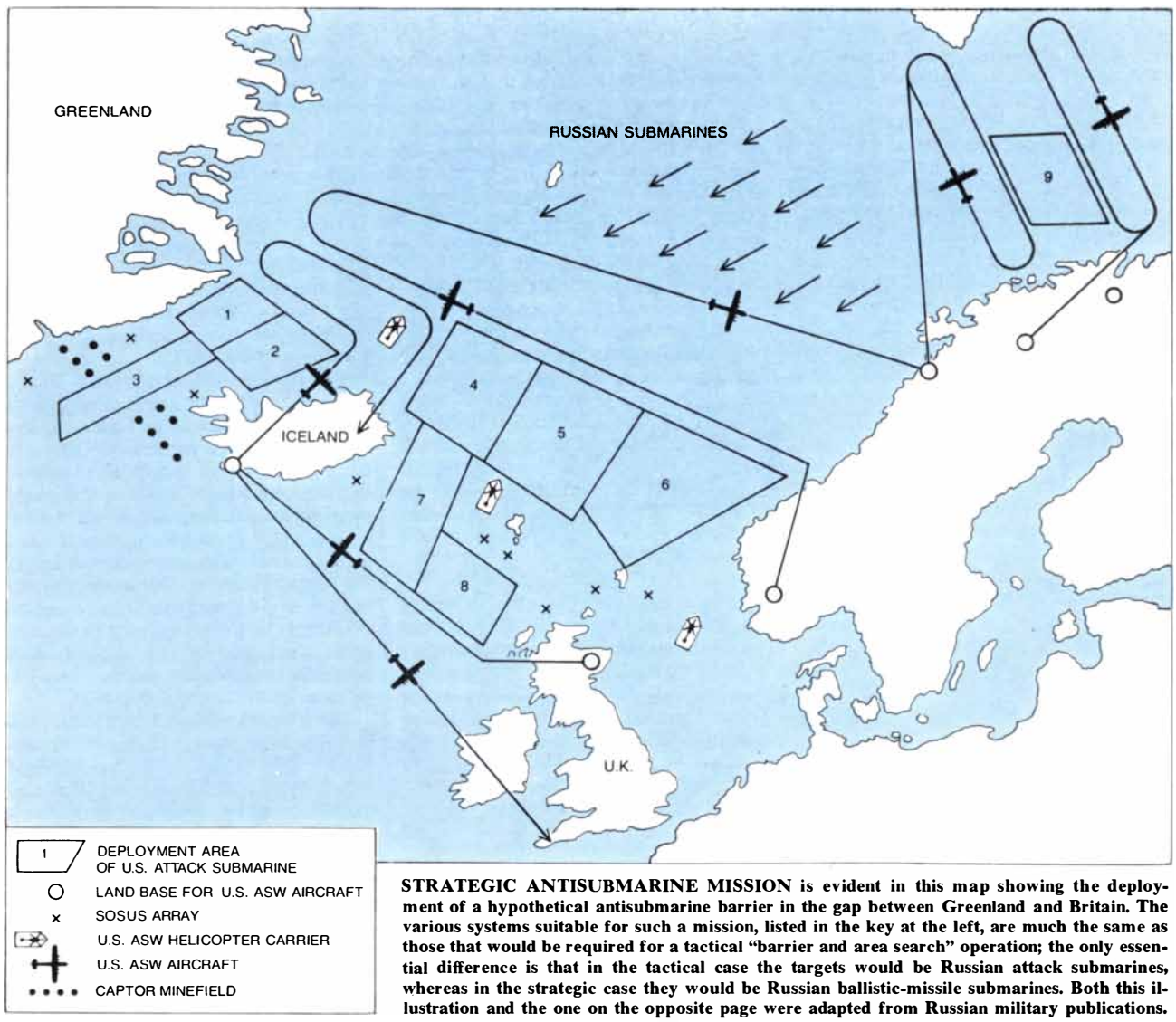
Perhaps even more significant in terms of the arms-control impact of the American antisubmarine-warfare program is its effect on future American positions at the strategic-arms-limitation talks and on the prospects for the success of those negotiations. One of the major objectives of the U.S. throughout the history of the SALT process has been to produce agreements that encourage both sides to maintain highly secure retaliatory forces and to reduce the deployment of weapons that threaten those forces. Since this goal would be served best if the Russians relied less on increasingly accurate ICBM's with multiple warheads, which appear to threaten American land-based missiles, the U.S. has tried to "drive the Russians out to sea," that is, to induce them to divert resources from destabilizing land-based missiles to sea-based missiles, which do

not have the perceived ability to destroy ICBM's.

Thus the SALT I agreement, while seeking to establish limits on the Russian land-based-missile buildup, also allowed freedom to mix nuclear-weapons systems, but in only one direction: out to sea. The SALT II treaty (in its current unratified form) contains important limitations on land-based missiles with multiple warheads and tight restraints on new ICBM's. Sea-launched missiles are comparatively free from restraints, and each side is given the freedom to mix its sea-based-missile totals upward as it sees fit. It is quite possible that in the next round of negotiations the U.S. will seek to capitalize on the SALT II restraints on land-based missiles by pressing for reductions, possibly substantial ones, in those systems, which could force greater reliance on sea-based missiles for nuclear deterrence.

In the past the Russians have shown a definite aversion to placing greater reliance on sea-based nuclear forces. American SALT negotiating positions designed to drive the Russians out to sea (the most prominent of which was President Carter's 1977 comprehensive proposal) have been rejected. Neither the SALT I treaty nor the unratified SALT II treaty has forced the Russians to transfer significant strategic forces out to sea. Russian force-building programs continue to place an emphasis on land-based systems. Although it is true that over the past decade Russian sea-based nuclear capabilities have increased dramatically, there has been no significant redistribution of capabilities away from land-based missiles to sea-based ones. Moreover, in the next few years the concentration on land-based missiles by the U.S.S.R. could conceivably increase, according to some static indicators used to measure strategic capabilities.

There are a number of explanations for the Russians' resistance to moving out to sea, ranging from the bureaucratic dominance of the land-based Strategic Rocket Forces to the qualitative inferiority of the Russian sea-based nuclear forces compared with those of the U.S. Another factor has probably been the American advantage in antisubmarine-warfare forces and the potential threat this capability presents to Russian sea-based forces. In this context the success of any arms-control strategy that seeks to force the Russians to reduce their land-based forces and therefore to rely to a greater degree on sea-based nuclear forces will depend in part on their confidence in the survivability of their strategic submarine force. Therefore it is almost certain that in considering such a step the Russians will examine American antisubmarine forces, deployments, procurement plans and research-and-development activities more intensively than ever before. Their conclusions about the nature and extent of the threat this program presents to their ballistic-missile submarines could be an important factor in determining the outcome of future SALT negotiations.



STRATEGIC ANTISUBMARINE MISSION is evident in this map showing the deployment of a hypothetical antisubmarine barrier in the gap between Greenland and Britain. The various systems suitable for such a mission, listed in the key at the left, are much the same as those that would be required for a tactical "barrier and area search" operation; the only essential difference is that in the tactical case the targets would be Russian attack submarines, whereas in the strategic case they would be Russian ballistic-missile submarines. Both this illustration and the one on the opposite page were adapted from Russian military publications.

California Rice Culture

Sowing seed and herbicide by air and exploiting other modern agricultural methods, California rice growers achieve remarkably high yields that play an important role in the world rice market

by J. Neil Rutger and D. Marlin Brandon

The production of rice in California has evolved into one of the most highly mechanized agricultural operations in the world, including the leveling of fields by laser beam, the sowing of seed by airplane and the harvesting of the crop by special combines that do not bog down in the mud of the rice paddy. The 1979 California yield of 6,450 pounds of rice per acre was 50 percent higher than the average in the other rice-producing states in the U.S. and nearly three times higher than the world average of 2,360 pounds per acre. Although the acreage devoted to rice in the U.S. is only .9 percent of the world total, the U.S. produces 1.7 percent of the world crop and in many years is the world's largest rice exporter.

About 60 percent of the annual American rice crop of seven million short tons is exported, with more than half of the exported rice going to Asia. About a fourth of the American rice crop is grown in California. Arkansas, with slightly more than twice as many acres under rice cultivation as California, harvests not quite 60 percent more rice than California and is the country's largest producer. The other major rice-growing states are Texas, Louisiana and Mississippi. The labor required to cultivate and harvest one acre of rice in the five major rice-producing states is seven man-hours per crop. More than 300 man-hours per acre per crop are still needed today in most of Asia and Africa, where the yields per acre are also much lower.

Rice is generally considered a tropical crop, but it is now grown on all the continents except Antarctica, extending from 53 degrees north latitude to 40 degrees south. More than 90 percent of the world's rice production of 406 million short tons (368 million metric tons) is in Asia. Worldwide, rice was grown on 344 million acres (139 million hectares) in 1979, making it second only to wheat among the cereal crops in area and production. (Worldwide production of wheat in 1979 was 448 million metric tons, harvested from 227 million hectares.) In Asia, where the annual per capita consumption of rice is about 95 kilograms, rice accounts for a third to a half of the daily caloric intake and is a major source of protein. Americans consume about five kilograms of rice per year.

Virtually all cultivated rice belongs to the Asian species *Oryza sativa*. A small amount of the related species *Oryza glaberrima* is grown in Africa. All told 20 species of *Oryza* are known. Archaeological evidence indicates that rice was under cultivation between 6,000 and 7,000 years ago in Southeast Asia and southern China. Rice later spread outward from that area to India, to Indonesia and the Philippines, to the rest of China and to Korea and Japan. In the process *Oryza sativa* differentiated into three ecogeographic races: Indica, Japonica and Javanica. The tropical race, Indica, seems to have been the progenitor of the other two. When the tropical race was carried northward into China and Japan, the cold-tolerant Japonica race developed. As Indica rice was taken to Indonesia the tall, thick-culmed Javanica race emerged. California rice varieties are basically cold-tolerant Japonicas, whereas the varieties grown in the southern U.S. are intermediate between Japonica and Indica. No Javanica rice is grown in the U.S.

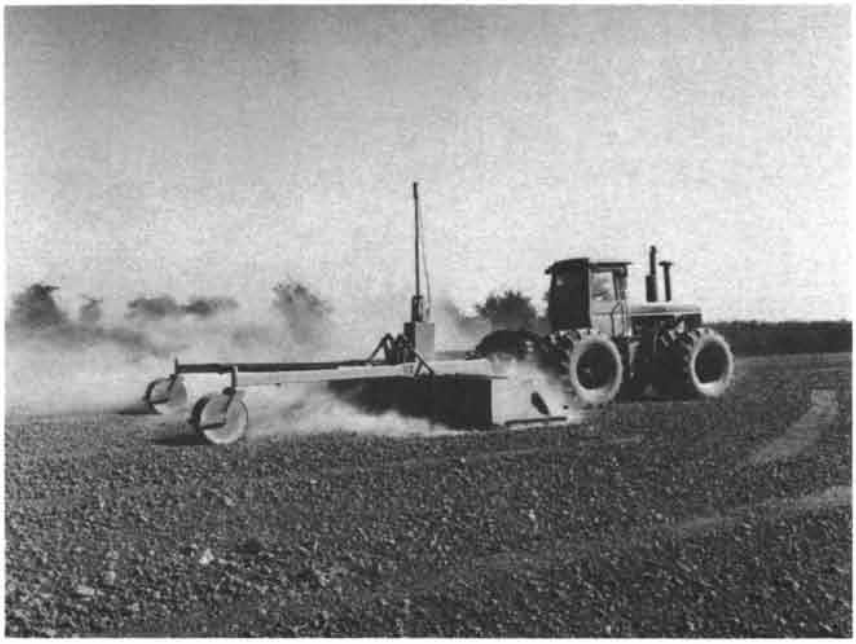
Rice was introduced into North America at least as early as 1609 and became established as a crop in South Carolina by 1690. Until about 1890 it was grown mainly in the southeastern states. The production of rice was established in Louisiana by 1888, and it soon spread to Texas, Arkansas and California. Following experimental plantings in the Sacramento Valley in 1909 rice became a commercial crop in that area in about 1912. Rice is therefore a comparatively new crop in its current areas of largest production in the U.S.

In California rice culture is largely confined to the basins of the Sacramento and San Joaquin valleys. Here dense clay soils and soils with impervious layers (hardpans) largely prevent the downward percolation of water. Therefore in these areas it is easy to keep the rice crop continuously flooded during the growing season with minimum water loss and maximum production efficiency. The region has an abundant supply of inexpensive water of the necessary quality. Ninety percent of California's rice is irrigated with water from the Sacramento and Feather rivers. Annual precipitation in the form of rain and snow is impounded behind the Shasta Dam on the Sacramento and the Oroville Dam on the Feather. Water is released in the course of the year to irrigate crops and to supply other users.

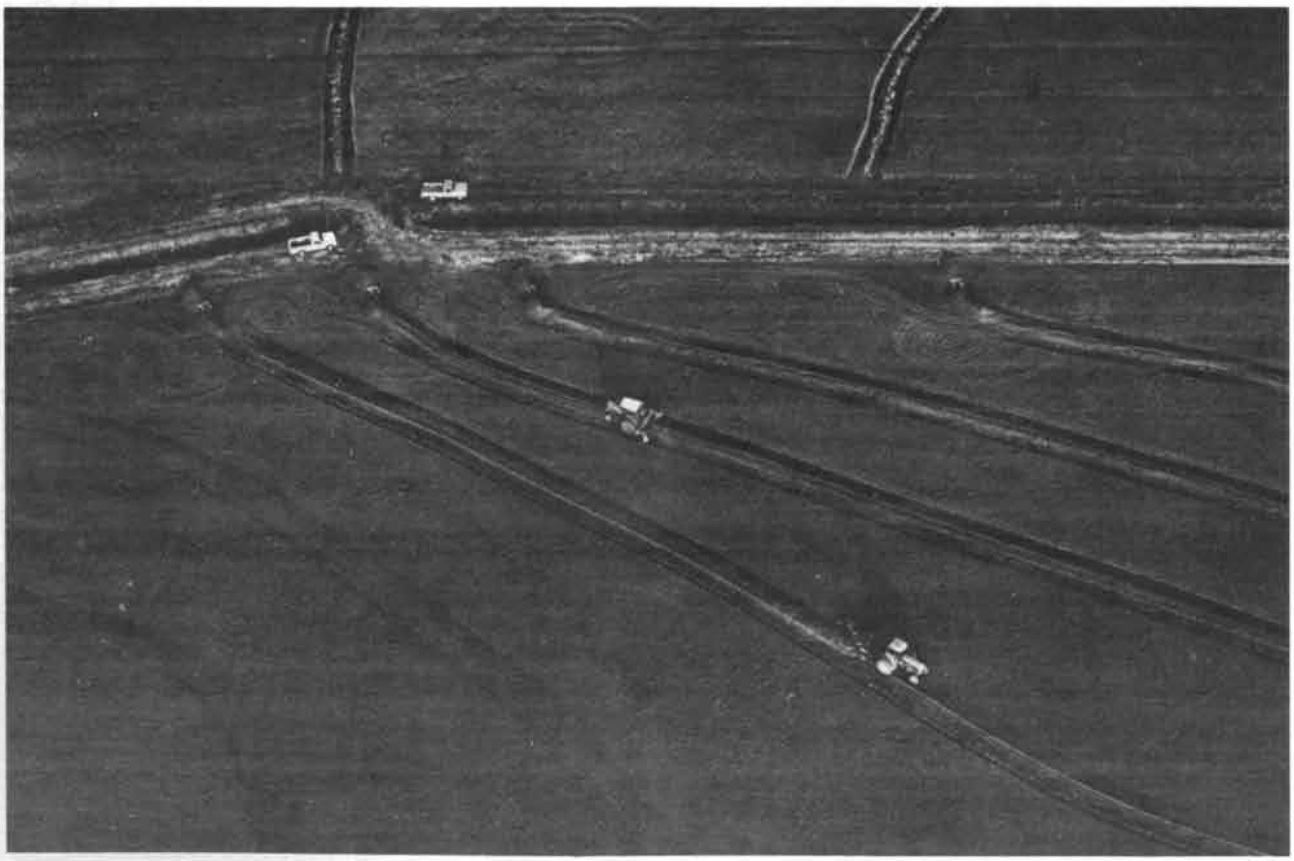
The continuous submergence of the soil needed for the growing of rice in California calls for some eight acre-feet of water per acre per season. Three of the eight acre-feet supply the needs of the growing plants and are dissipated through evapotranspiration. Of the remainder half percolates downward and recharges the water table and half leaves the field and recharges the surface drainage systems downstream. Hence almost two-thirds of the water used in the rice fields is recycled into the ground-water system or is reused downstream for agricultural and municipal purposes.

The temperate Sacramento Valley climate is nearly ideal for rice production. An abundance of sunshine combined with low humidity and warm days and nights contributes much to the region's

GRANULAR HERBICIDE IS DISPENSED by an airplane flying over rice fields in the Sacramento Valley of California. The rice grows in carefully leveled fields that are flooded with water to a depth of between two and four inches. The fields are separated by sinuous levees that follow the natural contours of the land. Weeds are controlled by careful regulation of the depth of the water in combination with the sparing use of a small number of approved herbicides.



PRECISE LEVELING OF RICE FIELDS is accomplished with the aid of a rotating laser beam mounted on a mast (*left*), which establishes a reference elevation that can be detected by earthmovers operating anywhere within a substantial radius. The reference laser beam is picked up by photocell detectors mounted on a special earthmover called a triplane leveler (*right*). As the earthmover travels across the field the intercepted laser beam is processed by a small computer that controls the raising and lowering of the triplane leveler's hydraulically actuated blade. By tilting the reference laser beam slightly the field can be given the desired slope of one or two parts per 1,000.



LEVEES ARE CONSTRUCTED by special twin-disk plows that pile up the soil into a dam between two and three feet high. Two plows are at work in this aerial view. The levees are spaced so that ideally the depth of water is no less than two inches adjacent to the "uphill" levee and no more than four inches adjacent to the "downhill" one. The close spacing of the levees shown in the photograph indicates that the surface is dropping quite steeply in this part of the field. In the flatter parts of the field the levees can be several hundred feet apart.

high productivity. Disease and insect problems are minimized by the dryness of the summer months, when the relative humidity rarely exceeds 40 percent. (Even though the lower parts of the growing rice plants are submerged the parts above water are benefited by low humidity.) Because low temperatures often come early in August the rice varieties grown in California must be cold-tolerant.

In recent years the key to increased rice yields in California has been the improvement in the varieties of rice. The broad objectives have been to develop hardy, high-yielding varieties with good grain quality. Within these broad objectives rice breeders have sought to shorten the growing time, to increase cold tolerance, to improve grain shape and cooking quality and to increase resistance to disease and insects. A special problem of rice has been a tendency for plants near maturity to lodge, or fall over. In the past decade the most significant improvement by far in California rice varieties has been the development of short-stature types, which are highly resistant to lodging.

REGION	AREA HARVESTED (1,000 ACRES)	YIELDS (POUNDS PER ACRE)	PRODUCTION (1,000 SHORT TONS)
ARKANSAS	1,190	4,450	2,650
CALIFORNIA	534	6,450	1,720
LOUISIANA	533	3,950	1,055
TEXAS	520	4,200	1,090
MISSISSIPPI	205	4,200	430
MISSOURI	35	4,150	75
U.S.	3,017	4,650	7,020
WORLD	344,085	2,360	405,920

U.S. RICE PRODUCTION IN 1979 of 7.02 million tons represented slightly more than 1.7 percent of world production, grown on only .9 percent of the world acreage devoted to rice. The U.S. yield per acre was therefore nearly twice the world average. Yields in California were 50 percent higher than the average in the other principal rice-growing states. The value of the U.S. rice crop in 1979 was more than $1.3 billion. About 60 percent of the crop was exported, with more than half of the exports going to Asia. In many years the U.S. is the leading exporter.

Work at the International Rice Research Institute in the Philippines in the mid-1960's demonstrated that the genetic reduction of plant height led to a dramatic increase in rice yields. The shorter plants were not only more resistant to lodging but also more responsive to the application of fertilizer; they showed yields almost double those of the older tall varieties. The greater resistance to lodging has two advantages. The first advantage is that the plants remain erect to maturity and are therefore able to continue vigorous photosynthesis through the critical period when the grains are being filled. The mutual shading of lodged plants curtails photosynthesis. The second advantage is ease and efficiency of harvesting. Lodged plants often end up lying in the mud, which slows the harvest and decreases the percentage of the crop harvested.

Since American rice yields were already high, the introduction of the new short varieties had less impact in the U.S. than it did in the Tropics. Nevertheless, the short-stature varieties have raised California yields some 15 percent. In 1979, when half of the state's rice acreage was planted to short-stature varieties, the statewide average yield of 6,450 pounds per acre was some 600 pounds higher than it had been in any previous year.

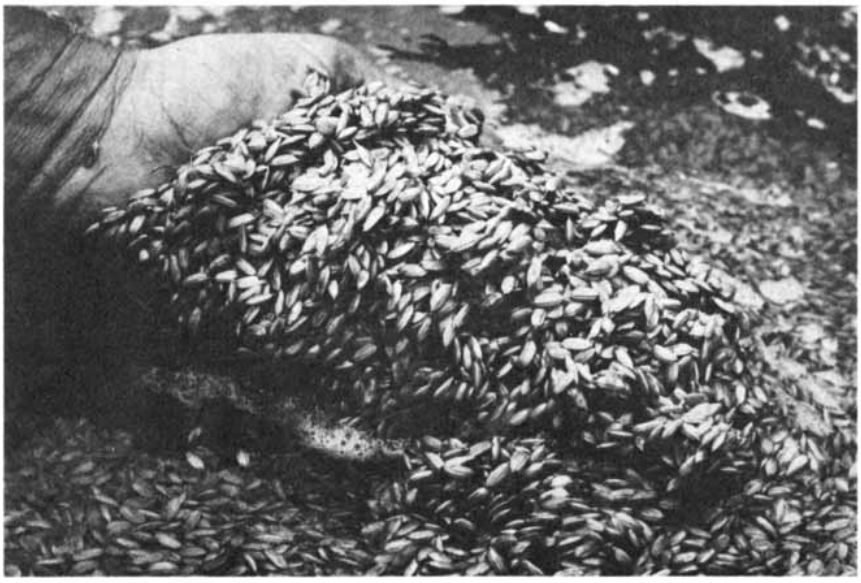
In California short-stature rice varieties have been developed by induced mutation, by hybridization and by a combination of the two breeding methods. The main centers for rice improvement are the Rice Experiment Station operated by the California Cooperative Rice Research Foundation at Biggs and the University of California Rice Research Facility at Davis, supported in part by the U.S. Department of Agriculture and the California rice industry. Both facilities have had unusual success in inducing favorable mutations by exposing rice grains to gamma radiation from the radioactive isotope cobalt 60. The mutations are not expressed until the second generation, and like all induced mutations they are largely deleterious. The first successful short-stature variety released in California, Calrose 76, was a mutant derived from Calrose, a popular tall variety. Calrose 76 in turn has been hybridized with other tall varieties to create four additional short-stat-

NITROGEN FERTILIZER is applied to California rice fields a few days before planting at a rate of 120 pounds of nitrogen per acre. The nitrogen can be dry in the form of urea or ammonium sulfate or liquid in the form of ammonium hydroxide, as is the case with the fertilizer being applied here. In either form the fertilizer is incorporated between two and four inches below the surface to minimize oxidation and to be accessible to plant roots in the preferred reduced form.

ure varieties. At present the most popular short-stature variety, M9, is a hybrid developed by the Biggs rice breeders in which the gene for short stature was supplied by IR8, a naturally occurring variety from the Tropics.

It has turned out that the gene responsible for short stature is identical in the mutant source, Calrose 76, and in the natural source, IR8. The Calrose 76 source has been easier to use in California rice breeding than IR8, mainly because the induced mutation has contributed the desired gene to an already adapted genotype. IR8 and other tropical gene donors are cold-susceptible and otherwise poorly adapted to California, which makes it more difficult to transfer the short-stature gene to a successful hybrid plant.

Early-maturing varieties of rice are desirable because they enable the grower to begin his harvest earlier and lessen the risks from bad weather in the fall. The standard varieties grown in California for many years needed from 150 to 165 days from planting in early May to harvesting in September and October. The first of the early-maturing varieties introduced into California, which could be harvested some 135 days after planting, generally yielded less per acre than full-season late varieties. Within the past few years, however, several improved early-maturing varieties, such as M9 and M-101, have come to rank among the highest-yielding varieties available to California growers.



RICE SEEDS are treated with a fungicide to control seedling diseases. Then they are soaked in water for 24 hours and are drained for 12 to 24 hours after that before they are planted. The rice shown here is a new variety called M9, which is specially developed for California climate.

SEED-DISPENSING AIRPLANES such as this one can carry 1,200 pounds of presoaked seed. Presoaking ensures that seed broadcast from the air on flooded fields will sink promptly.

Cool temperatures affect the California rice crop at two stages: during the emergence of the seedlings and between 10 and 14 days before flowering, when the reproductive spores are being formed by the process of meiosis. At seeding time the temperature of the water is often 65 degrees Fahrenheit or lower, and the initial growth is slow. The establishment of strong stands is favored by rapid growth and emergence through the cool water. When California plant breeders first sought to develop rice plants for short stature, they feared that short-stature varieties would lack the seedling vigor required for strong stands. By means of intensive selection, however, such short-stature varieties as Calrose 76, M7 and M-101 have proved to be as vigorous as the older and taller varieties.

In the later cold-susceptible stage, at meiosis, a drop in the nighttime temperatures to about 55 degrees F. can sharply increase sterility, resulting in empty grains. Cold-induced sterility, or "blanking" as it is called in California, can go as high as 40 percent in some years in some places. Hence much effort has been devoted to selecting varieties with enhanced cold tolerance. Fortunately the old variety Calrose, which had been widely grown in California, had a very good cold tolerance, and the short-stature variety Calrose 76 has proved to be still hardier. Even in the Tropics sterility in rice runs between 10 and 12 percent, which therefore appears to be a practicable lower limit. The present goal in California is to hold sterility to somewhere between 10 and 15 percent. Intensive screening for low sterility in the cool environment that prevails at the Davis Rice Research Facility has enabled breeders to achieve this goal in the newer varieties.

Until recently all California rice varieties have been either short-grain (less than 7.5 millimeters long) or medium-grain (7.5 to 8.5 millimeters). In the southern regions of the U.S. and in much of the Tropics varieties with long grains (about 9.5 millimeters) have been more popular, but they could not be grown in California because they were susceptible to cold. Over the centuries long-grain rice has evolved in the Tropics, but as rice moved into the northern regions of China and then to Japan selection for increased cold tolerance was apparently accompanied by the development of short grains. Thus most long-grain varieties have been cold-susceptible, and many short- or medium-grain varieties have been fairly cold-tolerant. Current studies indicate that there is no rigid genetic association between grain length and cold tolerance, but many

SEEDING AIRPLANES fly carefully guided patterns over the flooded rice fields, dispensing the seed at the rate of 150 pounds per acre (about 170 kilograms per hectare). The seed passes through a ram-air dispenser aboard the airplane that broadcasts the seed evenly over a band some 30 feet wide. Seed can be seen here striking the surface of the water. One plane can sow 300 to 500 acres in an eight-hour day.

years of breeding work have been necessary to undo the results of several centuries of evolution. At least one long-grain variety with improved cold tolerance is now available in California, and more varieties are expected in the future.

Short- and medium-grain rices are moist and chewy or sticky when they are cooked; long-grain rices are dry and flaky. A principal reason for these differences is the amylose content of the starch. Short- and medium-grain varieties have an amylose content of between 15 and 20 percent; U.S. long grains have one of about 24 percent. In a general way there has been an association between amylose content and grain length: short- and medium-grain varieties are low in amylose and long-grain varieties are high in it. Several studies have now shown, however, that there is no genetic basis for the association. Therefore it is possible to make a long-grain rice low in amylose, so that it will cook like a short- or medium-grain rice, and to make a short- or medium-grain rice high in amylose, so that it will cook like a long-grain rice. U.S. markets, however, are accustomed to the traditional association between grain length and texture after cooking, and so most varieties are purposely selected to preserve that association. In California the development of long-grain, high-amylose varieties has been slowed by the almost universal cold susceptibility of the long-grain gene donors. The problem is rapidly being solved by the continued breeding work for cold-tolerant long grains with a high amylose content.

Rice production calls for continuous inputs all year round. Land preparation, fertilization, pest control, irrigation, water management and harvesting must all be done at the proper time for rice production to be profitable. The rice farmer who relies on modern technology usually excels in rice production.

Efficient production begins with fields that are leveled with great precision and

SHORT AND TALL VARIETIES OF RICE are shown in an experimental planting in the Sacramento Valley. California growers have turned increasingly to short-stature varieties such as M-301, shown at the right, because it yields at least 15 percent more grain than the tall-stature varieties. Tall varieties also tend to lodge, or fall over, after reaching their maximum height.

carefully terraced along the natural contours of the land. Level fields with a slight slope, between .1 and .2 foot per 100 feet, are needed to accurately control the depth of the water while the rice is growing and to facilitate the rapid drainage of the fields at harvesttime.

Within recent years modern physics and electronics have been widely applied for land leveling. In the latest practice a rotating laser mounted on a mast is set up in the field to be leveled. The rotating laser beam provides a precise elevation reference that is detected by a receiver mounted on a tractor pulling a scraper blade. An automatic hydraulic linkage positions the blade to maintain a preselected level, including the small slope required for drainage. Several scrapers can be controlled simultaneously by a single laser. Such precision leveling is needed only for the initial preparation of the rice field.

After the initial leveling the soil is tilled by large tractors pulling disks or plows that loosen the soil and reduce the size of the clods. A final leveling is accomplished with a triplane leveler, so named because the wide blade is supported at three points: by a large wheel at each end of the blade and by a pivot at the rear of the tractor. The leveler removes or fills in any high or low areas that have developed since the initial precision leveling.

The final preparation step is the raising of levees two to three feet high for controlling the water level. The distance between the levees depends on the slope of the field. They follow the ground contours needed to achieve the desired drop of .1 to .2 foot per 100 feet. A laser beam is now often used to identify and mark the contours along which the levees are to be emplaced. Most levees are "pulled," or built up, by a specially designed tractor equipped with two sets of large disks set at an angle such that soil is piled into a continuous mound behind them. When the levees are finished, the field is ready to receive pesticides and fertilizers.

For the quick and timely application of pesticides and some types of fertilizers before seeding most growers rely on airplanes. Although nitrogen is the commonest limiting plant nutrient, for the maximum rice yield in certain areas phosphate and zinc fertilizers also must be applied. In determining the appropriate levels of plant nutrients California rice growers are guided by chemical analyses of both plant tissues and soil. In this way they can attain optimum yields with the lowest fertilizer cost and without polluting the runoff and percolating water with excess fertilizer nutrients.

Rice growers have learned that most of the nitrogen needed by their crop is best applied before planting. Dry nitrogen fertilizers such as urea and ammonium sulfate are usually applied at a rate that provides 120 pounds of nitrogen per acre. An alternate source of nitrogen is liquid ammonia. Whether the fertilizer is in dry form or liquid, it is introduced into the soil at a depth of between two and four inches. At that depth, where the ammonium-nitrogen is below the oxidation zone at the interface between the soil and the water, it remains in the reduced state and is continuously available to the roots of the growing plants. If plants show evidence of nitrogen deficiency late in the season, nitrogen can be added by airplane.

In preparation for seeding the rice fields are flooded to a depth of two to four inches, a level that is maintained throughout the growing season. The rate at which water flows into fields is controlled by weirs, or inlet boxes. The depth of the water on the fields is regulated by outlet boxes built into the levees. The source of irrigation water is usually adequate to flood a 100-acre field in four or five days.

The rice seed is first treated with a fungicide to control seedling disease and then soaked in water for 24 hours. After draining for between 12 and 24 hours the seed is immediately loaded into an airplane and is broadcast onto the flooded fields at a rate of 150 pounds per acre. The presoaking serves two purposes. It makes the grains heavy enough for them to sink as soon as they hit the water on the field and it initiates germination. Prompt germination gives the seedlings an advantage over weeds and makes them more resistant to pests.

The first three weeks after seeding are critical. Unless the seedlings become established with sufficient density in this period a maximum yield of grain cannot be attained. The seedlings must emerge completely through the overlying water and gain access to the oxygen in the air before the nutrient reserves in the seed are exhausted. The oxygen needed by the plant roots diffuses from the air through the stomata of the leaves and

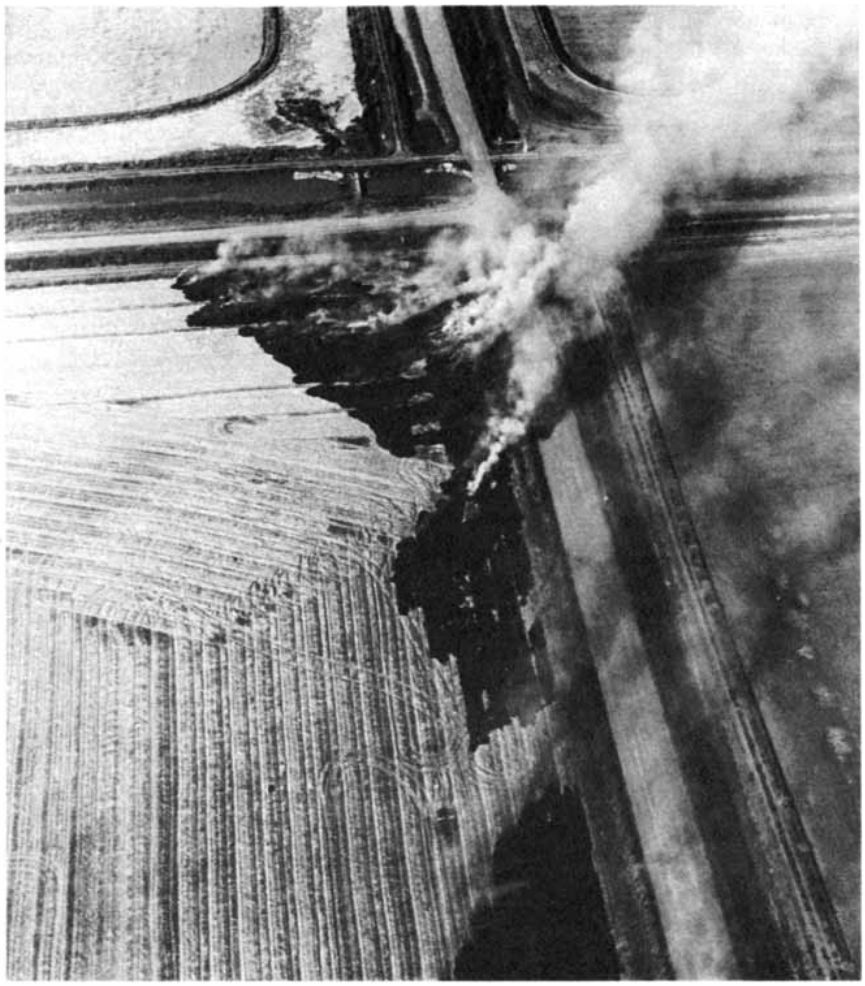
thence to the roots through intercellular capillaries.

Chemical control of weeds is essential to successful rice production. The crop's aquatic environment favors the development of infestations of aquatic weeds that can drastically reduce yield. Chemicals for fighting the infestations are readily introduced by airplane. All applications of chemicals to rice fields are subject to close government regulation, however, because of potential pollution of the surface waters that are reused repeatedly downstream. Understandably the number of pesticides, including herbicides, that are registered as being allowable for rice production is strictly limited. As a result the development of acceptable weed-control measures is one of the severer problems facing California rice growers.

Current practice combines careful water management and the limited application of herbicides. The continuous water depth of two to four inches in combination with a thiocarbamate herbicide greatly decreases infestations of barnyard grass (*Echinochloa crusgalli*), which is the most serious problem. The continuous flooding of the soil prevents infestations of sprangletop (*Leptochloa fascicularis*), which can be serious when the field is drained at early stages in the growth of the rice plant. California growers also must deal with lesser infestations by several species of broadleaf and sedge weeds. These weeds are reasonably well controlled with a phenoxy herbicide, but certain species of sedge escape the herbicides now available and substantially reduce rice yields.

Beyond controlling weeds and adding

RICE HARVESTING begins between 20 and 30 days after water has been drained from the fields. The selection of the drainage date depends critically on the maturity of the grain, on the characteristics of the particular variety of rice and on knowledge of the drainage characteristics of the particular soil. The harvesting is done by large grain combines fitted with tracks instead of rubber tires so that they can operate in the muddy soil of the rice paddy. The harvested grains are transferred on the go from the combines to rice-paddy wagons, which deliver the harvest to waiting roadside trucks. In California most of the rice is harvested between September 20 and October 20.



CONTROL OF FUNGUS DISEASES in California has depended heavily on the practice of burning the rice straw left in the fields after harvesting. Burning destroys the stem-rot fungus that would otherwise survive the winter. Concern with air pollution has now placed restrictions on the practice of straw burning. Alternative methods of controlling fungus are being studied.

supplementary nitrogen as it is needed there is little for the California rice grower to do in midseason except to irrigate and hope for favorable weather conditions in the critical period when the rice-pollen grains are forming and the plants are being pollinated. With the current California rice varieties air temperatures that are lower than 60 degrees F. or higher than 105 degrees cause the "blanking" mentioned above: they greatly inhibit the formation of rice grains. Higher cold tolerance has been developed, however, in new rice varieties.

The California crop is fairly free of the major diseases and pests that afflict most of the world's rice crops. The tropical diseases and pests, most of which are favored by humid conditions, are inhibited by the semiarid California environment. The most serious rice disease in California is stem rot, caused by the fungus *Sclerotium oryzae*. The disease usually appears during the later stages in the growth of the rice plant as small, irregular blackish lesions on the leaf sheath near the surface of the water. As the lesion progresses it enlarges and the fungus penetrates the stem, eventually causing it to collapse and lodge. Yield losses from stem rot are variable, with occasional fields suffering major damage. The fungus has been controlled by the burning of the rice straw after the harvest, which destroys the fungus that otherwise would overwinter on the straw. In the past few years increased concern about air pollution has led to restrictions on straw burning. As a result alternative methods for the control of stem rot are being investigated, including chemical control, altered cultivation practices and improved genetic resistance.

The rice water weevil (*Lissorhoptrus oryzophilus*) is a potential threat to the California rice crop. The larvae of this insect feed on the roots of the rice plant for some 50 days, starting in the seedling stage. Their feeding activity greatly decreases the volume of the roots, so that the young seedlings cannot obtain soil minerals for their growth and development. The weevil can stunt plant growth and severely reduce yields. The pest is controlled with a registered carbamate insecticide that is applied to the soil before flooding.

Another seedling pest is the tadpole shrimp (*Triops longicaudatus*), a freshwater crustacean that hatches from previously deposited eggs as early as three days after the soil has been wetted by the initial flooding of the rice field. This pest feeds on the delicate emerging coleoptile, or leaf-containing shoot, of the infant seedling and arrests the seedling's growth and development. Pesticides that control the pest are parathion and copper sulfate at relatively low concentration. Other minor rice pests in California include the rice-leaf miner, midges, armyworms and leafhoppers, all of which are controlled as necessary by the application of pesticides.

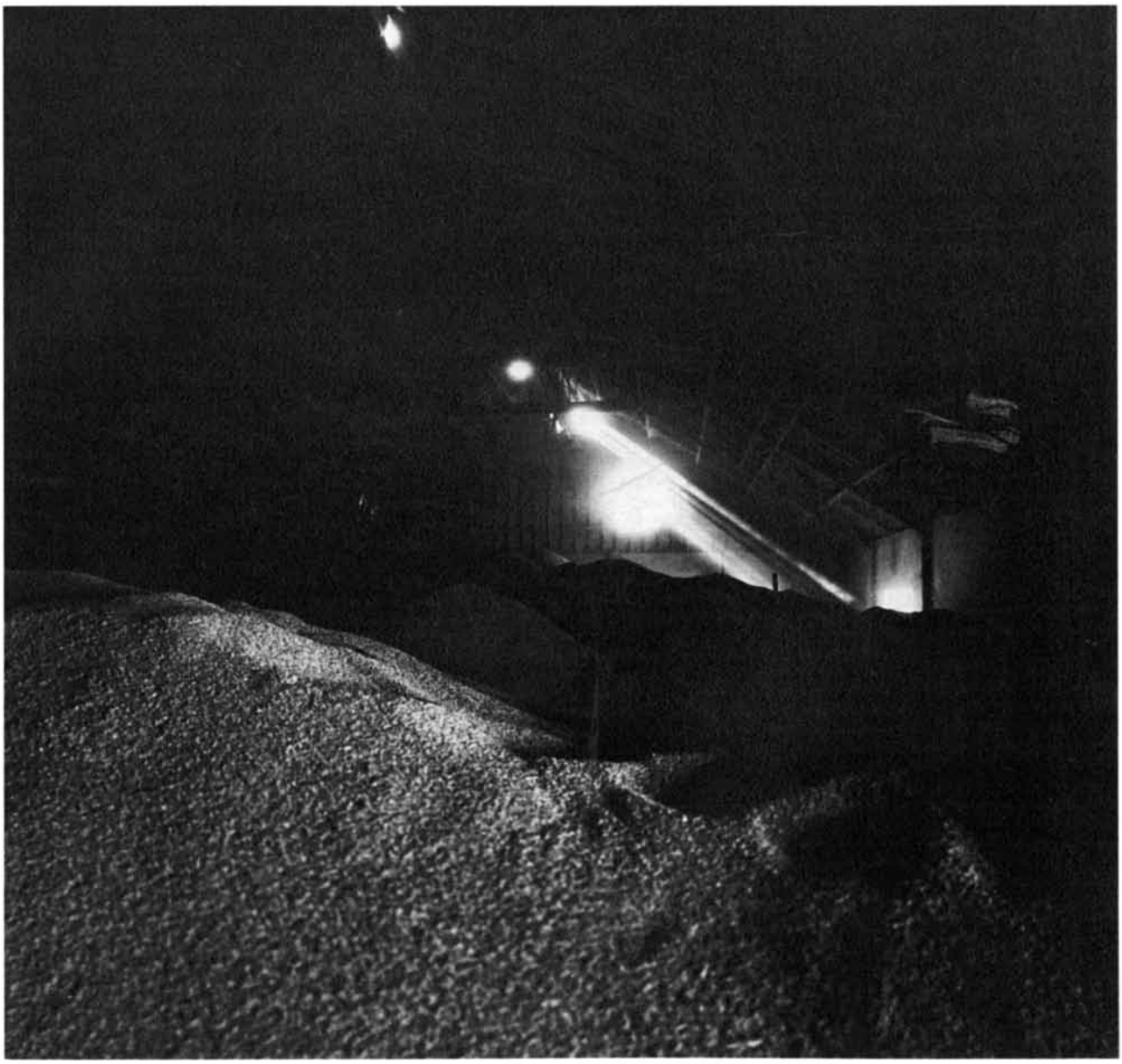
Flood water is drained from the rice fields about 20 to 30 days before the harvest. The timing of the drainage of the fields in preparation for the harvest is critical for maximum yields of high-quality rice. The fields are usually drained when the grain in the lower part of the panicle, or branching flower, is in the soft dough stage, but the exact time is determined by the stage of grain maturity, the drainage characteristics of the soil, the predicted climatic conditions and the particular characteristics of the rice variety. Draining the fields too early in relation to the maturity of the grain reduces the grain's yield and quality, and draining them too late can increase harvest costs because the soil is excessively wet and muddy.

The rice harvest in California is begun when the moisture content of the rice grain drops below 24 percent. Large grain combines are fitted with tracks instead of rubber tires to propel them through the muddy soil. The moisture of the rice must not drop below 20 percent if the maximum milling quality of the grain is to be maintained. The large spike-tooth cylinders that thresh the grain from the straw will fracture the rice grains if they are too dry when they are harvested. In addition the flux of moisture into and out of grains that are too dry can cause hairline fractures in the grain and make it susceptible to damage in the course of milling. The combines usually harvest 10 to 15 acres per day, depending on the percentage of the crop that has lodged. A rice-paddy wagon, sometimes called a bankout wagon, receives the harvested rice from the combine on the go and delivers it to trucks at the roadside. The paddy wagons are four-wheel-drive vehicles capable of operating in muddy soil. The harvested rice grain (paddy rice) is hauled

to local central dryers or to bins on the farm, where the moisture is reduced to 13.5 or 14 percent for storage and milling. The rice is stored in large centrally located commercial facilities or in bins on the farm. The stored rice must be aerated (to prevent the buildup of moisture, spontaneous heating and spoilage) until it is shipped to the mills.

Rice is milled by rotating abrasive disks that remove the outer bran layers containing most of the grain protein and fat. Brown rice is simply dehulled but unmilled rice that retains the bran layer. Rice growers are paid on the basis of the percentage of whole grains remaining after milling and the percentage of the other products of milling. The output of the mill is typically 55 percent whole-kernel (head) rice, 15 percent broken kernels, 20 percent hulls and 10 percent bran. The whole kernels are used for table rice, the broken kernels for infant cereals and brewing, the hulls for soil conditioning and chicken litter, and the bran for the production of animal feeds.

Most California rice is milled and marketed by grower-owned cooperatives, although significant amounts are handled by independent millers. The price paid to the growers is based on the total milling yield, with the highest price paid for whole milled kernels. Lower prices are paid for broken milled rice and other rice products. The price paid for rice grown in the U.S. is determined by international rice markets. Since the U.S. produces less than 2 percent of the world supply, it has little influence on total world production levels. On the other hand, when world production is low, rice prices increase dramatically. Conversely, when world production is high, the prices can drop sharply. As a result American rice growers have little control over the price they receive for their crop. Since some 60 percent of the California and U.S. rice crop is exported, however, the U.S. is a major source of the rice available for export in world markets. When catastrophic events interrupt rice production and supplies in the major rice-consuming countries, the U.S. crop is indispensable.



AFTER HARVESTING rice is delivered to drying sheds, where a gentle flow of warm air from below reduces the moisture content of the grain from the range of between 20 and 24 percent at the time of harvest to about 14 percent, the level desired for storage and milling.

The Nucleosome

The elementary subunit of chromosome structure is a DNA superhelix wound on a spool made of histone proteins. Here is a report on the discovery of the nucleosome and the determination of its structure

by Roger D. Kornberg and Aaron Klug

When chromosomes, the carriers of genetic information in higher cells, were first observed through a microscope some 100 years ago, they were seen as dense, ropelike bodies moving in two groups toward opposite poles of a dividing cell. The chromosomes could be followed as each group was incorporated in one of two daughter cells and then enclosed in a membrane-bounded nucleus. Then a strange thing happened: the chromosomes seemed to disappear! They had not, of course, really vanished. They had simply become so thin and diffuse as to be invisible in the microscope. Having been highly condensed during cell division to facilitate their movement and equipartition, the chromosomes had opened up to expose the genetic information needed for the daughter cells' growth and function.

The information in chromosomes is divided into the units called genes, many thousands of which are arrayed along the length of the chromosomal material in a typical plant or animal cell. Genes specify the structure of proteins, which in turn carry out cellular functions. These functions differ for different cell types: blood cells, liver cells, brain cells and so on. The sets of proteins each cell type manufactures are therefore different. Yet every cell of an organism contains the same genes. What differs from cell to cell and from time to time is which genes are expressed, or translated into proteins. The necessary selectivity in the expression of genetic information is accompanied by, and may be the consequence of, selectivity in the unfolding of chromosomes: only the gene regions that are being expressed in a particular cell at a particular time are maximally unfolded and exposed. The great variety of cell types is therefore reflected in an extraordinary diversity of chromosome form and structure. What is the basis of that diversity? The structural flexibility of chromosomes must account not only for selective expression but also for the inclusion, within a cell nucleus less than a hundredth of a millimeter in diameter, of chromosomal material that has a total length (in its most expanded form) of about two meters. What principles underlie that structural flexibility?

This article reports on investigations, by us and by others, from which one of those principles has emerged. Our own work was done largely at the Medical Research Council Laboratory of Molecular Biology in Cambridge over a period of some eight years, sometimes jointly but for the most part independently and at different times. We have had the close collaboration of several colleagues: Jean O. Thomas of the University of Cambridge; Marcus Noll, who is now at the University of Basel, and John T. Finch of the Laboratory of Molecular Biology. For the sake of simplicity in what follows, however, we shall for the most part take refuge in a collective "we" rather than identifying every step in the story with one or the other of us or our collaborators.

The first studies of chromosomes focused on a mystery of their composition. The chromosomes of higher cells are composed of the substance called chromatin, which consists of two kinds of chemical compound: protein and the nucleic acid DNA. Although protein is the more abundant component, all the genetic information of chromatin resides in the DNA. Why then is there so much protein? This question is made particularly intriguing by the nature of the protein. By the early 1970's it was apparent from the work of many investigators that the protein component of chromatin consists largely of just five types known as histones. The same five histones are found throughout the wide range of eukaryotic organisms (organisms whose chromatin is contained in a nucleus), from comparatively simple ones such as yeasts and molds to the most complex, including man. A major goal has been to dispel the mystery of the histones by finding out where in a chromosome they are and what they do.

The first indication of the role of histones came almost 20 years ago from X-ray-diffraction studies of chromatin carried out by Maurice F. Wilkins of King's College of the University of London and Vittorio Luzzati of the Centre de Génétique Moléculaire in Paris and their colleagues. X-ray diffraction is a technique for the study of repeating structures (for example crystals) in which a pattern of atoms or molecules is repeated over and over again in a three-dimensional array. Wilkins and Luzzati got a striking result: they found evidence for a repeating structure in chromatin. The degree of order was rather low compared with that of crystals, but nonetheless a repeat was clearly discernible. Moreover, the same repeat could be demonstrated in a mixture of histones and DNA. Analysis of the X-ray data indicated that the repeat comes at intervals of about 100 angstroms. (An angstrom unit is 10^{-10} meter, or one ten-millionth of a millimeter.)

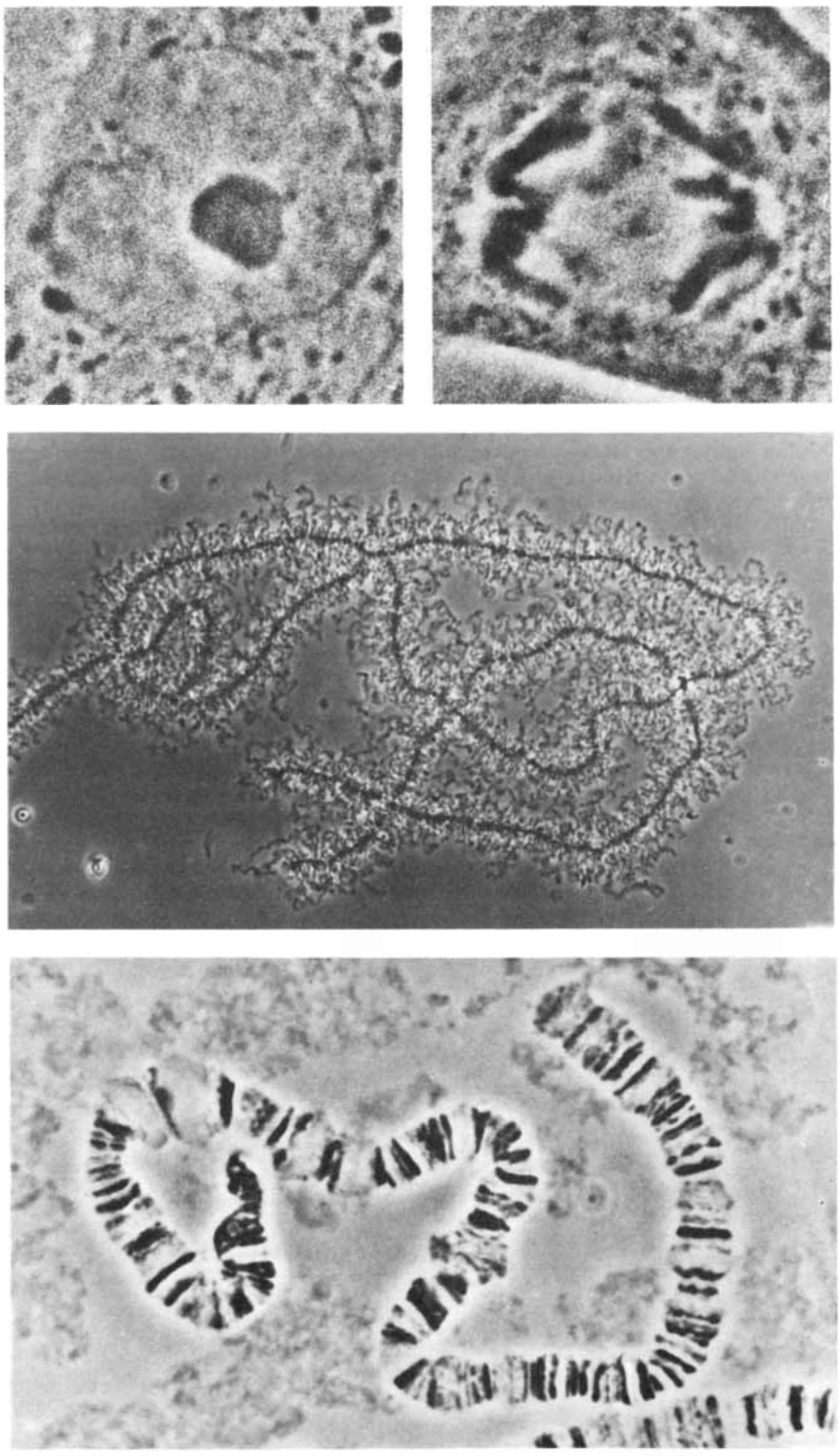
To understand this order within chromatin it is necessary to consider the structure of proteins and of DNA. A protein is a chain of the 20 kinds of building blocks called amino acids. The chain spontaneously folds on itself in a manner dictated very precisely by the sequence of amino acids. The folded structure is usually compact except for cavities or protrusions on its surface that serve as sites for binding selectively to other molecules. It is by means of such binding that a protein performs its function. For example, enzymes bind to other molecules and catalyze their chemical transformation; antibodies play a key role in the immune response by binding to any foreign substance that enters the body. Histones perform their function in chromatin by binding to DNA by means of an ionic interaction: many of the amino acids in histones are positively charged and associate with negatively charged groups in the DNA.

The consequences for the configuration of DNA are profound. DNA is long and thin; a single DNA molecule runs the length of a chromosome. The DNA molecule consists of two chains of the building blocks called nucleotides, and the sequence of the nucleotides constitutes the genetic message. The chains are wound around each other, and the

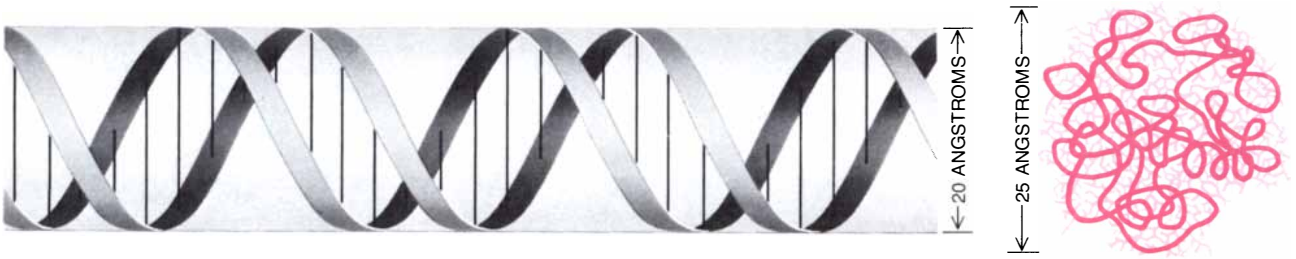
resulting cablelike double helix is fairly stiff. This slender rod has no features that recur at intervals of 100 angstroms. Yet when the DNA is combined with histones in a chromatin, a 100-angstrom repeat of structure is observed. One possible interpretation would be that histones bind to the DNA in such a way as to constrain it into a pattern of folding or coiling that has a periodicity of 100 angstroms, performing an architectural function required for the organization of DNA in chromatin.

A completely different kind of evidence leading to a similar conclusion was obtained by Dean R. Hewish and Leigh A. Burgoyne of Flinders University of South Australia in 1973, when they came on a nuclease (an enzyme that cleaves DNA molecules) in the nuclei of rat-liver cells. DNA fragments generated by the nuclease were analyzed by the technique of gel electrophoresis, in which molecules migrate through a porous matrix under the influence of an electric field. The sieving effect of the matrix sorts the molecules by size: small molecules migrate through the gel more rapidly, and thus farther, than large ones. Hewish and Burgoyne found that the DNA fragments cleaved from chromatin by the rat-liver nuclease formed a regular pattern of bands in the gel; the pattern showed the fragments were multiples of two, three, four and so on times a smallest, unit size. Such a result was in striking contrast to the uniform smear across a gel formed by nuclease-cleaved fragments of naked DNA. In other words, the rat nuclease cleaved chromatin at sites spaced at regular intervals along the DNA, whereas naked DNA was cleaved at random. Hewish and Burgoyne reasoned that the proteins in chromatin somehow confer a regular pattern of protection against nuclease, and so the proteins must be distributed in a regular manner along the DNA.

In retrospect one can see that these results from X-ray diffraction and nuclease digestion embodied the solution of the histone-DNA problem, but it was by no means clear at the time. The results raised more questions than they answered. Could both results be explained by a repeating fold of the DNA? Or were both due to a periodicity of the proteins, with no structural constraint on the DNA at all? Were the two results even related? If the answer had to do with folding, then what was the actual path of the bent rod of DNA? If proteins were responsible for the X-ray and nuclease-digestion results, were the proteins histones? If they were, were all five histones involved or only some of them? These questions were further complicated by the then current belief of many investigators that the histones were somehow responsible for the diversity of chromosome structure and gene expression. A simple repeating pattern of



CHROMOSOMES of higher organisms exhibit extraordinary diversity of structural forms. In the active cell nucleus of a rat kangaroo (*top left*), enlarged some 3,000 diameters in a photomicrograph made by Susan Stallman and Zacheus Cande of the University of California at Berkeley, the chromosomal material is in a highly extended state, diffused through the nucleus and hence unobservable. (The dark disk is the nucleolus.) In a dividing rat-kangaroo cell (*top right*) the chromosomes are highly condensed, stubby *V*-shaped objects. These two extremes of chromosome condensation can be observed in the cells of all tissues at the appropriate times. In addition there are special forms of chromosomes with strikingly different structures. Lampbrush chromosomes, seen in germ cells of many animals, represent an active form in which the genes being expressed are arrayed along loops radiating from a central axis. A lampbrush chromosome from a newt oocyte is enlarged 375 diameters in a micrograph made by Joseph G. Gall of Yale University (*center*). Polytene chromosomes are seen in the cells of larval flies. Each one consists of hundreds of copies of a single chromosome aligned in exact register. A polytene chromosome of the fruit fly *Drosophila melanogaster* is enlarged 2,500 diameters in a micrograph (*bottom*) made by George Lefevre of California State University at Northridge.



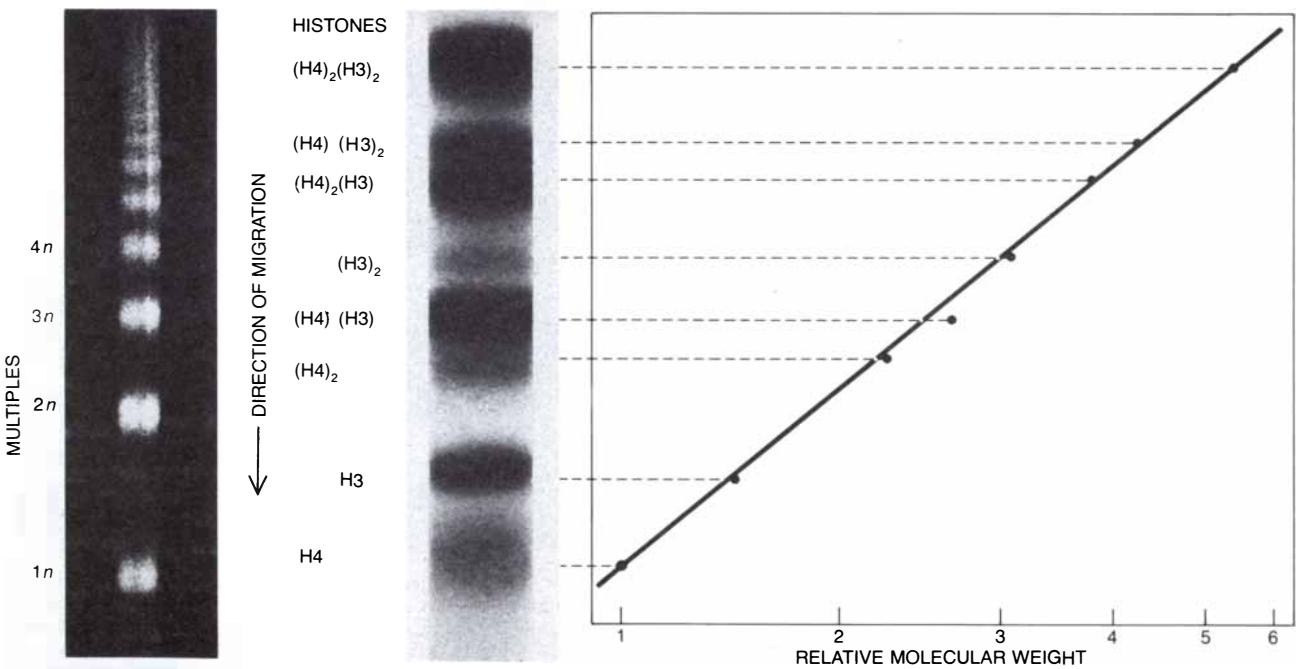
CHROMATIN, the chromosomal material in higher cells, is composed of DNA and proteins, including the five histones. The rodlike molecule of DNA is a double helix made up of two chains of nucleotides, the sequence of which encodes the genetic information; here the tubelike structure is an envelope encompassing the outermost chemical groups of the two chains. A protein (*drawn highly schematically*) is a chain of 20 kinds of amino acid subunits; the intricately folded main chain (*heavy line*) is studded with amino acid side chains.

histones along the DNA would be incompatible with such a role; it seemed more likely that different combinations of the five histones would be found in different regions of a chromosome, giving rise to a complex, highly varied structure.

Against this background of uncertainty Wilkins and his colleagues had put forward a specific proposal for a repeating fold of DNA to explain the X-ray diffraction from chromatin. They suggested that the DNA double helix is itself coiled in a larger helix with a periodicity, or distance between gyres along its length, of about 100 angstroms. The histones were thought to be involved in this "supercoil" structure, but their mode of action was not specified in any detail.

Although the supercoil model was consistent with the diffraction data, it did not gain wide acceptance. The trouble lay not in the model but rather in the paucity of the data. Many patterns of folding DNA could be imagined that recurred at intervals of 100 angstroms and so would explain the data. In 1971 F. H. C. Crick and one of us (Klug) undertook, at the Laboratory of Molecular Biology, a theoretical analysis of alternatives to the supercoil model. The other of us (Kornberg) arrived in Cambridge in 1972 and took up X-ray diffraction of chromatin in the hope that additional data would help to decide among the alternative structures. We sustained this hope for a time, always believing the next diffraction pattern would hold the solution, but one year and perhaps 100 diffraction patterns later this direct approach had brought the solution no nearer.

The X-ray effort was nonetheless fruitful because at the same time we were trying to reconstitute chromatin from DNA and isolated histones, using the characteristic X-ray pattern of chromatin to assay the degree of reconstitution achieved. The object was to learn which of the histones were involved

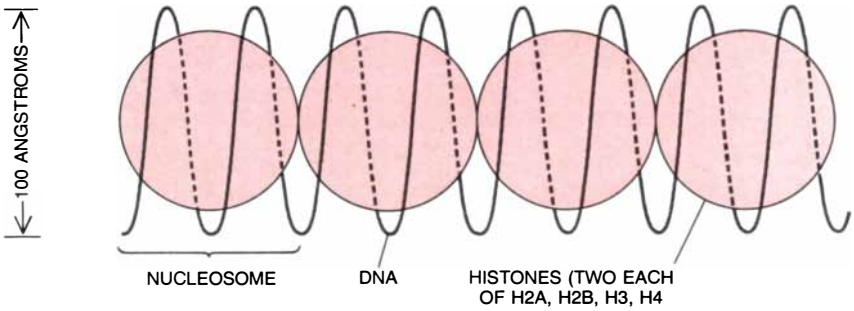


GEL ELECTROPHORESIS, which sorts molecules by size as they migrate through a gel at a rate inversely proportional to the logarithm of their molecular weight, produced early evidence for the existence of nucleosomes (*left*) and a clue to their composition (*right*). When chromatin is cleaved with a nuclease and the resulting DNA fragments are extracted and subjected to electrophoresis (*left*), the fragments form a pattern of discrete bands made visible by staining with a fluorescent dye. The bands correspond to multiples of a basic size 1*n* nucleotide pairs in length (*bottom*). The pattern indicates that the nuclease cleaves chromatin at regularly spaced sites: between nucleosomes. In a cross-linking experiment (*right*) a mixture of the two histone proteins H3 and H4 was exposed to a reagent that forms covalent bonds between the chains of a protein aggregate; unlinked products were separated with a detergent. When the cross-linked products were separated by electrophoresis and stained with a visible dye, eight bands were found, corresponding in size to the eight molecules indicated: H3 and H4 monomers and all possible stages of cross-linking of a tetramer made up of two H3's and two H4's.

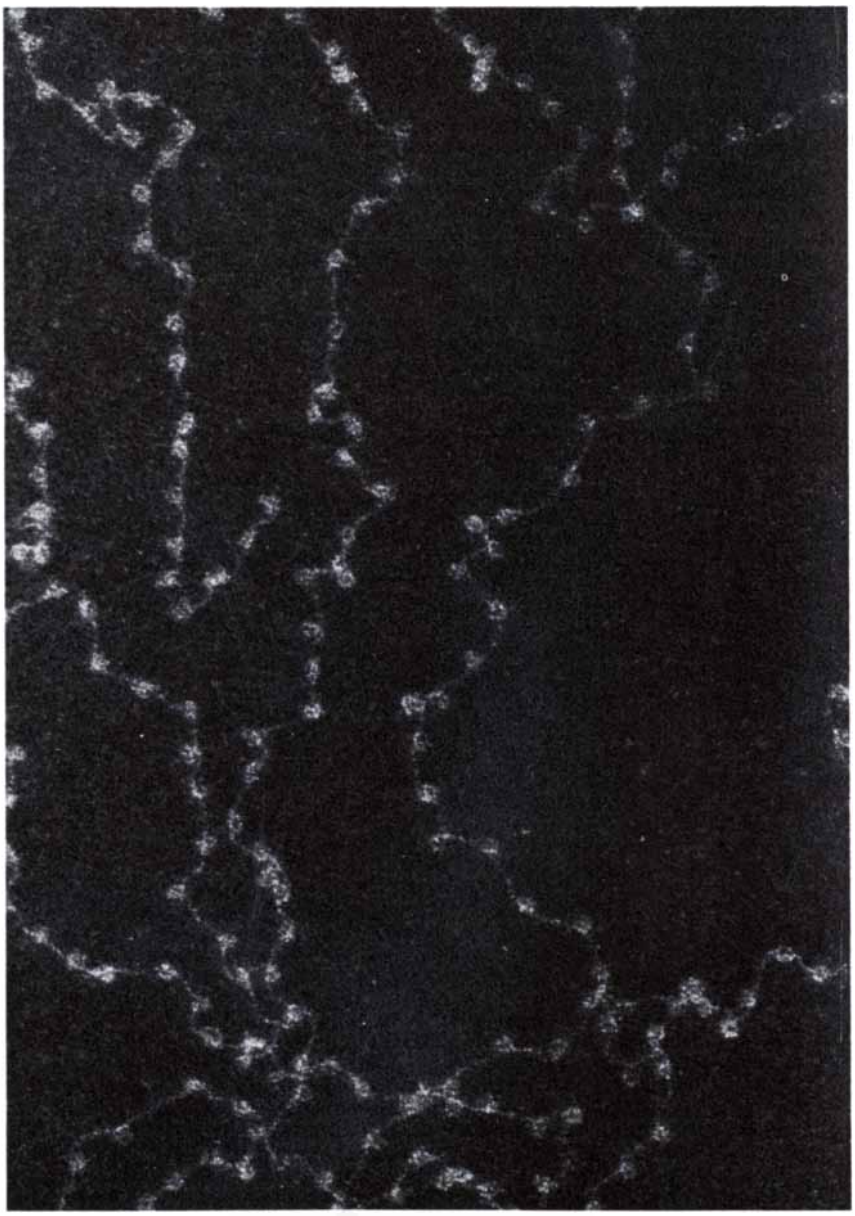
in the folding or coiling of DNA. Almost 90 percent reconstitution could be achieved when DNA was mixed with an unfractionated total histone preparation, but all attempts to reconstitute chromatin by mixing DNA with a set of all four purified single species of histone failed. We concluded that the process whereby we separated the histones was denaturing them: the compactly folded "native" conformation of the proteins, which was required for their proper functioning, was being unraveled. Clearly a milder method of histone extraction was required.

We turned to an observation made the year before by Deneys R. van der Westhuyzen and Claus von Holt of the University of Cape Town, who were trying to separate the mixture of histones obtained from chromatin into the five individual histone types: H1, H2A, H2B, H3 and H4. The separation was made difficult by the similarity of the histones to one another. They are chains of about the same length (except for H1, which is about twice as long as the others) and with a very similar amino acid composition, with about 20 percent of the amino acids positively charged and the remainder mostly neutral. The separation of the histones is further complicated by their tendency to stick to one another. The sticking can usually be overcome with concentrated acid and urea, but these reagents denature most proteins. Van der Westhuyzen and von Holt departed from the common practice, seeking to separate the histones under conditions where the native folded structure would be preserved. They filtered mixed histones through a column of porous gel particles and achieved a clean separation into two groups. A group consisting of H1, H3 and H4 was the first to emerge from the column; the second group consisted of H2A and H2B.

We were intrigued by the possible meaning of this result. In gel filtration molecules are usually separated by size because small molecules can enter pores in the gel particles, whereas large molecules are excluded, pass around the particles and move more rapidly down the column. (This is the opposite of the situation in gel electrophoresis, where the gel is continuous rather than broken up into particles, so that all molecules must pass through the gel and large molecules move less rapidly than small ones.) The behavior of histones on the gel-filtration column was surprising in that H3 and H4 moved at the same rate as H1 even though they are only half the size. The possibility came to mind that H3 and H4 naturally associate to form a dimer, or double molecule, the same size as the H1 monomer. Now, the idea of an H3-H4 dimer was not the only conceivable explanation of the results of gel filtration, nor was its significance for the structure of chromatin immediately apparent, but it represented something



ORIGINAL PROPOSAL in 1974 for the structure of the 100-angstrom-wide chromatin fiber showed successive 200-nucleotide-pair stretches of DNA wound on a series of beads: octamers composed of two molecules each of the four histones H2A, H2B, H3 and H4. At the time neither the actual shape of the histone complex nor the path of the DNA was yet known.

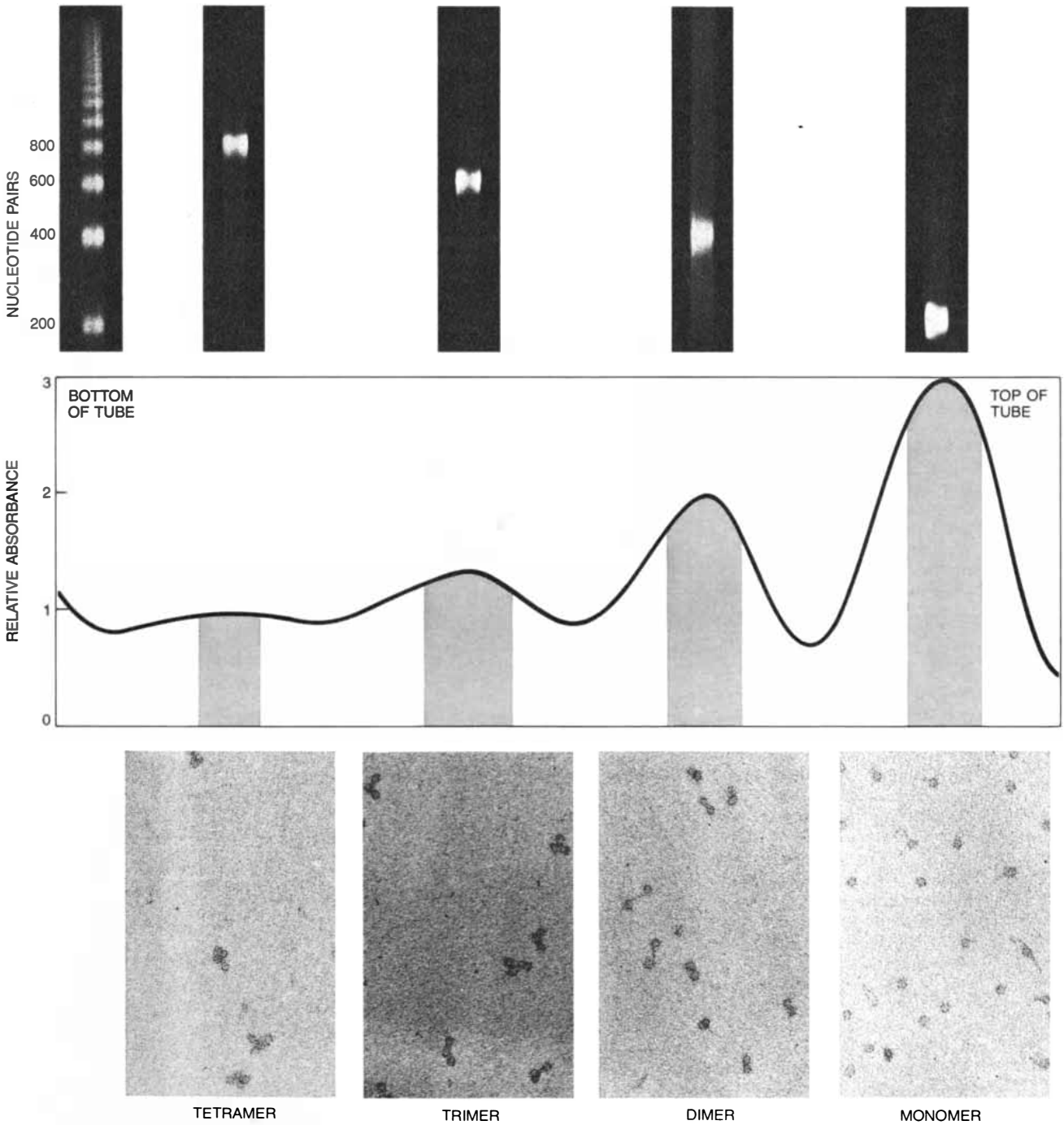


CHROMATIN FIBERS were shown to have the appearance of "particles on a string" in electron micrographs made by Ada L. Olins and Donald E. Olins of the University of Tennessee's Oak Ridge Graduate School of Biomedical Sciences. In this micrograph made by the Olinses the chromatin in a chicken red-blood-cell nucleus is negatively stained with uranyl acetate and enlarged about 325,000 diameters. The chromatin was stretched in the preparation process, increasing the distance between nucleosomes and making it easier to distinguish them.

definite at a time when there was little else to go on, and we decided to see if it was right. It turned out to be exactly half right.

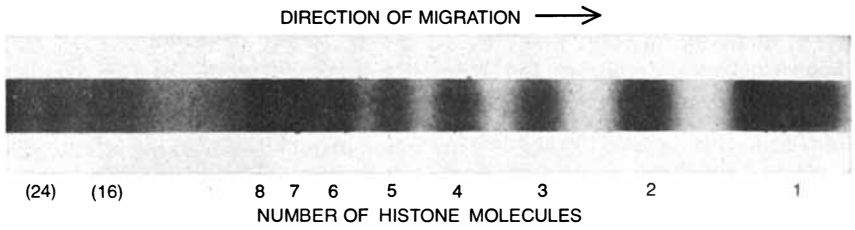
We found that the material prepared by this milder separation method was indeed functional when we repeated the histone-DNA reconstitution experiments. The H3-H4 aggregate prepared from the gel-filtration column, mixed with H2A and H2B (from the same column or from a separate experiment) and added to DNA, consistently yielded chromatin that had the characteristic native X-ray pattern.

The next step was to investigate the idea of an H3-H4 dimer, and we were joined at this stage by Jean Thomas, who was studying protein-to-protein associations by the "chemical cross-linking" method. In the most effective version of this method, devised by Gregg E. Davies and George R. Stark of the Stanford University School of Medi-

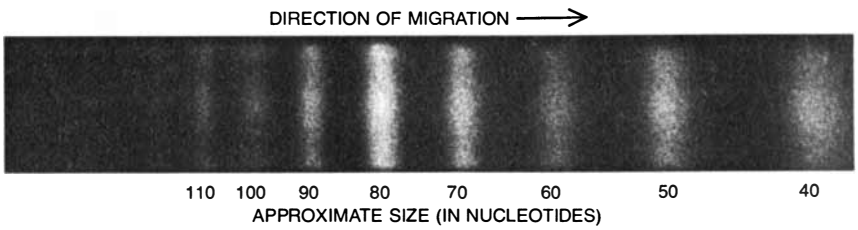


CHEMICAL AND PHYSICAL SUBUNITS of chromatin, identified respectively by biochemical analysis and electron microscopy, are shown to be identical by this experiment. The products of partial micrococcal-nuclease digestion of chromatin were fractionated by ultracentrifugation in a sucrose density gradient, which separates the histone-DNA complexes by size; four absorbance peaks were observed when the gradient was scanned with ultraviolet radiation (*center*). DNA extracted from each peak (*shaded regions*) was subjected to gel electrophoresis (*top*) on a separate track of a gel and the tracks were calibrated by comparison with the gel for an unfractionated nuclease digest (*left*). The DNA from each fraction formed a single band corresponding either to the size of a 200-nucleotide-pair unit (*right*) or to a dimer, a trimer or a tetramer of that unit. Electron micrographs (*bottom*) of material from each fraction enlarged 160,000 diameters showed single beadlike units in the lightest fraction (*right*), pairs of beads (dimers) in the next-heavier fraction and so on.

cine, a solution of protein is treated with a double imidoester reagent. Imidoesters form stable linkages to the amino groups in proteins; when a double reagent molecule combines with amino groups on two adjacent chains of a protein aggregate, a hybrid equal in size to the sum of the sizes of the two chains is formed. The hybrid can be detected by dissolution in SDS (a detergent that separates unlinked molecules of a protein aggregate and unfolds the chains from their compact configuration) followed by gel electrophoresis, in which the chains are separated according to size. We expected that imidoester treatment of the putative H3-H4 dimer and gel analysis would reveal three sizes of molecule as bands in the gel, one band corresponding to H3 and H4 cross-linked together and the other two bands due to individual H3's and H4's that had not been linked by the reagent. When we did the experiment we found, to our great surprise, not three bands but eight. These corresponded in size to H3, H4, H3-H3, H3-H4, H4-H4, H3-H3-H4, H3-H4-H4 and H3-H3-H4-H4. On reflection this could be seen to represent all the intermediate stages of cross-linking possible for an aggregate composed of two H3's and two H4's. That is, the results could be simply explained if H3 and H4 were present not as a dimer but rather as a double pair of dimers: an $(H3)_2(H4)_2$ tetramer. Further work confirmed that just such a tetramer was present.



CHROMATIN was treated with a cross-linking reagent and the cross-linked products were separated by electrophoresis. The bands show the presence of histone monomers (*1*) and all cross-linked intermediates up to the octamer (*8*). (Different histone types are not distinguished at the scale of this gel.) The result shows that the histones are strongly associated in sets of eight. Faint bands near the top of the gel probably represent dimers and trimers of basic octamer.



SINGLE-STRAND DNA fragments cleaved from chromatin with pancreatic DNA-ase I (instead of with micrococcal nuclease) and separated by gel electrophoresis form discrete bands at positions corresponding to multiples of about 10 nucleotides. The enzyme apparently can cleave only one side of the DNA double helix, whose periodicity is about 10 nucleotides per turn; the other side is protected by the nucleosome's histone core. In other words, the DNA is shown by this experiment to be on the surface of the nucleosome, wrapped around the histones.

What might the implications be for chromatin structure? The homogeneity of the tetramer (the fact that all the H3 and H4 was in the form of a single type of molecular aggregate) suggested that it was a unique unit of structure. The possible relation of the other histones and the DNA to this unit could be surmised from their amounts with respect to H3 and H4. The chromatin of most organisms has roughly equal numbers of H2A, H2B, H3 and H4 molecules, and it has about 25 nucleotide pairs of DNA double helix for each of these molecules. If chromatin were composed of many identical units, each based on an $(H3)_2(H4)_2$ tetramer, the unit would be expected to contain an octamer made up of two each of all four histones, along with about 200 nucleotide pairs of DNA.

A further implication of the tetrameric form of H3 and H4 followed from the similarity of other proteins, for example hemoglobin, the protein that carries oxygen in the blood. Hemoglobin is made up of two types of amino acid chain, designated alpha and beta. They form a tetramer: two alpha chains and two beta chains. The structures of hemoglobin and of many other multichain proteins have been determined to atomic detail by X-ray diffraction, and a striking common feature of the structures is that they are close-packed and roughly spherical in shape. They never have holes large enough to admit a molecule the size of DNA. To pursue the analogy, if the set of histones in the structural unit of a chromosome (eight histone molecules, two each of the four types) is a close-packed complex, the DNA associated with the histones must be bound on the outside of the complex; a single long DNA molecule running the length of a chromosome would pass from one set of histones, or one structural unit, to the next. The picture thus emerged of a chromosome as a chain of spherical units, rather like beads packed close together on a string.

To complete the picture one needed dimensions, and rough guesses could be made from the available information. Assuming that the chain of beads corresponded to the repeating structure revealed by X-ray diffraction, the center-to-center distance of the beads could be assigned the value of 100 angstroms from the X-ray data. A further assumption was that the chains of beads corresponded to the chromatin fibers seen in electron micrographs of uncondensed chromosomes. The thickness of these fibers was variously reported as being from 30 to 300 angstroms; it was most often about 100 angstroms, which could be taken as the diameter of a bead.

All of this was exceedingly speculative, the kind of thing one might muse about among friends but would never expose to criticism. The turning point came with the recognition that a structure organized as beads on a string could explain the nuclease-digestion results of Hewish and Burgoyne: the alternation of DNA on beads with DNA free in the regions between them could account for the regular pattern of nuclease digestion because the free DNA was more likely to be cleaved. The resulting fragments would be integral multiples of the DNA content of a bead—or, we could now predict, about 200 nucleotide pairs. This straightforward prediction of fragment size provided the first test of the beads-on-a-string idea.

The outcome was not long in doubt. There was already an indication in the technical literature. Hewish and Burgoyne had referred in their paper to a similar pattern of DNA fragments observed in a different context by Robert Williamson of the University of Glasgow. We looked up Williamson's work and found he had reported sizes for the DNA fragments that were multiples of about 200 nucleotide pairs. The agreement with the size of fragments expected from the beads-on-a-string idea was remarkably good. From this moment on it seemed the idea must be right. Proving it was another matter.

The sizes determined by Williamson were only approximate, and the relation of his DNA fragments to those studied by Hewish and Burgoyne was not clear. It was important to repeat the experiments of Hewish and Burgoyne and measure the sizes very precisely. We decided to try a method of measurement based on gel electrophoresis in which

the DNA fragments in question are analyzed alongside marker fragments of known nucleotide sequence and therefore of known size. Marcus Noll, who had just joined us, did the analysis. He obtained values of 205, 405 and 605 nucleotide pairs for the first three fragments, and so our concerns about fragment size were laid to rest.

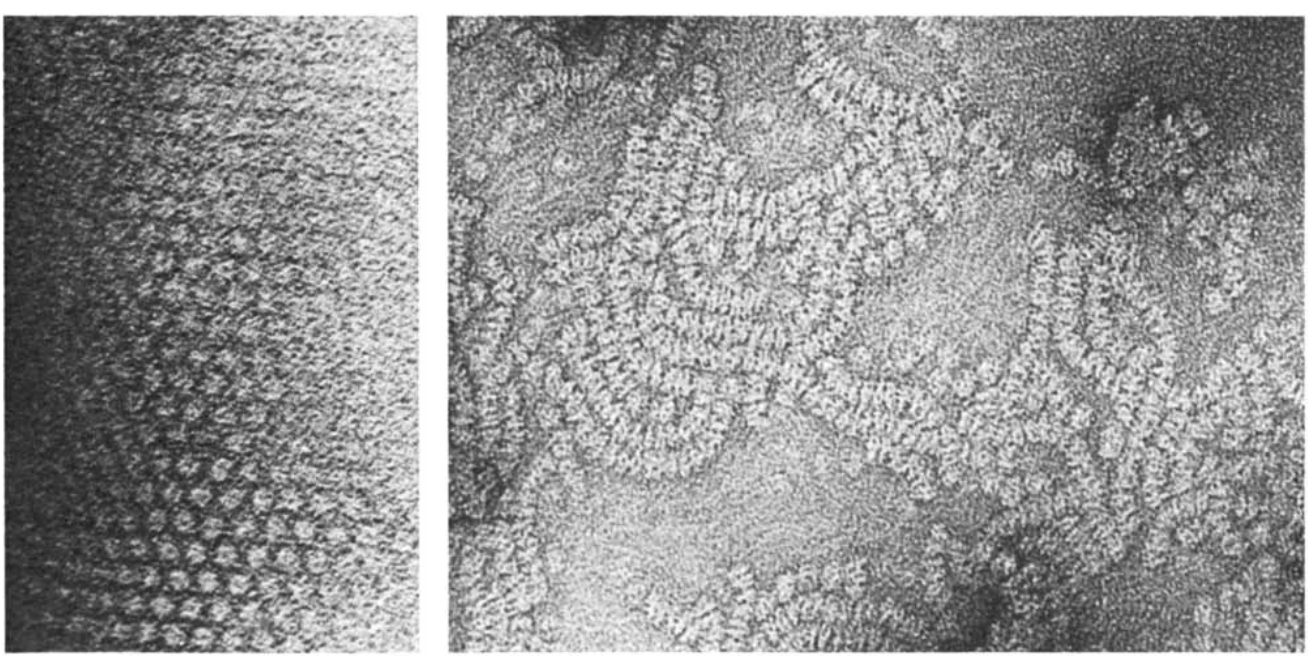
A further finding of some practical importance was that the cleavage of DNA in chromatin at intervals of 200 nucleotide pairs is not a unique property of the nuclease in rat-liver cells. The key to this finding came from the work of Gary Felsenfeld of the National Institute of Arthritis, Metabolism, and Digestive Diseases and Kensal E. van Holde of Oregon State University, who were studying the digestion of chromatin with micrococcal nuclease, an enzyme purified from the bacteria called micrococci. On extensive digestion with this nuclease about half of the DNA was fully degraded and about half was protected from degradation, persisting as lengths of roughly 100 to 175 nucleotide pairs. The protected material was in a compact, particulate form, as judged from its rate of sedimentation in the centrifuge, which was faster than it was for the same length of fully extended, histone-free DNA.

We wondered whether these particles corresponded with our beads, and so we carried out micrococcal-nuclease digestion of chromatin and analysis of the DNA fragments by gel electrophoresis. Brief digestion resulted in the same pattern of bands, multiples of a unit size of about 200 nucleotide pairs, as had been found with the rat-liver nuclease; on more extensive digestion virtually all the DNA was cleaved to the unit size (and eventually was further degraded to the smaller sizes reported by Felsenfeld and van Holde, as will be discussed in more detail below). These experiments showed that the cleavage of chromatin at sites spaced at regular intervals along the DNA is a property of chromatin structure, not of any particular nuclease. (In addition future experiments were greatly facilitated because micrococcal nuclease is commercially available, whereas the rat-liver enzyme had to be purified in the laboratory.)

At about this time we became aware of a completely independent line of work done by Ada L. Olins and Donald E. Olins of the Oak Ridge National Laboratory, C. L. F. Woodcock of the University of Massachusetts, Pierre Chambon and his colleagues at the Laboratoire de Génétique Moléculaire des Eucaryotes in Strasbourg and Jack D. Griffith of Stanford University. These investigators had improved the methods for preparing chromatin fibers for electron microscopy to the point where a clear and more or less regular substructure could be observed. The fibers appeared as linear arrays of spherical particles, about 100 angstroms in diameter, connected by thin strands of apparently naked DNA. The Olinses described what they saw as "particles on a string." Their observations made the beads-on-a-string idea a visible reality.

It was possible, of course, that the particles seen in the electron micrographs bore no relation to the 200-nucleotide-pair unit conceived from studies of histones and revealed by nuclease digestion; the connection between electron microscopy and the biochemical studies remained to be established. This connection was made first by Chambon's group and then in our laboratory. We digested chromatin with micrococcal nuclease for a time sufficient to cleave the DNA at some, but not all, of the sites between 200-nucleotide-pair units, giving rise to a mixture of individual units (monomers), pairs of the units (dimers) and chains of three units (trimers) and of four (tetramers). The mixture was subjected to centrifugation and thus fractionated, the dimers sedimenting faster than the monomers, the trimers faster than the dimers and so on.

The purity of the fractions was tested by gel electrophoresis of the DNA. The gels revealed a single band for each fraction, that of the monomer corresponding to the 200-nucleotide-pair unit's size, that of the dimer to twice the unit size and so on. When the same fractions were examined in the electron microscope, the monomer fraction showed only isolated 100-angstrom particles, the dimer fraction only pairs of particles and so on. This perfect correspondence proved the identity of the 200-nucleotide-pair units with the particles seen in the microscope. The repeat unit demon-



NUCLEOSOME CORE PARTICLES are homogeneous in size and composition, and they form good crystals. In these electron micrographs the core particles in a thin crystal are enlarged about 425,000 diameters and are negatively stained with uranyl acetate. An end-on view of columns of nucleosome cores (*left*) shows that they are hexagonally packed; the center-to-center distance (and thus the outer diameter of a core) is 110 angstroms. Columns of cores can be viewed from the side (*right*) in a growing crystal. The cores are seen to be flat, disklike, roughly bipartite objects about 55 angstroms high. They are wedge-shaped and hence tend to stack in arcs, making wavy columns.

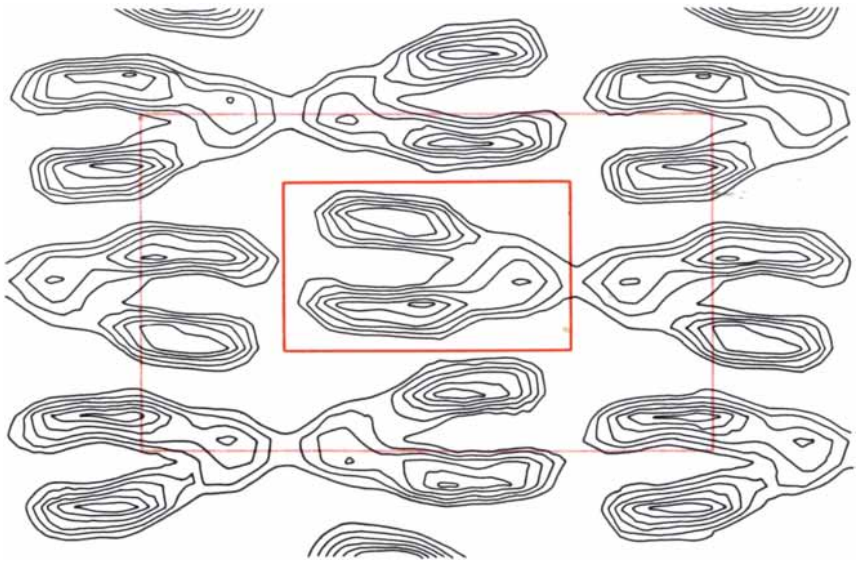
strated both by electron microscopy and by micrococcal-nuclease digestion has come to be known as the nucleosome.

The last part of the beads-on-a-string idea to be placed on a secure experimental footing was the relation to the histones. Again chemical cross-linking played an important role, but whereas previously we had been concerned with associations among histones free in solution, we now wanted to extend the analysis to histones in chromatin. For this purpose we first had to get a pure, soluble form of chromatin. This was done by subjecting cell nuclei to brief micrococcal-nuclease digestion, which released long fragments of essentially native chromatin. The next problem was that histones in chromatin are less reactive with the imidoester reagent than free histones are, and so there was not much cross-linking. That difficulty was overcome when Thomas altered the conditions to enhance the reactivity, and the result was striking: all cross-linked products up to the histone octamer were formed, but little beyond it. Moreover, the molecular weight of the cross-linked octamer was as expected for a set of two each of H2A, H2B, H3 and H4.

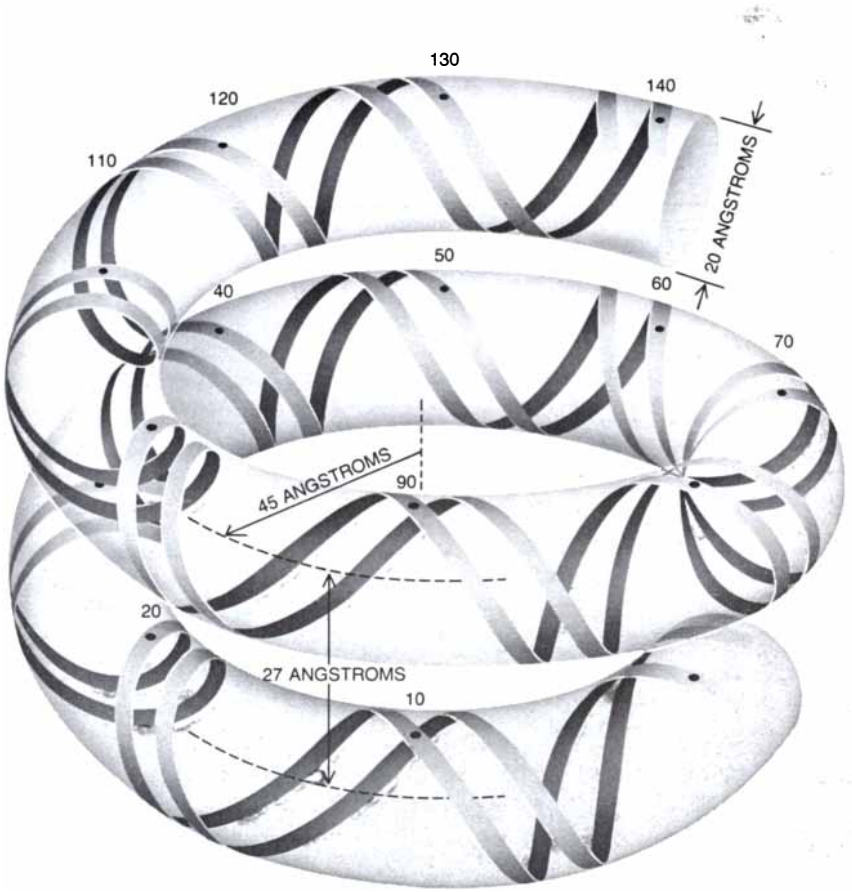
Real proof for the existence of this octamer came when it was isolated free of DNA, following dissociation of the ionic bonds between histones and DNA in solutions of high salt concentration. The isolated octamer could be cross-linked completely, giving rise to a single band on electrophoresis; it could also be demonstrated, without cross-linking, by sedimentation in the centrifuge. Finally, combined cross-linking and nuclease-digestion studies established the association of a histone octamer with a 200-nucleotide-pair unit of DNA.

The beads-on-a-string idea provided a solution to the histone-DNA problem but left open many intriguing questions. It told us there were beadlike 100-angstrom units, the nucleosomes, but left us wondering about their shape and structure. It defined the histone composition of the unit in terms of a complex of eight histone molecules but did not specify the arrangement of these molecules in space. Above all, it told us the DNA was folded compactly but gave no indication of how that folding might be achieved. Moreover, there was still the fifth histone, H1; where was it and what did it do?

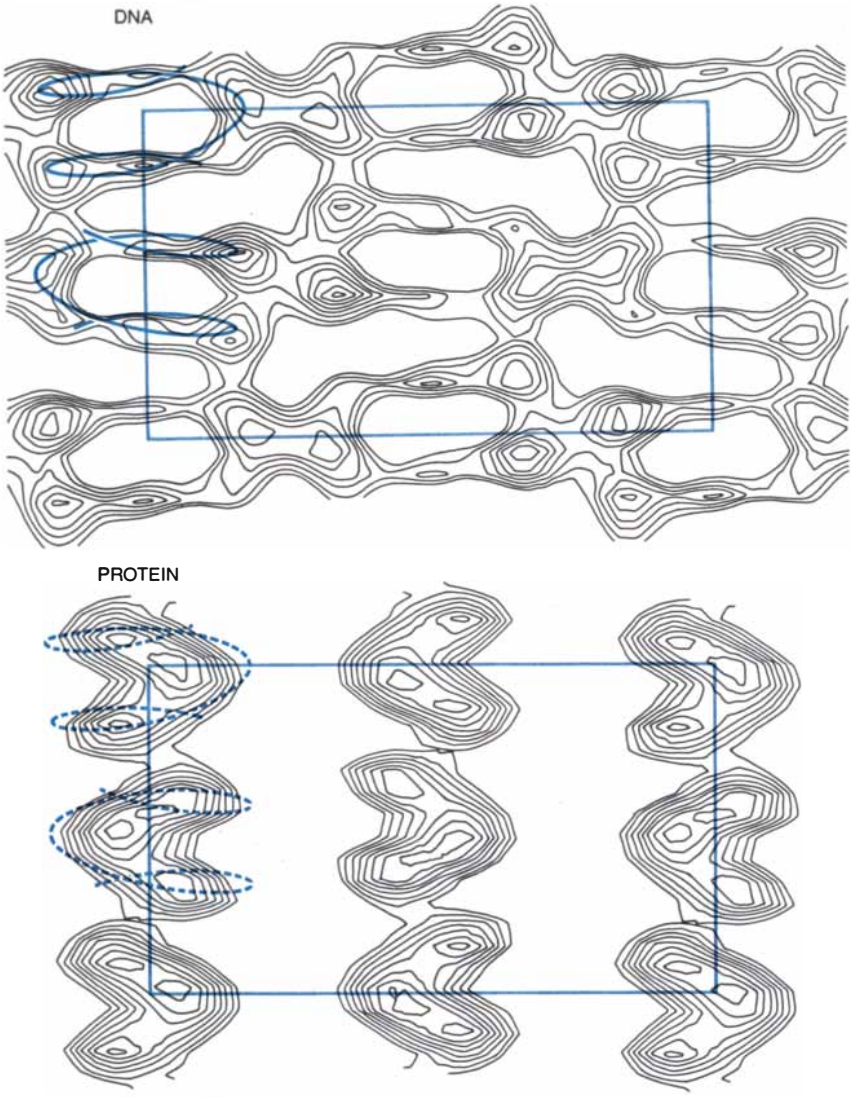
That the DNA must be folded was evident from the contrast between the small diameter of a bead, about 100 angstroms, and the length of the DNA on it: approximately 700 angstroms. This implied a degree of sharp bending, or tight coiling, that was difficult to reconcile with the well-known rigidity of DNA. One could not help but be fascinated by the question of how the his-



ELECTRON-DENSITY MAP of columns of cores seen from the side was made by combining data from X-ray diffraction and electron microscopy. What is shown is a projection of the total density in the line of view. The light-color rectangle outlines the unit cell, or repeat unit, of the crystal. The map resolves elements more than 20 angstroms apart. The density of each particle (*dark-color rectangle*) is seen to be divided roughly into two halves, reflecting the wedge shape.



PATH OF DNA that can account for the bipartite structure of the nucleosome core is a superhelix with an external diameter of 110 angstroms and a pitch of 27 angstroms; the turns of the 20-angstrom-wide DNA helix are nearly in contact. There are about 80 nucleotide pairs of DNA per turn; the nucleosome core, an enzymatically reduced form of the nucleosome consisting of some 140 nucleotide pairs, has about one and three-quarter turns wrapped on it.



NEUTRON-SCATTERING MAPS show separately the density of the DNA (*top*) and of the protein (*bottom*) in a nucleosome-core crystal. The DNA density correlates well with the projection of about one and three-quarter turns of the DNA superhelix (*dark color*). The DNA superhelix also appears to fit well (*broken colored line*) around the protein, the histone octamer.

tones mediated this bending or coiling, and many imaginative mechanisms were proposed—practically every mechanism but the right one.

The focus therefore shifted from trying to identify the role of the histones in folding the DNA to trying to determine the path followed by the DNA, and thus from biochemistry to X-ray crystallography. Even in the absence of crystallographic evidence we were confident of one thing about the DNA's path: it must be on the outside of the histones. The most graphic display of this fact came from the digestion of chromatin not with micrococcal nuclease (which does not cleave DNA on a solid surface very efficiently and therefore cleaves it primarily between nucleosomes) but with pancreatic DNA-ase I, which readily cleaves one strand of the double helix on a solid support.

The initial observation, made in our laboratory by Noll, was that cleavage by DNA-ase I produced single-strand fragments that fell into a repeating pattern on a much finer scale than the products of micrococcal-nuclease digestion. The series of electrophoresis bands corresponded to DNA sizes that were integral multiples of about 10 nucleotides. (Later it was shown that they are multiples of 10.4 nucleotides.) The simplest interpretation of this observation is that the digestion is confined to one side of the DNA at a time (the approach of the enzyme to the other side being hindered by the presence of the histones) and that each strand of the DNA is therefore alternately exposed and protected with the periodicity of the double helix: about 10 nucleotides per turn. In other words, the DNA-ase I digestion results can be explained if the DNA lies on the surface of the nucleosome, wrapped around the histones.

These observations confirmed our earlier proposal (based on the notion that the histones form a close-packed globular complex) that it is not the histones that coat the DNA but rather the DNA that coats the histones. Indeed, it would be truer to say the basic chromatin fiber is a string on beads rather than beads on a string. Evidence of a different kind that the DNA is on the outside of the nucleosome came from neutron-scattering experiments carried out by John F. Pardon, Brian M. Richards and their colleagues at the Searle Research Laboratories and later confirmed by E. Morton Bradbury's group at the Portsmouth Polytechnic. This work showed the DNA to be farther from the center of the nucleosome than the protein is.

Approaches such as nuclease digestion and X-ray scattering in solution reveal certain features of the nucleosome, but a full description of the structure can come only from crystallographic analysis, which gives complete three-dimensional structural information. In the summer of 1975 we therefore set about preparing nucleosomes in a form suitable for crystallization.

Because nucleosomes purified from the products of micrococcal-nuclease digestion do not all contain exactly 200 nucleotide pairs of DNA, they do not crystallize. (This size heterogeneity arises because cleavage by the nuclease between nucleosomes is not confined to a single site but can take place over a fairly broad stretch of DNA.) The variability in size can be eliminated by carrying the process of micrococcal-nuclease digestion beyond the stage of cleavage between nucleosomes. The further digestion removes DNA from both ends of the nucleosomes, consistently yielding particles containing a defined length of DNA: about 146 nucleotide pairs. This enzymatically reduced form of the nucleosome is referred to as the core particle; the DNA removed by prolonged digestion, which previously had joined one nucleosome to the next, is called the linker DNA.

A collection of core particles is homogeneous not only in the size of its DNA complement but also in its protein composition, since each core particle possesses the full set of eight histones (two each of H2A, H2B, H3 and H4) but has lost virtually all other components of chromatin, including—and this is particularly significant—the fifth histone, H1. Eventually our colleague Leonard C. Lutter found a way to produce exceptionally homogeneous preparations of nucleosome cores, and these formed good single crystals. In our laboratory Daniela Rhodes, Ray Brown and Barbara Rushton have over the years grown crystals of core particles prepared from

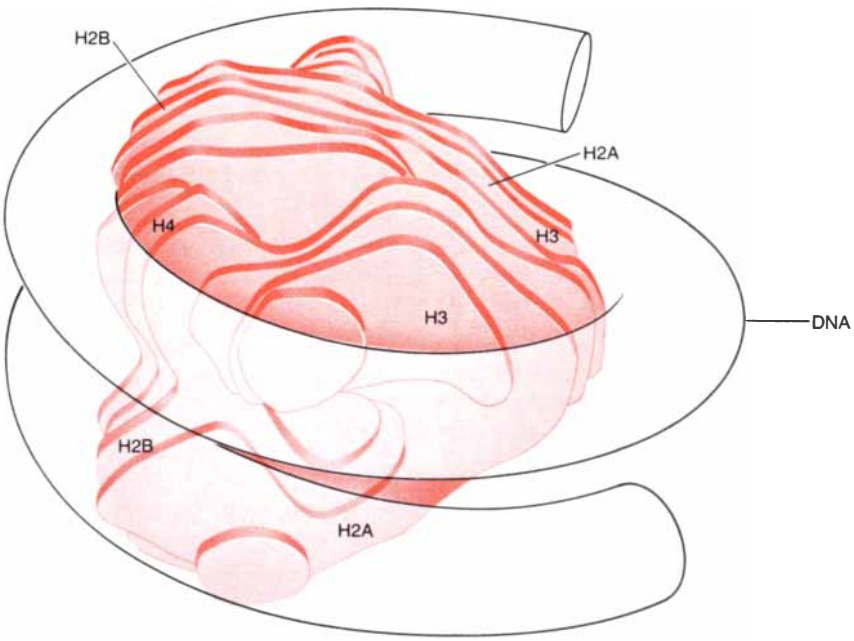
seven different organisms. All the crystals give essentially identical X-ray patterns, testifying to the universality of nucleosomes. Indeed, the success of this crystallization proves that the great majority of the nucleosomes are identical in structure throughout a chromosome. The idea that most of the DNA in chromosomes is in a regular repeating structure would have been almost unbelievable 10 years ago, when it was commonly thought variation at the level of the histones would account for the diversity of chromosome structure and gene expression.

The derivation of a three-dimensional structure from a crystal of large molecules is a laborious process that may take many years. We therefore concentrated on obtaining a picture of the nucleosome core particles at low resolution by a combination of X-ray diffraction and electron microscopy. This gave an overall picture of the structure of the particle and so provided a solution to an important question: How is the DNA coiled in the nucleosome?

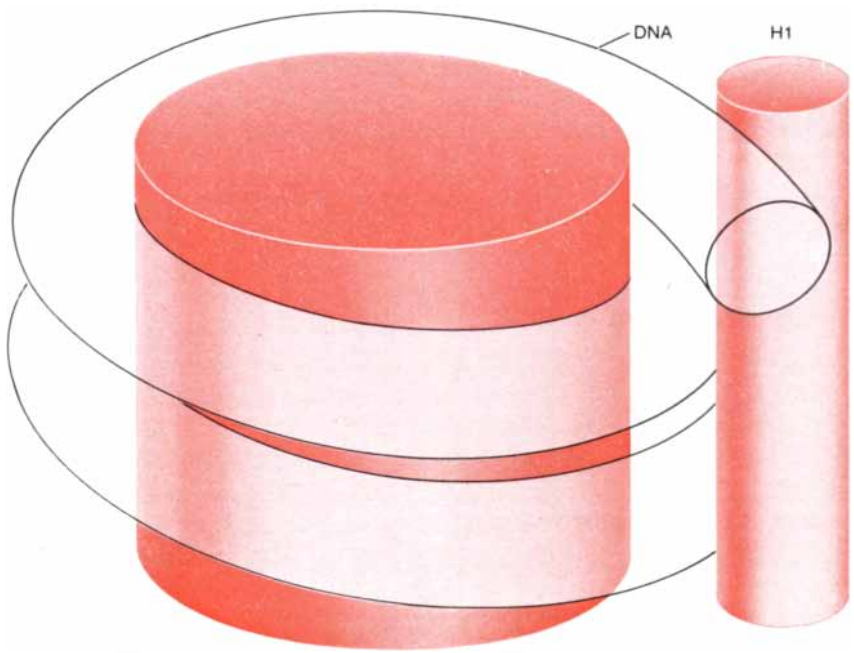
An electron micrograph of one face of a thin crystal of nucleosome cores shows a hexagonal array of round objects about 110 angstroms in diameter, which is about right for a nucleosome. The appearance arises from nucleosome cores stacked on one another to form columns whose width, determined more accurately from X-ray measurements, provides us with the value for the external diameter of a nucleosome. An electron micrograph of a crystal made at a right angle to the first view would give a side view of the columns, but because the columns overlap, individual columns and nucleosome cores cannot be distinguished. The individual columns are best seen in growing crystals before they have begun to pack in many layers. These side views have the appearance of a stack of plates or disks about 55 angstroms high. From the wavy nature of the columns it is evident that the plates are not perfectly flat; they are wedge-shaped, rather like the keystone of an arch. The nucleosome core, then, is shaped more like a short cylinder, about 110 angstroms in diameter by 55 angstroms high, than like a sphere.

To get more detailed information from electron micrographs it is necessary to do X-ray diffraction of the crystals themselves and to apply various image-processing and reconstruction techniques developed in our laboratory over the past 15 years. These procedures exploit the repetitive nature of the crystal to produce an image of the genuine features that repeat from particle to particle; "noise" in the micrographs and variations in the packing of the nucleosomes are averaged out over the array of particles. Distortions in the structure of individual particles (which arise during the preparation and staining of the particles for electron microscopy) are eliminated with the help of data from X-ray diffraction of the crystals. X-ray and electron-microscope data are thus combined to produce a detailed contour map of the density of electrons in the crystal. This is the kind of map normally produced by X-ray crystallographers working with smaller proteins, but here we have called on electron microscopy to help map these larger and more complicated structures.

In this way maps showing three dis-



MODEL OF NUCLEOSOME CORE was made by winding a tube simulating the DNA superhelix on a model of the histone octamer, which was built from a three-dimensional map derived from electron micrographs of the histone octamer. The ridges on the periphery of the octamer form a more or less continuous helical ramp on which a 146-nucleotide-pair length of DNA can be wound. The locations of individual histone molecules (whose boundaries are not defined at this resolution) are proposed here on the basis of chemical cross-linking data.



ROLE OF FIFTH HISTONE, H1, is suggested by this model of the full nucleosome rather than the core particle. Two full turns (166 nucleotide pairs) of the DNA superhelix are wound on the histone octamer, represented schematically in this drawing as a drumlike object. The H1 molecule (whose actual shape is not yet known) is attached to sites on the particle at which DNA enters and leaves the nucleosome; in effect the H1 "seals off" the complete nucleosome.

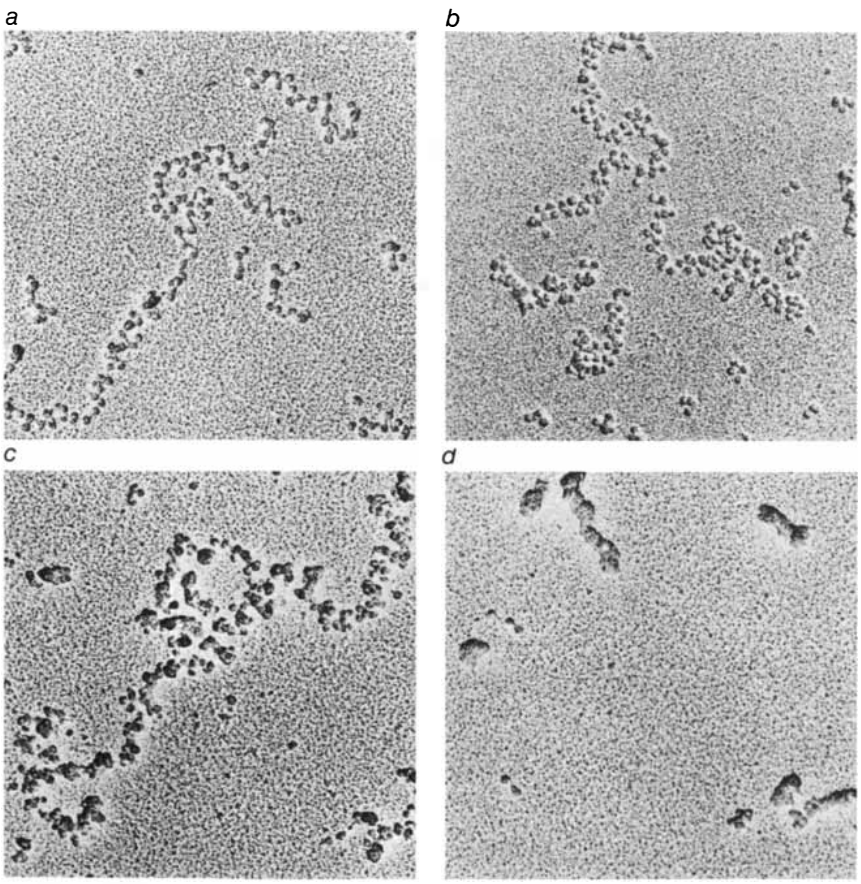
tinct views, or projections of electron densities along the three principal axes of the crystals, have been obtained. The most informative of the maps is the one of the view perpendicular to a column in a direction in which the overlap of columns is minimized [*see top illustration on page 59*]. The wedge shape of a nucleosome core particle is apparent, and the density appears to be divided into two roughly symmetrical halves (such as would be consistent with a twofold axis of symmetry lying close to the plane of projection).

The simplest arrangement of DNA that would account for this bipartite structure is one in which the DNA double helix is coiled into a larger helix, or superhelix, that makes about two turns around the histones in the middle of the particle. The two turns of the superhelix must nearly touch, since the diameter of the DNA helix is about 20 angstroms and the height of the particle is only 55 angstroms. One can calculate from the structure of the DNA double helix and the diameter of the core particle that two superhelical turns would have about 160 nucleotide pairs. The length of DNA in a core particle is only 146 pairs, however, or enough for one and three-quarter turns. Because that falls short of two turns the particle will be thinner on one side, in part accounting for the wedge shape.

The resolution of the maps described above was only 22 angstroms, that is, two features separated by much less than 22 angstroms are hard to distinguish from each other. Higher resolution can be achieved only by resorting to more sophisticated "isomorphous replacement" methods, and that effort is under way in our laboratory. Moreover, these first maps gave the total density of the nucleosome; the density of the DNA was not distinguished from that of the protein. To separate the contributions of the protein and the DNA we turned to the scattering of neutrons at low resolution by means of contrast variation. This method has been applied to solutions of large molecules that have two components of different density, for example viruses (which contain nucleic acid and protein) or cell membranes (which contain protein and lipid). The basis of the technique is to match the density of the solvent to the density of one of the two components, so that the scattering from only the other component is observed. This is done by mixing ordinary water and heavy water (water in which the hydrogen is the heavy isotope deuterium) in various proportions. When the solvent is 39 percent heavy water, the scattering from the solvent is equal to the scattering from the protein, so that the neutrons in effect "see" only the DNA; with 65 percent heavy water the scattering from the DNA is matched by that from the solvent and the scattering observed is from the protein alone.

The method of contrast variation had already been applied to nucleosome core particles by other workers, as was mentioned above, but the particles were in solution, where they are in random orientation, and so only one-dimensional information was obtained. In our neutron-scattering studies of nucleosome core particles we have examined crystals, and so we have been able to determine the relation of protein to DNA in three dimensions. Neutron scattering is weak and requires large single crystals. These were grown in our laboratory and then the experiments were carried out by Finch and by Graham Bentley, Anita Lewit and others at the Institut Laue-Langevin in Grenoble. They obtained projection maps of the DNA and the protein separately [*see illustration on page 60*]. The map of the DNA confirms the earlier conclusion about the DNA's path based on electron-micrographic and X-ray analysis. The map of the protein shows that the histone octamer itself also has a wedge shape, as would be expected if the histones form a short helical ramp to which the DNA is bound.

An alternative to separating the contributions of the DNA and the protein by neutron diffraction is to physically remove the DNA and study the histone octamer directly. The octamer can be isolated and kept stable in solutions with a high salt concentration, as was described above, and we have been trying to crystallize this isolated octamer in order to make a full structure determination. These attempts have so far been unsuccessful, but in the course of the work we obtained very regular fibers. We studied these ordered aggregates in the electron microscope and processed the images essentially as was described above for the nucleosome-core crystals. Because of the particular geometry of the aggregate one image contains views of the octamer from many different directions. These views were combined by a method, introduced in 1968 by David J. DeRosier and one of us (Klug), in which a map of a three-dimensional



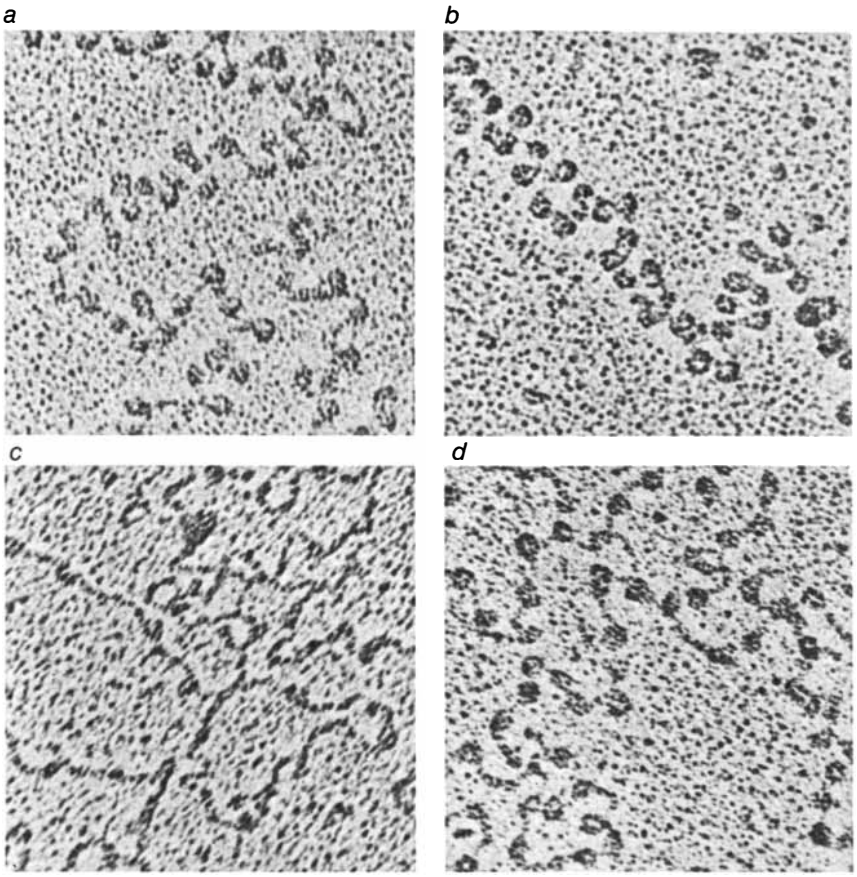
CONDENSATION OF CHROMATIN with increasing salt concentration is demonstrated in electron micrographs made by Fritz Thoma and Theo Koller of the Swiss Federal Institute of Technology. At a very low salt concentration (*a*) chromatin forms a loose fiber about 100 angstroms thick: nucleosomes connected by short stretches of DNA. At a concentration with an ionic strength closer to that of normal physiological conditions (*d*) chromatin forms a thick fiber some 250 to 300 angstroms thick. The origin of this "solenoid" can be deduced by examination of chromatin at increasing intermediate ionic strengths (*b*, *c*). It arises from a shallow coiling of the nucleosome filament. The chromatin is enlarged here about 80,000 diameters.

structure is derived from a set of two-dimensional projected images.

This structure of the octamer embodies in three dimensions what was seen in the various projections of the nucleosome core particle obtained from X-ray and neutron diffraction, in particular its wedge-shaped and bipartite character. The shape shows it is the histone octamer that constrains the DNA to follow the superhelical path described above; it is the octamer that determines the architecture of the nucleosome.

The resolution of the octamer map is too low to define the individual histone molecules, but we have exploited the relation of the octamer to the superhelix of DNA to interpret the map in terms of individual histones. This interpretation takes into account both histone-to-histone cross-linking results and chemical cross-linking studies between histones and DNA carried out by Andrei D. Mirzabekov and his colleagues at the Institute of Molecular Biology in Moscow. They located specific sites along the DNA superhelix that interact with each of the four types of histone. By following the path of the DNA in our nucleosome model we assigned these sites to regions of the octamer map and so arrived at an arrangement of the eight histone molecules in three dimensions.

From this spatial arrangement one can deduce the roles of the individual histones in folding the DNA on the nucleosome. The $(H3)_2(H4)_2$ tetramer defines the central turn of the DNA superhelix. H2A and H2B add as two (H2A)(H2B) dimers, one on each face of the tetramer, each binding additional DNA and completing the superhelix. This structure explains the finding by many workers that H3 and H4 alone, in the absence of H2A and H2B, can confer nucleosomelike properties on DNA, whereas H2A and H2B alone cannot.

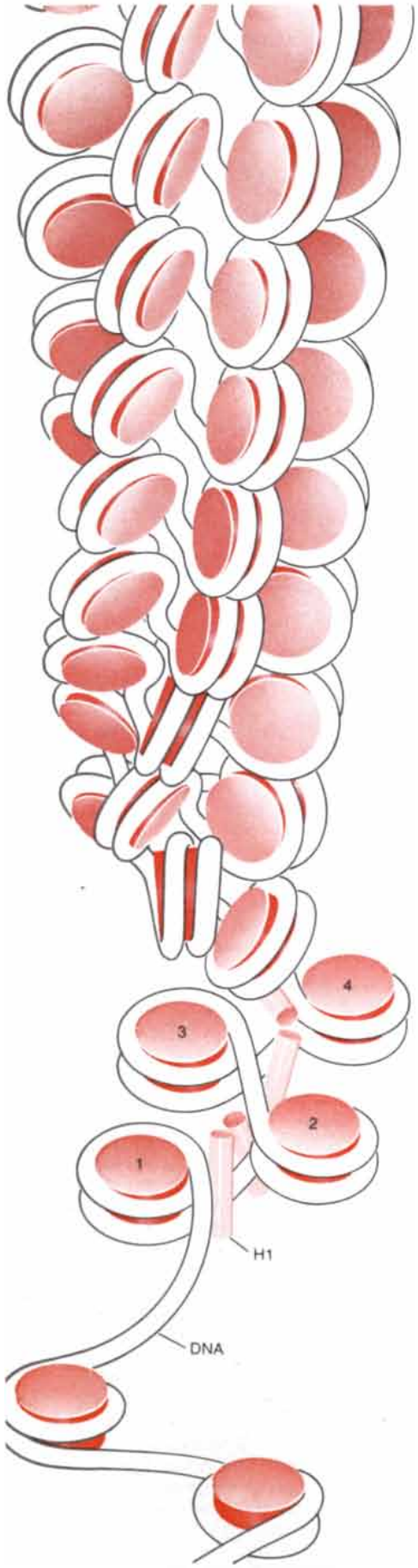


LOCATION OF H1 and its role in chromatin structure are indicated by a comparison of the appearance of fibers with and without H1 at intermediate ionic strengths. With H1 present the first recognizable ordered structure at a low salt concentration is a loose zigzag (*a*), which arises because the DNA enters and leaves the nucleosome at sites close to each other (and because the nucleosomes tend to settle on the supporting grid on their flat faces). At a somewhat higher concentration (*b*) the zigzag is tighter. In the absence of H1 (*c*, *d*) chromatin shows no such ordered structure; indeed, at the low salt concentration (*c*) the nucleosome opens up, producing a fiber of DNA coated with histones. These observations suggest that H1 lies on one side of the nucleosome, stabilizing the DNA. The enlargement is about 200,000 diameters.

All of this gave a fairly detailed picture of the internal structure of the nucleosome but still no clear idea of the relation of one nucleosome to another along the nucleosome chain, the basic chromatin fiber. To understand the relation between successive nucleosomes it is necessary to consider again the digestion of chromatin by micrococcal nuclease. As was described above, when micrococcal-nuclease digestion is continued beyond the point of cleavage between nucleosomes, further DNA is removed and the nucleosomes are converted into core particles. On examining this conversion in detail we noted a pause at an intermediate stage where the length of the DNA was 166 nucleotide pairs; it is during the degradation of that intermediate to the final 146-nucleotide-pair nucleosome core particle that the H1 falls off. Since the nucleosome core particle consists of two symmetrical halves it is reasonable to expect the conversion from 166 nucleotide pairs to 146 would come about by the removal of 10 pairs from each end of the nucleosome DNA. This suggests that H1 is associated with the ends. Moreover, the 166-nucleotide-pair particle contains two full superhelical turns of DNA, which brings the two ends as close together as they can come, so that it is possible for a single molecule of H1 to be bound simultaneously to both ends of the DNA of the two-turn nucleosome. We therefore reasoned that the H1 would be on the side of the nucleosome in the region of the entry and exit of the DNA superhelix.

H1 is clearly an accessory protein in the sense that it is on the outside of the nucleosome and is not essential for the coiling of the DNA on the core particle. The function of H1 has to do with the further condensation of the chromatin fiber. There had been indications over the years that H1 was somehow involved in the condensation of chromatin, but the level at which H1 performs this function was not known. Hans Ris of the University of Wisconsin had shown that fibers observed in electron-microscope studies of whole chromosomes had a diameter of either about 100 angstroms or about 300 angstroms, depending on whether chelating agents (which sequester metal ions) were present in the preparation. The 300-angstrom fiber had been variously interpreted as being a single coiled-up 100-angstrom fiber or two 100-angstrom fibers lying loosely side by side.

To resolve that ambiguity we found conditions under which the two kinds of fibers could be interconverted. In electron micrographs of 100-angstrom fibers undergoing this conversion it could be seen that they coiled up on themselves to form a 300-angstrom-wide helix with five or six nucleosomes per turn, in which successive turns came close together, so that their center-to-center distance was about 100 angstroms. We called the 300-angstrom structure a solenoid. (Parallel X-ray experiments sug-



gested it was this spacing between turns of the solenoid, rather than the center-to-center distance between nucleosomes along the chromatin fiber, that gave rise to the characteristic 100-angstrom X-ray reflection.) We also showed that H1 mediated the folding of the 100-angstrom fiber to form the 300-angstrom solenoid: when the experiments were repeated with chromatin depleted of H1, no ordered structures with a definite fiber path were formed, only irregular, condensed clumps of nucleosomes. The solenoid, although ordered, may not be completely regular because it probably has to fold or coil in some way when chromatin is condensed still further.

More refined experiments of a similar nature were carried out by Fritz Thoma and Theo Koller of the Swiss Federal Institute of Technology. They showed that the simple 100-angstrom fiber—a filament of nucleosomes in a loose, linear array—is found only at very low ionic strength, when chromatin is in its most extended form. As the ionic strength is increased the fiber changes from a loose nucleosome filament to a zigzag structure and eventually to the solenoid. These experiments led us to a specific proposal for the way in which the H1 molecule mediates the coiling of the 100-angstrom filament into the 300-angstrom fiber.

The zigzag appearance of the intermediate form arises because the DNA enters and leaves a nucleosome at sites close together on the same side of the nucleosome. This is where H1 is bound, and in the zigzag intermediates the H1 regions of adjacent nucleosomes appear to be close together or touching. With increasing ionic strength the H1 regions would form a helical polymer, giving rise to the geometrical form of the solenoid. Polymers of H1 have indeed been shown, by chemical cross-linking experiments, to exist; it remains to be demonstrated that they play the postulated role. The important point is that the aggregation of H1 accompanies, and may control, the formation of the solenoid.

HELICAL SUPERSTRUCTURES might be formed with increasing salt concentration (*bottom to top*) as is suggested here. The zigzag pattern of nucleosomes (*1, 2, 3, 4*) closes up, eventually to form a solenoid, a helix with about six nucleosomes per turn. (The helix is probably more irregular than it is in this drawing.) Cross-linking data indicate that H1 molecules on adjacent nucleosomes make contact. Extrapolation from the zigzag form to the solenoid suggests (but does not prove) that the aggregation of H1 at higher ionic strengths gives rise to a helical H1 polymer (*not shown*) running down the center of the solenoid. In the absence of H1 (*bottom*) no ordered structures are formed. The details of H1 associations are not known at this time; the drawing is meant to indicate only that H1 molecules contact one another and linker DNA.

With this proposal for the mode of formation of a 300-angstrom fiber we have gone about as far as it is possible to go on the basis of well-established facts. To take stock of the extent to which the condensation of DNA into chromosomes is now understood one can adopt as a quantitative measure the packing ratio: the ratio of the length of DNA in the fully extended state to its length in the coiled or folded state achieved at any stage of condensation. The formation of the two-turn nucleosome, for example, compresses 166 nucleotide pairs of DNA with a length of about 600 angstroms into a coil 55 angstroms high, for a packing ratio of about 10. The further helical coiling of this chain into the solenoid of the 300-angstrom fiber increases the packing ratio by a factor of about five, yielding an overall packing ratio of about 50. This is to be compared with a packing ratio of about 5,000—100 times greater—that is observed in the most highly condensed chromosomes during cell division. Clearly one can make models involving further coiling or looping of the 300-angstrom fiber to attain this highly condensed form, but as yet there is no definite information to support any of the many possible choices.

What has been learned is how the histones, ubiquitous and abundant proteins of the nucleus, form the core of an elementary subunit of chromosome structure. They transform the problem of the condensation of DNA from the intractable one of packing a stiff wire cable—the DNA molecule—to the more straightforward one of winding the cable on a spool and then packing identically wrapped spools.

The histones are not directly involved in the expression of genetic information, but they may facilitate the changes in chromosome structure that attend selective expression, when the genes of the chromosomes are transformed into an active state. Although little is known about that transformation, it has recently become clear that active chromatin still has histones attached to it; even more striking, the nucleosomal repeat periodicity is maintained. There are indications from several laboratories that active chromatin contains, in addition to the histones, some particular nonhistone proteins that somehow modify the structure of the nucleosome to an opened-out form. One line of evidence for this is that active chromatin is more sensitive to nucleases such as DNA-ase I. Here we are just at the beginning of another step in the story.

At this point one is in effect sitting in a darkened theater, having seen the first act and the interplay of the main characters: the DNA and the histones. The full cast has not yet appeared; no one knows quite how the plot will unfold.

On photography, the three Rs, and articulateness

That right-brain/left-brain business has become fashionable doctrine. Vast numbers of words are spilled about it. Those words are mostly spilling out of the left sides of brains, if we understand the doctrine itself, which we may not. We feel more comfortable making judgments in the field of chemical engineering than in neuroanatomy or psychology. We would steer quite clear of this subject but for the fact that the major product of our chemical engineering finds one of its uses in preparing children for adulthood.

In pre-TV days little was spent on special help for kids who were finding it especially hard to learn how to read and write. It was assumed they would be making their way with their muscles. That has become very hard to do. So special arrangements are made. Oddly enough, the special classes consist mostly of little boys. Whatever the adult result, development schedules in the brain seem to differ between the sexes in childhood.

If Albert Einstein were eight years old now, he might well be in one of those classes as a non-intellectual despite latent power enough in the spatially reasoning right side of his brain to discover special relativity. Little Albert did it without TV stimulating that nonverbal right brain. Classmates similarly slow in the left sides of their heads would tend to turn into young men whose every statement will sound more or less alike because they will have too few words (and even fewer mathematical equations) with which to express their thoughts.

The schools and the traditions of scholarship favor the user of words. If overexposure of children to the pictures on the tube is causing the trouble and is too hard to prevent, pictures, *if under control of the child himself,* are seen by many educators as also the cure.

Overcoming verbal handicap is the price of admission to the world as now constituted, where writing advertisements for large companies beats felling large trees by hand axe. To help overcome it, photography is used in many schools to transfer strength from the overstimulated right brain to the underdeveloped left brain, even if the educators who offer evidence of the effectiveness of their techniques for doing this do not all rely on brain-splitting to explain their results.

Though the use of photography to encourage literacy in children represents a very small part of our business and probably always will, we have plenty of material to send you about the techniques and the evidence. It may help in confrontation with taxpayers who claim that a hickory stick works better than a camera for driving the three Rs into young heads.
Write Jim Sucy, Education Markets, Kodak, Rochester, N.Y. 14650.

Kodak

SCIENCE AND THE CITIZEN

C^3

Three decades of progress in the development and deployment of nuclear weapons by the U.S. and the U.S.S.R. have had the primary if unintended effect of reducing the national security of both countries. Perhaps nowhere is this central paradox of the strategic arms race clearer than it is in the concerns currently being voiced in the U.S. about the perceived vulnerability of the land-based Minuteman force of intercontinental ballistic missiles (ICBM's) to a preemptive attack by the U.S.S.R. As defense analyst Joel S. Wit points out elsewhere in this issue (see "Advances in Antisubmarine Warfare," page 31), the Russians have, if anything, greater reason to be concerned about the long-term survivability of their strategic deterrent forces in the event of a preemptive attack by the U.S.

The technological advance that has played the most important role in this new epidemic of national insecurity has been the development—first by the U.S. and later by the U.S.S.R.—of multiple independently targetable reentry vehicles (MIRV's). Increasingly accurate MIRVed warheads on both sides are expected eventually to make the present generation of fixed land-based ICBM's obsolete. The American answer to this largely self-inflicted dilemma is presumably going to be some version of a mobile missile system.

The enormously enhanced destructive capability created by the advent of MIRV's, however, has exposed a much greater vulnerability on both sides of the strategic balance. Arms-control advocates have argued for some time that the weakest link in the deterrent system is the information network connecting its parts—referred to in military circles as command, control and communications (or C^3). The overriding importance of C^3 vulnerability was acknowledged by the Carter Administration in its announcement last summer of a set of presidential directives that incorporated, in addition to a controversial new "countervailing," or flexible-response, targeting policy, an increased emphasis on the destruction of Russian C^3 centers and the protection of American ones.

Critics of the apparent change in policy represented by the presidential directives maintained at the time that the new targeting options were more likely to undermine the deterrence of limited nuclear war than to achieve the stated objective of strengthening it. In particular, it was said, preparations to attack Russian strategic forces, including C^3 centers, would presuppose the launching of such a "counterforce" attack in the early stages of a nuclear war. By putting the strategic forces on both sides on a "hair trigger" the new policy would encourage rather than discourage escalation to an all-out nuclear exchange.

Moreover, according to the critics, attacks on C^3 centers would only make it harder to terminate a nuclear war once one broke out. Even threatening such attacks could have the adverse effect of inducing each side to give its military commanders special instructions to fire at will if their ability to communicate was degraded. Instead of planning to attack C^3 centers, therefore, it would make more sense for both sides to avoid such attacks, even if the other side were to deliberately or accidentally launch a first strike.

The renewed concerns about C^3 vulnerability and seemingly contradictory U.S. plans to deal with the problem were summed up in an issue of *F.A.S. Public Interest Report,* the monthly newsletter of the Federation of American Scientists. In calling for a wider discussion of the C^3 vulnerability problem the F.A.S. suggested several "tentative conclusions." First of all, the newsletter said, "we should improve the survivability of our C^3 to the point where it does not tempt attack in crises as a way of neutralizing our entire strategic force. But we ought not talk of attacking Soviet command and control lest we simply encourage the Soviet Union to devolve nuclear authority in advance on ever more junior officers. Further, we ought not, in fact, launch such attacks, unless *our* command and control is attacked, lest we lose all chance of war-termination.... We ought not kid ourselves that we are prepared to fight a protracted nuclear war when no plausible improvement in C^3 is likely to permit it; countervailing strategies with numerous complicated options that cannot, in fact, be carried out could become an expensive kind of self-delusion."

Sunflower Boom

The cultivated sunflower, which 10 years ago was an insignificant factor in American agriculture, has now become a major commercial crop, ranking second only to soybeans as a source of vegetable oil. In 1970 sunflowers were grown commercially on a few thousand acres, largely for products other than oil. In 1980 some four million acres were planted to sunflowers, and most of the crop went into oil. The rise of the sunflower during the decade is described in *Agricultural Research,* a publication of the U.S. Department of Agriculture.

Two types of sunflower are grown commercially. One is the confectionery or nonoil type, which grows to a height of from eight to 12 feet and produces seeds that are gray or white with gray, brown or black stripes. The largest seeds are roasted and sold as snack food; the smaller ones are put into feed for birds and poultry. The size of this sunflower crop has remained about the same for many years.

The oilseed sunflower accounts for the great expansion of the crop after 1970. It grows to a height of from six to eight feet and has black seeds. The seeds are crushed so that the oil can be extracted; the yield is not only a vegetable oil of high quality but also a meal that is high in protein and can be fed to animals. The oil is employed in making such products as margarine, salad oil and cooking oil. It also serves in the manufacture of paints, varnishes and plastics and even as a mix of from 25 to 50 percent in diesel fuel. The production of "sunoil" amounted to 5.6 million tons in 1979–80.

Sunflowers are grown over a wide area. The heaviest plantings are in the Red River Valley of North Dakota and Minnesota. Much of the land was once planted to flax, the market for which has declined as latex paint has increasingly replaced oil-based paint. Flaxseed oil was one of the principal oils used in such paints.

The expanding role of sunflowers as a commercial crop has motivated workers at the Department of Agriculture's Russell Research Center in Athens, Ga., to study the effects of planting location and temperature on the average oil content of the flowers and their fatty-acid composition. They found that temperature and latitude had no significant effect on the oil content, which ranged from 37.6 percent at Rio Bravo in Mexico to 51.8 percent at Brooksville, Miss. Both temperature and latitude affected the fatty-acid composition. Sunflowers planted before June 1 at a latitude of 39 degrees north or higher generally had a linoleic acid content of 60 percent or more, whereas in plantings below 39 degrees the content of linoleic acid was less than 60 percent.

James A. Robertson, a research chemist at the Russell Research Center, explained the significance of the fatty acids in sunflowers. "They are regarded as essential in human and animal nutrition," he said. "Linoleic acid, a polyunsaturate, is thought to be generally desirable for people with heart disease or high blood pressure. It lowers both blood pressure and blood cholesterol. Oil from commercial sunflower varieties has been found to have a linoleic acid content ranging from 31.4 percent

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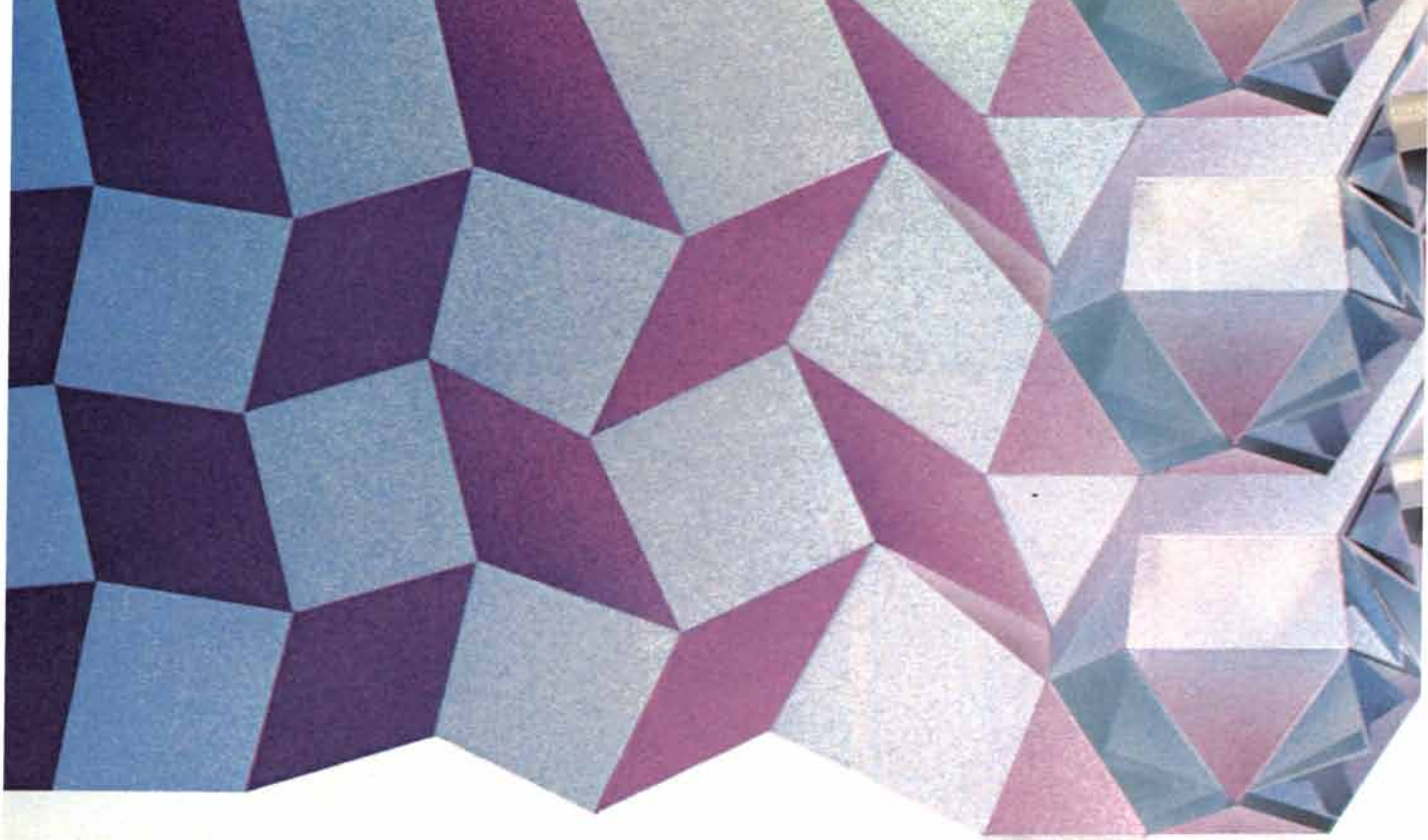

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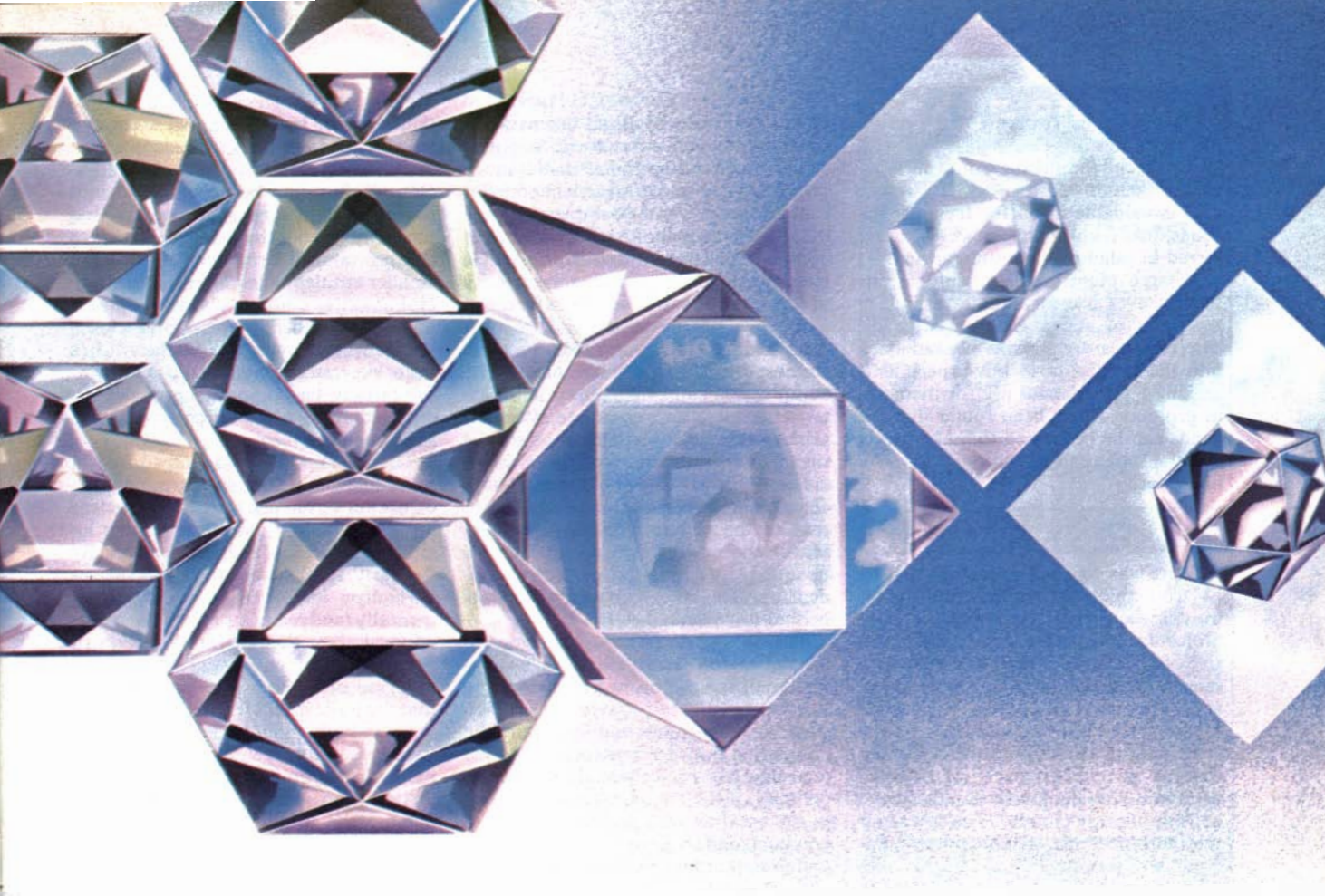

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for plantings in Texas to 75.5 percent for plantings in Canada. Differences in fatty-acid composition afford varied uses of sunflower oil. Lower linoleic acid is valuable in oil for frying snack foods, and high linoleic acid oil is preferred in salad oils and margarine."

A large plant grown mainly for its seeds leaves a considerable residue in the form of stalks and flower heads. The residues are mostly plowed back into the ground now, but experiments seeking a commercial use for them are in progress. It has been found that the heads can be processed to make pectin and the stalks can be shredded to make fiberboard.

Cosmic Cradles

There was no single moment when astronomers first realized that the almost invisible nebulas known as giant molecular complexes are the most massive objects in the galaxy. Instead a consensus came some two or three years ago, after two discoveries had been made. First large-scale surveys of the galaxy for the presence of carbon monoxide in interstellar space had detected carbon monoxide in loci with the shape of vast, clumpy clouds. Then it was established that interstellar carbon monoxide is more or less coextensive with other molecules (notably molecular hydrogen) and also with cosmic dust. Radio astronomy now detects the presence in the clumps of 54 different types of molecule, including ammonia, alcohol and formaldehyde.

A typical giant molecular complex is taken to be 50 parsecs (1.5×10^{15} kilometers) in diameter. Its content of cosmic dust and molecules is taken to constitute a mass as great as several hundred thousand times that of the sun. The complex is dark: it dims the light of the stars inside it and behind it along a line of sight from the earth by a factor of 10^{20} and more. In addition the complex is cold: the relative intensities of its spectral lines at radio wavelengths make it possible to calculate that its temperature is no greater in most places than 20 degrees Kelvin. At such a temperature the hydrogen molecules emit no detectable radiation. It is the emission of the carbon monoxide at a characteristic wavelength of 2.6 millimeters that reveals its full extent. According to Leo Blitz of the University of California at Berkeley, some 4,000 giant molecular complexes lie less than 13,000 parsecs from the center of the galaxy, a distance that includes much of the galaxy's visible matter. Blitz considers them to be cosmic cradles because the ones closest to the solar system have all been places of birth for stars, including the most massive and most luminous stars in the galaxy.

The history of a giant molecular complex, as outlined by Blitz, begins when the complex condenses from the interstellar medium: the thin distribution of dust and gas that permeates interstellar space. What drives the complex together may be the arrival of a galactic wave of compression, transmitted from particle to particle, which increases the density of the interstellar medium by a factor of as much as 10. The existence of the wave is posited by a theory in which the wave creates the galaxy's spiral arms. The compression causes the atoms in the interstellar medium to coalesce into molecules. The dust particles become the sites on which the more complex molecules assemble. The molecules absorb electromagnetic radiation in the visible part of the electromagnetic spectrum. Hence the newly formed cloud grows opaque. At visible wavelengths it is evident only because it conceals the stars behind it.

The cooling of the complex begins to disrupt it soon after it forms. In particular, small regions in the complex begin to cool, and the self-gravitation in each such region becomes dominant over the countering outward pressure due to the heat that had been there. The resulting collapse of the region is thought to end in the creation of a nodule of mass so compact, and so greatly reheated by the collapse, that thermonuclear fusion begins. The nodule is now an incipient star.

The largest of the nodules become the largest, brightest stars: the blue-white supergiants. At first their radiation, which peaks in the ultraviolet, does no more than simply ionize the hydrogen nearby. The result is the transformation of a part of the giant complex into a highly luminous cloud—an emission nebula—with the newly born stars in its meshes. Each quantum of the radiation carries momentum, however, and so it pushes whatever absorbs it. The nearby matter of the giant molecular cloud is compressed along a shock front, and there a new group of stars will form.

Meanwhile the pressure of the ultraviolet radiation has begun to dissipate the emission nebula. In effect the gas is blown away by the stars that made it glow. In some 30 million years the complex itself will be dispersed. The reason is the same. Only between 3 and 5 percent of the molecular gas in the complex is converted into stars; the rest goes back into interstellar space. In 100 to 200 million years a compression wave returns. Perhaps the entire cycle repeats.

Inside the Quark

Atomism, the ancient doctrine that the world is constructed out of indivisible units of matter, has been abundantly confirmed by the physics of the 20th century, but at the same time it has been profoundly subverted. Atoms certainly exist, but it is equally certain they are not indivisible. An atom can be broken down into a nucleus and a surrounding cloud of electrons; the nucleus in turn can be decomposed into protons and neutrons; it appears that the proton and the neutron are also composite structures, made up of the smaller entities called quarks. Now several tentative and speculative proposals could extend this progression of wheels within wheels one stage further. It has been suggested that the quarks themselves may be composite particles assembled from a few simpler or more fundamental objects.

The quark model was introduced in order to explain an alarming population explosion within one class of subnuclear particles: the hadrons, the class that includes the proton and the neutron. By the early 1960's more than 100 species of hadron had been observed experimentally (and many more have been discovered since then). This profusion of apparently elementary particles caused a degree of unease; it seemed unlikely that the basic bricks from which the universe is built should come in so many varieties. It also seemed odd that while the hadrons proliferated, the other major family of particles, the leptons, remained quite small: the only known leptons were the electron, the muon and the neutrinos.

The quark model accomplished a vast simplification: all the known hadrons could be accounted for as combinations of just three kinds of quark. Equally important to the success of the model, every allowed combination of quarks corresponded to a known hadron. Most of the properties of a hadron could be predicted by adding up the properties of the constituent quarks. For example, the proton, with an electric charge of $+1$, consists of three quarks with charges of $+2/3$, $+2/3$ and $-1/3$.

A major virtue of the quark model is its economy of means. The only constituents of matter regarded as elementary are the quarks and the leptons, and from the outset it was perceived that the two families might be closely connected. They are both small families, at least when compared with the sprawling clan of the hadrons. Moreover, all quarks and leptons have one vital property in common: they invariably have an intrinsic spin angular momentum of $1/2$ unit. It must also be conceded that the quarks and the leptons differ in important ways. Whereas the quarks are assigned fractional electric charges, the leptons all have integer charges ($+1$, -1 or 0). Moreover, leptons appear as free particles, but no one has yet extracted a quark from the interior of a hadron. In spite of these differences efforts are under way to devise a theory that would subsume both quarks and leptons in a single larger family.

The recent speculations on the possi-

bility of a still deeper level of structure do not aim at replacing the quark model; rather, they are attempts to explain its organization. The speculations derive from a growing worry that the model may be showing symptoms of the very disease it was meant to cure. In recent years the number of quarks and leptons has been growing steadily.

The three quarks of the initial model were labeled by three "flavors." It soon became apparent that each flavor must come in three "colors," so that the number of distinguishable fundamental objects was tripled. ("Flavor" and "color" are arbitrary labels that have nothing to do with the usual meanings of those words.) Additional flavors have since been discovered, and again each appears in three colors. A total of five flavors have definitely been observed (they are called up, down, strange, charm and bottom) and the existence of a sixth flavor (top) is all but certain. Meanwhile the family of leptons has also been expanded and is now thought to include six particles. Three of the leptons carry an electric charge: they are the electron, the muon and the new particle designated tau. The other three leptons are uncharged neutrinos, one kind of neutrino being associated with each charged lepton. Hence the complement of seemingly elementary particles consists of quarks in six flavors and three colors, for a total of 18 quarks, plus six leptons. Each of these 24 particles also has an antiparticle, and so a theory that would embrace all of them must have room for at least 48 distinct forms of matter.

It has become customary to arrange the quarks and leptons in three "generations" of sibling particles. The first generation is composed of the up and down quarks, the electron and the electron-type neutrino; the second generation takes in the strange and charm quarks, the muon and the muon-type neutrino; the third generation is made up of the bottom and top quarks, the tau and the tau-type neutrino. Since the quarks are present in three colors, each generation includes six quarks and two leptons, for a total of eight particles. Corresponding particles in different generations seem to be identical in all measurable properties except mass. Ordinary matter is constructed exclusively from the particles of the first generation, and so the higher generations have no apparent function in the present universe. It is not understood why nature should be so repetitious. Furthermore, now that three generations have been discovered, there is no fundamental reason to believe there are not others made up of particles with still larger masses. A successful substructure model might explain not only the multiplicity of the quarks and leptons but also this curious hierarchy of generations.

In the past 10 years or so the idea that quarks and leptons might have an internal structure has been suggested repeatedly, and at least a dozen models of such a structure have been formulated. The hypothetical constituents of the quarks and leptons have been variously named prequarks, preons, subquarks, maons (after Mao Zedong, who once expressed an interest in the quark model), alphons, quinks and rishons. In recent years, as the spectrum of quarks and leptons has been more accurately defined, the substructure models have become somewhat more detailed.

One constraint on any such model is that it must yield the correct value for the spin angular momentum of the quarks and leptons: 1/2 unit. There are two simple ways of meeting this condition. A quark or a lepton can be imagined as a complex of two constituent particles, one particle with a spin of either 0 or 1 and the other particle with a spin of 1/2. Alternatively, a quark or a lepton can be assembled from three components, each with a spin of 1/2. Because of the complicated way in which spins interact, either of these strategies can yield a net spin of 1/2. Models of both kinds have been proposed.

One of the earliest conjectures was first mentioned in 1974 by Jogesh C. Pati of the University of Maryland and Abdus Salam of the International Centre for Theoretical Physics in Trieste. Pati and Salam suggested that the quarks and the leptons be incorporated into a single family by assigning the leptons a fourth quark color. In a footnote they pointed out that all the quarks and leptons could then be formed as combinations of two kinds of prequarks, one determining flavor and the other determining color. Similar ideas were subsequently described in greater detail by O. W. Greenberg of the University of Maryland, and many other investigators have since contributed to the development of related models. The versions differ in the allotment of various properties to the two constituent particles, but all versions are alike in one respect: one of the constituents must have integer spin and the other constituent must have half-integer spin. The minimum number of fundamental objects needed is equal to the number of flavors plus the number of colors; for the quarks and leptons known today this sum is 10.

A year later Pati and Salam with John D. Strathdee of the International Centre for Theoretical Physics introduced a three-constituent model. Again many other investigators have proposed schemes of the same general kind, some of them much more elaborate. A distinctive feature of the three-constituent models is that the individual subparticles can be very simple. The reason is that each constituent need carry only one defining property of the quarks and leptons. A model proposed by Hidezu-

mi Terazawa and his colleagues at the University of Tokyo can serve as an example. In the Terazawa model a quark or a lepton is constructed by selecting one spin-1/2 subquark from each of three separate populations. One of the subquarks specifies a generation of particles, a second subquark determines flavor within that generation and the third subquark determines color. For the three known generations a total of nine subquarks is needed; for each additional generation one more subquark would have to be included.

A three-constituent model of a quite different kind has recently been suggested by Haim Harari of the Weizmann Institute of Science in Israel. It is perhaps the most intriguing of the substructure models because it is the most economical. Just two species of fundamental entity are postulated; in various combinations they can account for all the quarks and leptons, and hence for all the diversity of subatomic particles. (Another model similar to Harari's has been put forward independently by M. A. Shupe.)

Harari calls the fundamental entities rishons, from the Hebrew for "first" or "primary." The two species are designated T and V. In explaining his choice of these letters Harari cites a phrase in the first chapter of Genesis, "Tohu va-Vohu," which has been translated as "without form and void." Unlike other models of quark structure, the rishon model does not assign quantities of color, flavor and so forth to the individual constituents; instead these properties are assumed to derive from the arrangement of the rishons or from their state of motion. Indeed, the rishons themselves have few properties. They have a spin angular momentum of 1/2, and presumably they have mass. In addition the T rishon has an electric charge of $+1/3$, whereas the V rishon is electrically neutral.

In the Harari model a quark or a lepton is formed by combining either three rishons or three antirishons. There are exactly eight possible combinations of the two kinds of rishon taken three at a time, and another eight combinations of antirishons. These combinations can be identified with the eight quarks and leptons in any one generation and with the corresponding eight antiquarks and antileptons.

The combinations are classified as follows. The triplet TTT has an electric charge of $1/3 + 1/3 + 1/3$, or $+1$, and it corresponds to the positron (the antiparticle of the electron). The three combinations TTV, TVT and VTT all yield a net charge of $+2/3$ and represent states of the up quark; the three permutations correspond to the three possible colors of the quark. In a similar way TVV, VTV and VVT all have a charge of $+1/3$ and are identified as the

three colors of the down antiquark. The remaining combination, VVV, is neutral and represents the electron-type neutrino. Exactly the same combinations of antirishons (which are designated $\overline{T}$ and $\overline{V}$) give rise to the remaining particles and antiparticles in the first generation: the electron ($\overline{TTT}$), the up antiquark ($\overline{TTV}$, $\overline{TVT}$ and $\overline{VTT}$), the down quark ($T\overline{VV}$, $\overline{VTV}$ and $\overline{VVT}$) and the electron-type antineutrino ($\overline{VVV}$).

The higher generations of quarks and leptons do not differ in composition from the first generation. They are assumed to be mere excited states of the same system of rishons, distinguished only by their mode of motion, like the excited states of an atom. Thus a positive muon would have the same complement of rishons as a positron (TTT), and so would a positive tau lepton. It should be noted that no new rishons would have to be added to the scheme in order to account for any additional generations of quarks and leptons. Indeed, the model imposes no obvious limit on the possible number of generations.

The rishon model offers a tantalizing glimpse of how several properties of matter that now seem strangely arbitrary might be given a fundamental explanation. For example, it explains why quarks come in exactly three colors rather than in some other number: there are just three ways in which to arrange the rishons in a quark. The leptons cannot have multiple colors because there is only one possible arrangement of TTT or VVV rishons. The exactness of the relation between the electric charges of the quarks and those of the leptons is another seeming coincidence that the rishons might elucidate. The charges of the three quarks in a proton exactly cancel the charge of an electron; if they did not, atoms would not be electrically neutral. In the rishon model the exact cancellation is no longer fortuitous because both quark and lepton charges have the same source.

Harari's proposal might even have some bearing on a cosmological puzzle of long standing. The puzzle is that matter seems to be much more abundant in the universe than antimatter, even though the two kinds of substance are always observed to be created or destroyed in equal quantities. If one counts rishons and antirishons, however, instead of quarks and antiquarks or atoms and antiatoms, the asymmetry disappears. A hydrogen atom, for example, consists of three quarks with the rishon composition TTV, TTV, $\overline{TVV}$ (ignoring the color permutations) and an electron with the rishon content $\overline{TTT}$. The numbers of rishons and antirishons exactly balance.

It must be emphasized that these observations cannot be counted as evidence in support of the rishon model; in each case other explanations are possible. All the quark substructure models appeal to the prejudice that nature should be simple, but for now the models remain unsupported speculations. Indeed, some physicists suggest it is premature to begin analyzing the possible constituents of quarks when much remains to be learned about the quarks themselves. Even the existence of quarks has not yet been demonstrated unequivocally.

The substructure models are likely to remain speculative and without supporting evidence for some time to come. They cannot be tested against experiment because it is not clear exactly what new particles or other phenomena they predict. Reliable predictions cannot be made from the models until the motions of the constituent particles and their interactions with one another can be calculated with reasonable precision. In many cases calculations of this kind are not yet possible even for the quarks within a hadron, and so a detailed description of rishon dynamics would seem to be a distant prospect indeed.

One result that would probably come from at least some of the models is the prediction of quarks and leptons with a spin angular momentum of 3/2. Such particles would have the same composition as the known quarks and leptons, but they would have larger masses. The discovery of a spin-3/2 quark or lepton might be interpreted as support for the

substructure models, although it might have other explanations as well.

Constraints on the substructure models that can be deduced from the known properties of the quarks and leptons were recently reviewed by Stanley J. Brodsky and Sidney D. Drell of the Stanford Linear Accelerator Center. They point out that the size of the leptons imposes one limit on the models. The electron, the muon and the tau are all known to be pointlike, or without structure, to dimensions as small as 10^{-16} centimeter, roughly a thousandth the diameter of the proton. Any constituents of the leptons (and by extension of the quarks) would have to be much smaller.

A still stronger constraint is provided by measurements of the $g - 2$ factor of the electron and the muon, a factor related to the magnetic moments of the particles. The $g - 2$ factor has been calculated theoretically on the assumption that the leptons are pointlike particles, and the result agrees with the experimental value to within a precision of a few parts in 10 billion. If the leptons had an internal structure, it would alter the $g - 2$ factor. Any such contribution must be exceedingly small or it would already have been observed as a discrepancy between theory and experiment.

Both the size of the fundamental constituents and their contributions to observed magnetic moments could be kept within acceptable bounds by the same theoretical device. It is necessary to assume that the constituents are extremely massive, perhaps a few million times as massive as the proton. There is a seeming paradox here. Particles that are among the lightest known (including the neutrinos, which could have zero mass) are to be built up out of particles that are among the heaviest ever conjectured. The task is not impossible: some of the excess weight could be shed in the binding energy that holds the constituents together, and if a certain pairing of the constituents is assumed, some of the masses could be made to cancel entirely. Still, it seems the models must be strained to fit within these bounds, and Brodsky and Drell offer a reminder that "the simplest alternative may be that the leptons are in fact pointlike 'elementary particles.'"

Androgenesis

A hydatidiform mole is an abnormal product of conception: a spongy mass of grapelike cysts that can grow as large as a six-month fetus before being expelled, usually in about the 20th week of pregnancy. It represents an abnormal growth of the chorion, the membrane that would ordinarily give rise to the placenta. In a true, or complete, hydatidiform mole there is no embryo at all; in a partial mole the embryo is dead.

Hydatidiform moles account for a small proportion of miscarriages. A woman who develops a hydatidiform mole has normal symptoms of pregnancy, but her uterus enlarges faster than expected, and she may suffer from such complications as toxemia or preeclampsia. Sometimes the mole invades the wall of the uterus and causes bleeding, in which case it must be removed surgically. Very infrequently a mole develops into a highly malignant choriocarcinoma. The cause of hydatidiform moles has been assumed to be some kind of chromosomal abnormality in the fertilized ovum, or possibly (because there is a geographical pattern in the incidence of the moles) an unusual infection.

The cause is now revealed to be a chromosomal anomaly, and a remarkable one indeed. In the past three years a number of investigators have reported that the cells of almost all true hydatidiform moles have 46 chromosomes, the normal number, and that two of them are *X* chromosomes. That is the normal female diploid complement: 23 chromosomes from the mother's ovum and 23 from the father's sperm, each haploid set including an *X* chromosome. The surprising thing about the hydatidiform mole's chromosomes is that both sets come from the father. There is no maternal contribution. "This male form of parthenogenesis," as a *British Medical Journal* editorial reviewing the subject comments, "is far more remarkable, not to say miraculous, than the development of a conceptus entirely from maternal sources."

The androgenetic origin of hydatidiform moles was first shown by chromosome-banding studies. Certain dyes bind selectively to particular parts of chromosomes, giving rise to a pattern of bands that serves to distinguish individual chromosomes. Investigators found that when the father's two sets of chromosomes had different banding characteristics, both of the mole's two sets were identical with one of the paternal sets; they must have been derived from duplication of the 23 chromosomes of a single sperm. Why are hydatidiform moles always *XX*, never *XY* (as in the case of a normal male)? Apparently a cell derived from duplication of the 23 chromosomes of a *Y*-bearing sperm would not be viable. The original findings based on banding have since been confirmed by studies of histocompatibility antigens (cell-surface markers that are distinctive for every individual) and of distinctive enzyme variants. In almost all cases it appears that the moles arose from "fertilization" of the ovum by a single sperm that subsequently duplicated its chromosomes. Presumably the ovum had originally contained its own set of 23 chromosomes, which were somehow lost—perhaps having been driven out of the fertilized ovum by the presence in it of two sets of male chromosomes.

The True Romance of Spanish Fly

As organic molecules go, the molecule of cantharidin is not a particularly spectacular one. Its three-dimensional structure bears some resemblance to a reclining chair: a common edge is shared by two rings of carbon and oxygen atoms, the seat is supported by legs of methyl groups (CH_3) and a pair of serviceable armrests is provided by wings of double-bonded oxygen atoms. In the lore of adolescent males this stereochemistry might seem curiously appropriate, a design of nature that evokes the erotic purposes that have brought a certain fame to cantharidin, otherwise known as Spanish fly. The fact is, however, that Spanish fly (after the insect from which cantharidin is extracted) is better described not as an aphrodisiac but as a useful blistering agent currently in short supply.

An organic chemist can nonetheless find his own kind of romance in the deceptively simple architecture of the cantharidin molecule, a structure that has readily revealed its attractions to the eye but not to the hand. Chemists were able to synthesize cantharidin nearly 40 years ago, but the synthetic methods did not match the austere elegance of the

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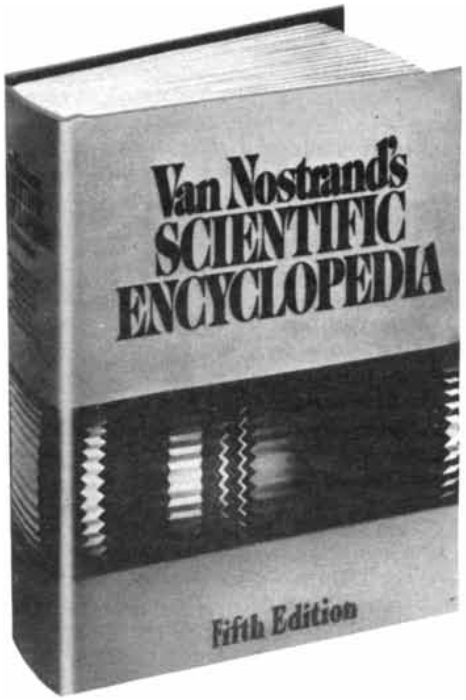

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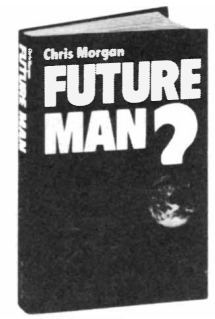

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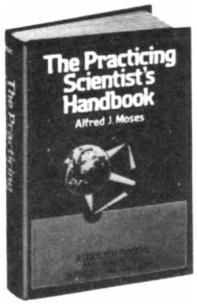

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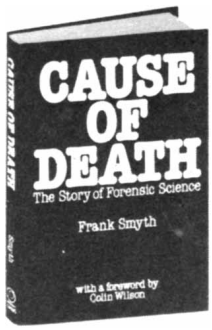

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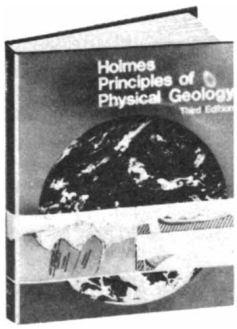

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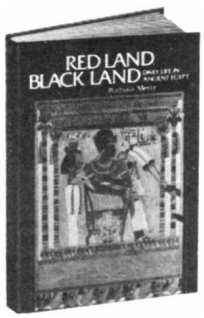

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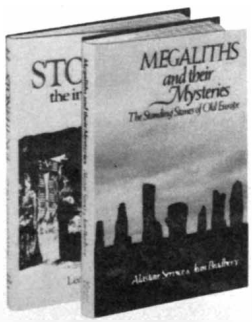

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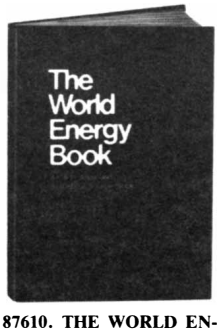

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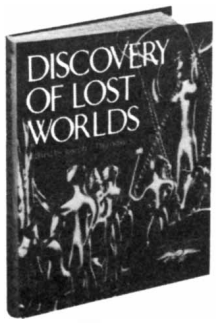

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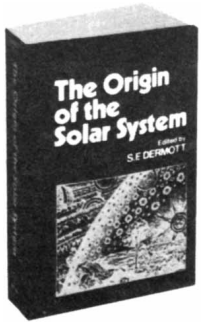

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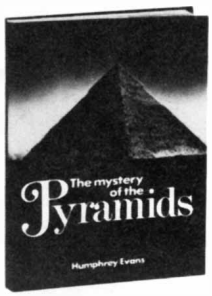

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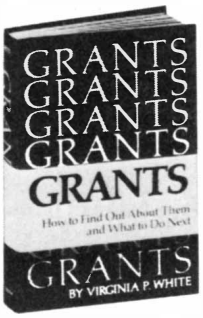

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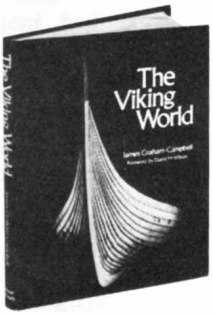

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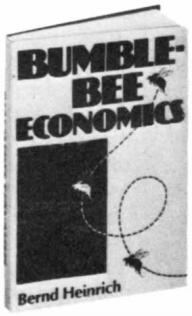

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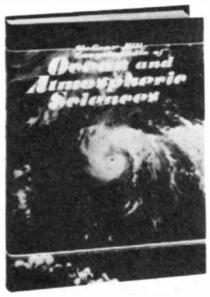

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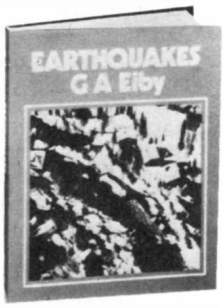

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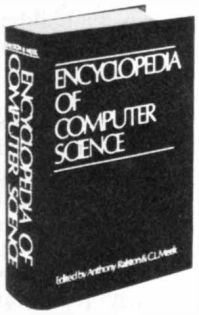

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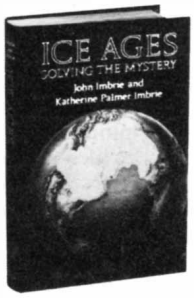

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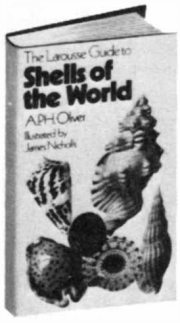

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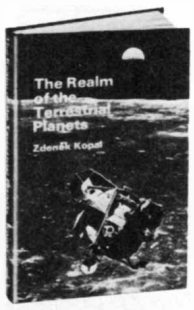

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molecule itself. Now a group of chemists at the University of California at Berkeley have given the structure its due. William G. Dauben, Carl R. Kessel and Kazuo H. Takemura report in *Journal of the American Chemical Society* that a combination of high pressure and a straightforward but unusual substitution of one of the reactants was sufficient to bring about "a simple synthesis of cantharidin in accord with its simple structure."

Like a rock climber, a synthetic chemist can choose the rules of his game with an eye to a formal aesthetic shared by his colleagues but seldom appreciated by others. Dauben and his colleagues began with furan and methyl thioglycolate, two compounds "off the shelf" from the chemical supply house. Their strategy involved achieving a reaction stage analogous to what had long seemed the obvious starting point for the synthesis, namely the linking of furan and dimethylmaleic anhydride. The direct assault from here, a cycloaddition of the Diels-Alder type, had led earlier workers into a cul-de-sac created by the unfavorable electronic and steric properties of methyl groups on dimethylmaleic anhydride. The Berkeley group proposed instead to substitute a compound that replaces the methyl groups with a bridge of methylene (CH_2) and sulfur, and then to proceed with the Diels-Alder reaction with furan under high pressure. Although the substituted compound can be readily synthesized, the group chose to begin by building it from methyl thioglycolate, thereby achieving not merely a formal synthesis of cantharidin but a total synthesis.

Dauben and his colleagues have exploited at least one benefit of their achievement: the production of isomers and other compounds closely related to cantharidin that may not occur in nature. They have also reduced the pressure requirements for their Diels-Alder reaction from nearly 15,000 atmospheres to a level low enough for industrial reactors. Both of these developments augur well for an increased supply of cantharidin, and perhaps even more effective compounds, for practical purposes.

The current practical purpose of cantharidin, according to William L. Epstein, professor of dermatology at the University of California at San Francisco, is the removal of warts. There may be other uses for a powerful blistering agent in the future. Although there is no support in the pharmacological literature for an aphrodisiac action of cantharidin, there may be, says Epstein, some basis for the folklorish reputation of the compound. When it is taken internally, it irritates the urethra. Hence although it may not induce a pleasurable kind of sexual arousal, it may induce a semblance of it.

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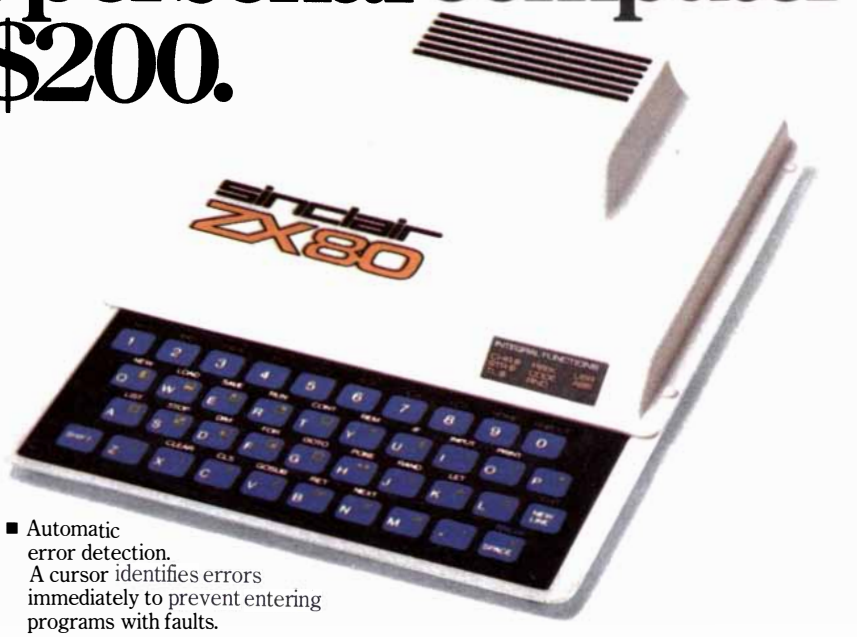

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Autoimmune Diseases

Malfunctions of the immune system in which the body attacks its own tissues are now known to cause several enigmatic diseases. The details of such processes suggest new strategies of treatment

by Noel R. Rose

Every person goes through life surrounded by potentially harmful microorganisms. Those that invade the body are usually held at bay by the body's immune defenses, an elaborate system that stands guard to intercept and destroy foreign cells. It is therefore a matter of great biological and medical significance that the system sometimes goes awry in such a way as to give rise to the diverse group of disorders known as autoimmune diseases. Such disorders result when the immune system, which ordinarily distinguishes self from nonself with great precision, begins to attack certain of the body's own cells.

The immune system is believed to have evolved from the need of the most primitive multicellular organisms to recognize other cells of the same kind. A further communication network among cells was needed in order for cells to cooperate in the development of specialized organs. A requirement of these recognition mechanisms was the general ability to discriminate between self and nonself, and that task became the special duty of the immune system now found in all vertebrate animals. In the course of evolution the system took on a second but equally important function: the elimination of any foreign cells that enter the body.

The ability to distinguish self from nonself applies not only to invading microorganisms and parasites but also to foreign molecules, including those with no harmful properties. The body will reject even nourishing proteins if they originate in alien sources, unless these large molecules are first broken down by enzymes in the gut. Only then can they be absorbed through the intestinal wall in the form of amino acids, their primary building blocks, and resynthesized into proteins that are uniquely the body's own.

The immune system also rejects cells from other individuals of the same species unless the cells are identical with the body's own. In the case of the relatively simple red blood corpuscles it is fairly easy to match the donor's blood with the recipient's, so that a transfusion can be carried out with minimal risk. Most tissue cells with a cell nucleus (which red cells lack) are more difficult to match, which is why the transplantation of a kidney is a much more demanding procedure than blood transfusion, usually requiring that the immune apparatus of the patient be crippled with suppressive drugs.

Human beings and other animals pay a high price in many other ways for their zealous protection of biological individuality. For example, the same mechanisms the body relies on to avoid immunological responses to its own cells sometimes allow cancerous cells to escape destruction. The differences between normal and cancerous cells of the same individual may be so subtle that the immune system fails to detect them. On the other hand, it is thought that the immune system does attack malignant cells if they are significantly different from normal ones.

The main functions of the immune system can thus be summarized as follows: (1) resistance to foreign cells and substances that may cause trouble and (2) searching out cancerous cells that may arise from time to time. Both of these functions require an effective recognition mechanism to distinguish self from nonself. It is the errors of this system in turning against the self, giving rise to an immunological attack on the body's own cells and tissues, that are a subject of intense interest and study among biologists and physicians.

The Recognition of Autoimmunity

The first investigator to seriously consider the importance of discrimination between self and nonself was the German microbiologist Paul Ehrlich. In 1900, having become interested in the fate of blood after internal bleeding, he began a series of experiments in which he injected blood into the abdominal cavity of goats. If the goats were injected with blood from another species, such as the sheep, they produced new factors in their blood serum that could lyse, or break down, the foreign red blood cells. These factors are the specialized proteins known as antibodies. Antibodies also are found in the blood of human beings or other animals after an infection by disease-causing microorganisms. The foreign substances that induce the formation of antibodies are antigens.

Somewhat to his surprise Ehrlich found that blood of other goats injected in the same manner was antigenic too. The antibodies induced by this blood could lyse the red blood cells of the donor goat and of most, but not all, other goats. They failed, however, to lyse the red blood cells of the recipient goat.

Ehrlich coined the term "isoantibodies" for antibodies synthesized by an individual that act against cells of other individuals of the same species. The antigens responsible for the development of isoantibodies are termed isoantigens; they can be thought of as chemical groupings occurring in some but not all individuals of the same species. An animal that lacks a particular isoantigen can develop antibody if the animal is injected with that isoantigen.

The fact that a goat never formed antibodies to its own red blood cells even when its cells were removed and reinjected fascinated Ehrlich. He characterized the phenomenon as *horror autotoxicus* to express the underlying biological principle that an animal generally does not respond to the chemical groupings of its own body, that is, it does not make autoantibodies: antibodies to autologous antigen, or self-antigen. Ehrlich speculated that if it did, the resulting antibodies could injure its own tissues, causing autoimmune disease.

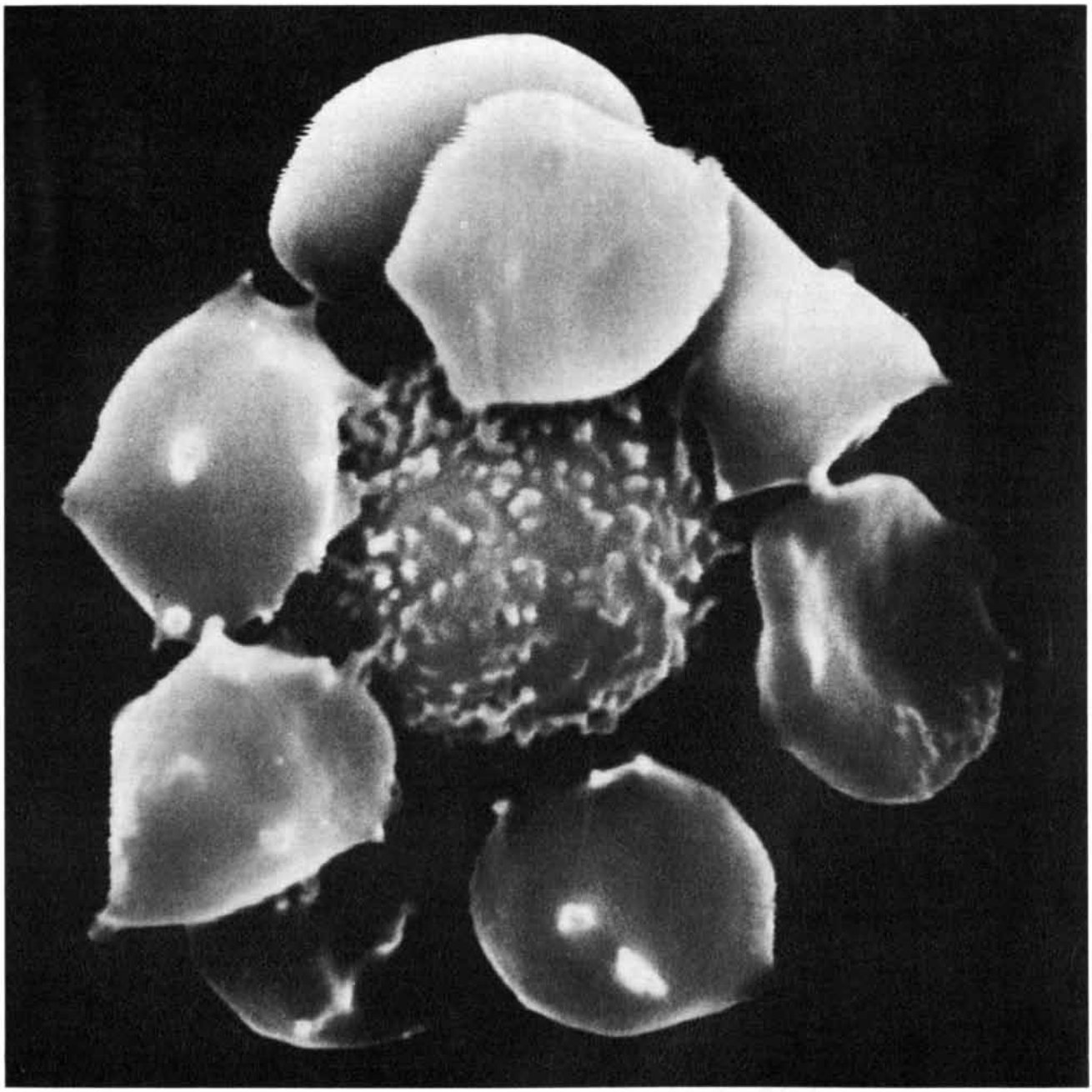
It is now recognized that autoimmunity is a primary cause or a secondary contributor in many enigmatic diseases. In 1904 Ehrlich's contemporary Karl Landsteiner described the first clear instance of a human disease resulting from the formation of autoantibodies. Blood serum of patients with the relatively rare disease paroxysmal cold hemoglobinuria contains an autoantibody that combines with the patient's own red blood cells, but only at low tem-

perature, as in winter weather. When the tissue is restored to the normal body temperature, the bound antibody can trigger the destruction of the red blood cells. The reaction is easily demonstrated by dipping the patient's finger in ice-cold water for a few moments and then letting it warm up. The lysis of the red cells is signaled by the pink color of the plasma of blood obtained by pricking a finger.

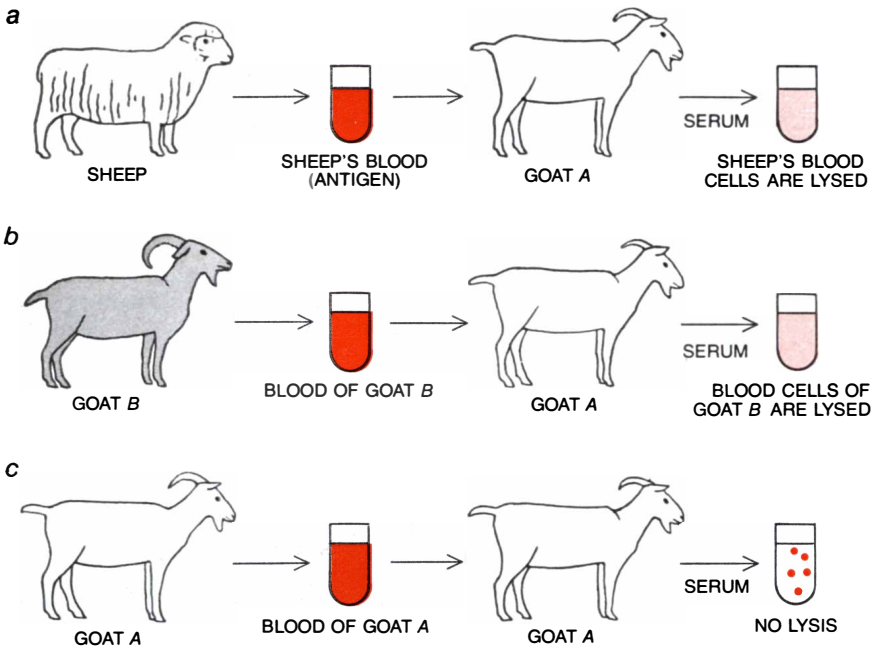
Several of the commoner forms of human anemia were later shown to be associated with autoantibodies to red blood cells. The antibodies combine with the cells at body temperature and promote their destruction. The demonstration of antibodies on the patient's own red blood cells is now the cornerstone of the diagnosis of autoimmune hemolytic anemia.

In a number of other important human diseases the presence of autoantibodies in the patient's blood serum points to a potentially dangerous self-directed immune response. For example, autoantibodies to the islet cells of the pancreas are found in the severer forms of diabetes mellitus, particularly the childhood-onset type. Such antibodies suggest that the islet cells, which manufacture insulin, are the victims of an autoimmune attack.

Antibodies reactive with certain junctions of nerve and muscle are found in the serum of most patients suffering from myasthenia gravis, a disease in which muscle groups do not obey nerve signals. The result is muscular weak-



HUMAN LYMPHOCYTE is a major cell in the immune defense system, recognizing invading antigens by means of special receptors on its surface. In this scanning electron micrograph a human *T* lymphocyte is surrounded by several washed red cells from sheep blood. The two kinds of lymphoctyes in blood, *T* and *B*, look the same in the electron microscope. For some unexplained reason, however, *T* lymphocytes carry receptors for the sheep red blood cells. Those receptors have caused the cells to adhere to the surface of the lymphocyte. In the light microscope such aggregates resemble a rosette. The rosettes provide a method widely used for counting *T* lymphocytes. The micrograph was made by C. Lynn Burek of Wayne State University School of Medicine. The enlargement is about 5,000 diameters.



EARLY EXPERIMENTS by Paul Ehrlich demonstrated that the immune system of vertebrate animals will normally not attack the animal's own cells. Ehrlich found that if he took blood from a sheep (*a*) and injected it into a goat, the blood acted as an antigen and the goat's serum lysed, or dissolved, the foreign cells. The same thing happened (*b*) if Ehrlich took blood from one goat and injected it into another goat, but when he withdrew a goat's blood and later returned it to the same goat (*c*), there was no lysis. Ehrlich gave the name *horror autotoxicus* to the biological principle that the immune system distinguishes between self and nonself.

ness. In Graves' disease, a thyroid disorder associated with the overproduction of thyroid hormones, antibodies can be found that react with human thyroid cells. Instead of damaging the thyroid cells these antibodies stimulate them, spurring the thyroid to make more hormones. The overproduction of thyroid hormones causes symptoms of restlessness, weight loss and palpitations.

Perhaps the epitome of autoimmune disorders in human beings is systemic lupus erythematosus. Here the patient forms a myriad of autoantibodies to different constituents of the body. Some of them are directed to the DNA of the cell nucleus and may combine with liberated DNA in the bloodstream. The antigen-antibody aggregates often bind in the glomeruli, the kidney's filtration system, where they can cause serious kidney damage.

Components of the Immune Response

Later investigators were impressed by the general validity of Ehrlich's *horror autotoxicus* principle, but they were frustrated in their efforts to explain it. In the late 1950's F. M. Burnet of Australia propounded the clonal-selection theory of antibody formation. It states that the body has a large number of diverse precursor cells, each with a specially patterned protein surface receptor. When an invading or experimentally injected antigen finds a precursor cell with a complementary surface pattern, it triggers the cell into a series of divisions. This exponential proliferation gives rise to a clone of cells that secrete the antibodies found in the bloodstream. Antibodies are specialized proteins genetically programmed to closely fit the antigen that stimulated their production.

The pioneering investigations of James L. Gowans of the University of Oxford showed that the key cell in the immune system is the lymphocyte, a small, round cell of the blood, the spleen and the lymph nodes that has the capacity to recognize antigens by means of the special receptors on its surface. Like other cells found in the blood, lymphocytes arise from multipotential stem cells of the bone marrow. One population of lymphocytes matures under the influence of the thymus gland; they are accordingly referred to as thymus-derived, or *T*, cells. The members of a second lymphocyte population, the *B* cells, evolve from the bone-marrow ancestor without the influence of the thymus. Certain other cells originating in the bone marrow aid the lymphocytes in their immunological task. They include macrophages, which take up antigens and present them to the lymphocytes in an appropriate way in order to initiate the immune response. The macrophages are also important phagocytic (scavenger) cells, engulfing and digesting invading microorganisms and other antigenic particles.

Lymphocytes have several properties that equip them to carry out their special immunological duties. Some circulate repeatedly through the body, providing efficient surveillance against foreign invaders. Some lymphocytes have a long life span and carry the memory of a previous contact with an antigen for many years. A second encounter with the same antigen results in a quicker and more vigorous response.

The most significant and distinctive feature of the mature lymphocyte is its unique surface receptor, which enables it to recognize a particular antigen. According to the clonal-selection theory, an individual lymphocyte responds to only one antigen because it has only one type of receptor. This special correspondence between a lymphocyte receptor and an antigen means that the immune response is specific for a particular antigen.

Everyone encounters a great variety of antigens every day in the form of microorganisms, food, drugs, venom from insect bites and so on. A normal immune system must include lymphocytes capable of recognizing all the antigens likely to be met in a lifetime. That number is large but not infinite. Similarities and overlaps in the structure of different antigens mean that about a million different lymphocyte receptors can recognize any antigen found in nature or synthesized in the laboratory. How does the body generate such a great diversity of lymphocyte receptors?

It is now known that the combining portion of the *B* lymphocyte's surface receptor and the combining portion of antibody are identical. In other words, the specificity of antibody must be the same as that of the surface receptor on the lymphocyte that secreted it. Second, lymphocytes are programmed with the genetic information necessary to make particular receptor molecules, so that each lymphocyte has the capacity to respond to one antigen.

The capacity to recognize antigens in such a selective way is due to a unique sequence of amino acids in the protein of the *B*-lymphocyte receptor. These sequences differ greatly from one lymphocyte receptor to another, so that they are called variable (*V*) regions to distinguish them from the more constant (*C*) regions of the receptors.

In order for a lymphocyte to synthesize a receptor it must select a few *V* genes—the genes responsible for a particular sequence of amino acids—from its vast array of genes and join those few with one of the limited number of *C* genes. The variable region is actually made up of two amino acid chains, one heavy (*H*) and one light (*L*). The *V* region of a receptor consists of the terminal 110 amino acids of each chain. Assuming that the cell can call on about 100 different *V*-region sequences for the *H* chain and the same number for the *L* chain, then random combinations could

yield about 100 × 100, or 10,000, different receptor sites. It is likely that random mutations in precursor lymphocytes further enlarge this repertory of *V* regions to at least a million at the time of birth, a number large enough to accommodate any conceivable antigenic specificity. The required number of *V* genes for a million specificities constitutes less than .1 percent of the human genome: the full set of human genes.

The Functions of *T* and *B* Cells

Although the recognition molecule of the *T* lymphocyte has not been identified with certainty, *T* and *B* cells seem to draw on the same supply of *V* genes to build antigen-specific receptors on their surface. The two lymphocyte populations differ dramatically in their response to an encounter with the appropriate antigen. After being stimulated by an antigen a subset of *T* cells differentiate into large lymphocytes that release soluble factors termed lymphokines. They are proteins of low molecular weight. The lymphokines attract lymphocytes, macrophages and other kinds of blood cells, thereby inducing an inflammatory response. They mediate the slowly evolving reaction associated with skin tests often done to diagnose many diseases caused by bacteria, viruses or fungi. In the test a specimen of the suspected pathogen is injected; about 72 hours later the skin at the site of the injection becomes inflamed if the organism is indeed the culprit. The reaction is termed delayed hypersensitivity.

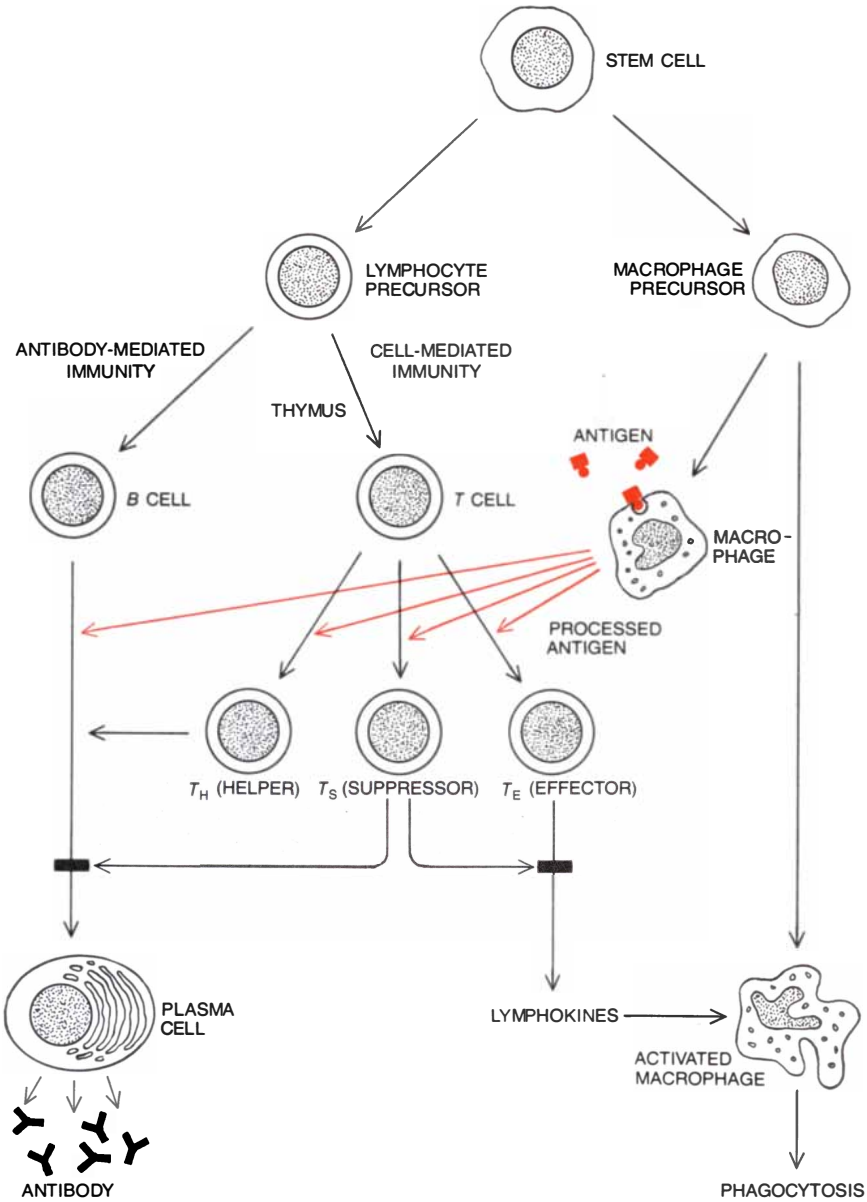
Antigen-stimulated *T* cells provide the resistance shown to many bacterial, viral and fungal agents of disease, particularly the agents that reside within the cells of the body. In addition a subset of *T* cells mediate the rejection of grafted organs and perhaps of some emerging tumors by killing cells that bear the particular antigen. As a group the *T*-cell functions are called cell-mediated reactions.

In contrast antigen-stimulated *B* lymphocytes differentiate into plasma cells that secrete large quantities of the antibodies responsible for eliminating the bacteria that do not enter cells and preventing infection by viruses before they enter cells. Antibodies cannot penetrate living cells and are therefore ineffective against microorganisms inside cells. Their amount can be easily measured, however, so that they are useful indicators of an immune reaction even though they may not themselves provide protection against certain microorganisms.

Functionally *B* and *T* cells differ in several other ways. Usually a *B* cell cannot be triggered to make antibody without help from a *T* cell. This *T*-cell cooperation requires a simultaneous *T*-cell response to the same antigen or to a different antigenic determinant carried on the same molecule. The activation of *T* cells in turn usually requires that a macrophage present the antigen in the proper orientation.

These interactions between macrophages and *T* cells, which are vital to an effective immune response, call for the two cells to have specialized complementary structures on their surface. The formation of these structures is controlled by the distinctive family of *I* genes. The genes regulate the immune response to highly purified antigens in inbred animals; they also govern the reactions that are likely to develop when macrophages, *T* cells and *B* cells are mixed in the test tube or interact within the body.

It is a matter of particular interest that the *I* genes are closely linked to the genes coding for the major transplantation antigens: antigens responsible for the rejection of tissue transplanted from one member of a species to another



DEVELOPMENTAL PATTERNS of *T* and *B* lymphocytes from their origin in stem cells of the bone marrow are depicted. The *B* cells evolve directly from the stem cells; the *T* cells develop under the influence of the thymus gland. On stimulation by an antigen *B* cells differentiate into plasma cells secreting the antibodies that attack bacteria and viruses before they enter the cells of the host; this is antibody-mediated immunity. *T* lymphocytes exert their effects directly; this is cell-mediated immunity. There are also subpopulations of *T* cells: helper cells, which interact with *B* cells to amplify the production of antibody; effector cells, which carry out the direct cell-killing functions of *T* cells and make the lymphokines that are responsible for delayed hypersensitivity, and suppressor cells, which regulate both parts of the immunological response. Some macrophage cells present antigens to *T* and *B* cells in the proper orientation; others are activated by lymphokines to destroy invading microorganisms (phagocytosis).

member of the same species. Every vertebrate animal has a complex of major histocompatibility genes that control the most important transplantation antigens on its cell surfaces. In human beings these genes are called HLA, in the mouse H2. In both species the major transplantation antigens are valuable markers of the *I* genes that regulate immune responses and so will come into this story.

Acquired Tolerance

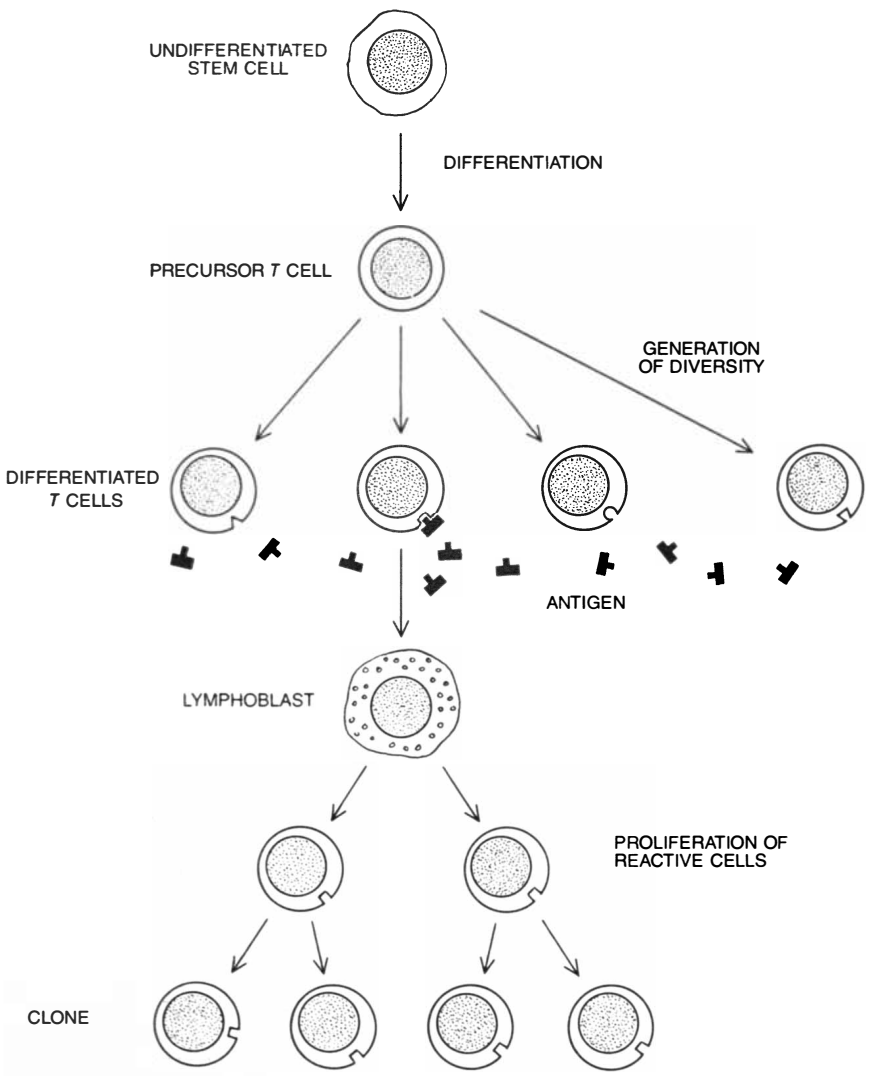
Given the ability of the immune system to respond to any foreign antigen that enters the body, the lack of response to self-antigens is particularly impressive. Burnet's clonal-selection hypothesis held that while the organism is in the embryonic stage the lymphocytes that encounter and recognize self-antigens are destroyed, leaving only the lymphocytes for recognizing nonself antigens.

This simple concept was tested some 25 years ago in a famous investigation of skin grafting by P. B. Medawar and his associates at University College London. They injected living spleen cells from one strain of mice into newborn mice of a genetically different strain. After the newborn mice had grown into adults they were tested for their ability to reject skin grafts from the same donors. The transplanted skin survived more or less indefinitely. This induced tolerance to the alien tissue was attributed to the destruction of the reactive lymphocytes in the newborn mice by the antigen of the donor. It is possible that self-recognition is acquired in the same way as induced tolerance.

How, then, can the exceptional instances of autoimmune response be explained? Burnet offered an ingenious explanation. Precursor lymphocytes committed to nonself but related-to-self antigens mutate during their multiplication and accidentally make lymphocytes reactive to self. On stimulation by self-antigen these "outlaws" proliferate to yield clones of self-reactive lymphocytes.

The exceptions to self-tolerance are not only interesting in themselves but also valuable for what they reveal about the normal mechanisms of immunological regulation. For example, certain antigens are not in contact with the circulatory system during the critical early phase of embryonic growth when the lymphocytes are most susceptible to the induction of tolerance. One such isolated antigen is found on mature sperm cells, which do not appear in the testes until relatively late in development. Moreover, they normally leave the body through the spermatic ducts and until then are sequestered behind an anatomical barrier that prevents them from entering the bloodstream. In vasectomy, the operation done to control fertility by sterilizing males, the spermatic ducts are blocked. Sperm are then forced to enter the body proper, where they often elicit autoantibodies. This autoimmune response is generally harmless, although continued observation is clearly advisable.

With tissues that are not so well isolated from the general circulation it is much more difficult to induce the production of antibodies. The injection of simple extracts of most tissues into the animal from which the extract was prepared rarely causes any production of antibodies. Many extracts of organs, however, become antigenic if they are injected with an adjuvant: a material that amplifies the antigenicity of other substances. The adjuvant most commonly used, Freund's adjuvant, is an emulsion of the antigen with mineral oil and killed tubercle bacilli. This adjuvant not only increases the production of antibodies but also markedly enhances cell-mediated immunity. An adjuvant is, of course, a highly artificial substance, and the natural equivalent of an adjuvant is a matter of debate.



DEVELOPMENT OF CLONES is the way *T* and *B* cells show their responsiveness to individual antigens. The process is depicted here for *T* cells but is the same for *B* cells. The precursor lymphocyte acquires a surface receptor for a particular antigenic determinant. When any lymphocyte prepared in this way encounters the antigen to which it has acquired a specific reactivity, it is triggered to enlarge into a lymphoblast and then to divide sequentially. The sequential and exponential division gives rise to a clone of lymphocytes with the same specificity.

Experimental Autoimmune Disease

Autoimmune disease can be caused experimentally by appropriate methods. A well-studied example is the disease resulting from the injection of myelin, the fatty covering of the nerve fibers. The injection of myelin with Freund's adjuvant results in the demyelinating disease called autoimmune encephalomyelitis. All the evidence suggests that the demyelination is due to the effects of cell-mediated immunity on a constituent of myelin. Circulating antibodies of myelin are also present, but they do not correlate with the severity of the disease. Moreover, the disease can be transferred from a diseased animal to a nor-

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mal one by injecting living *T* cells but not by injecting even large amounts of antibody-containing serum.

Experimental autoimmune encephalomyelitis resembles human demyelinating diseases such as multiple sclerosis. Firm evidence for the role of autoimmunity in multiple sclerosis has, however, remained elusive.

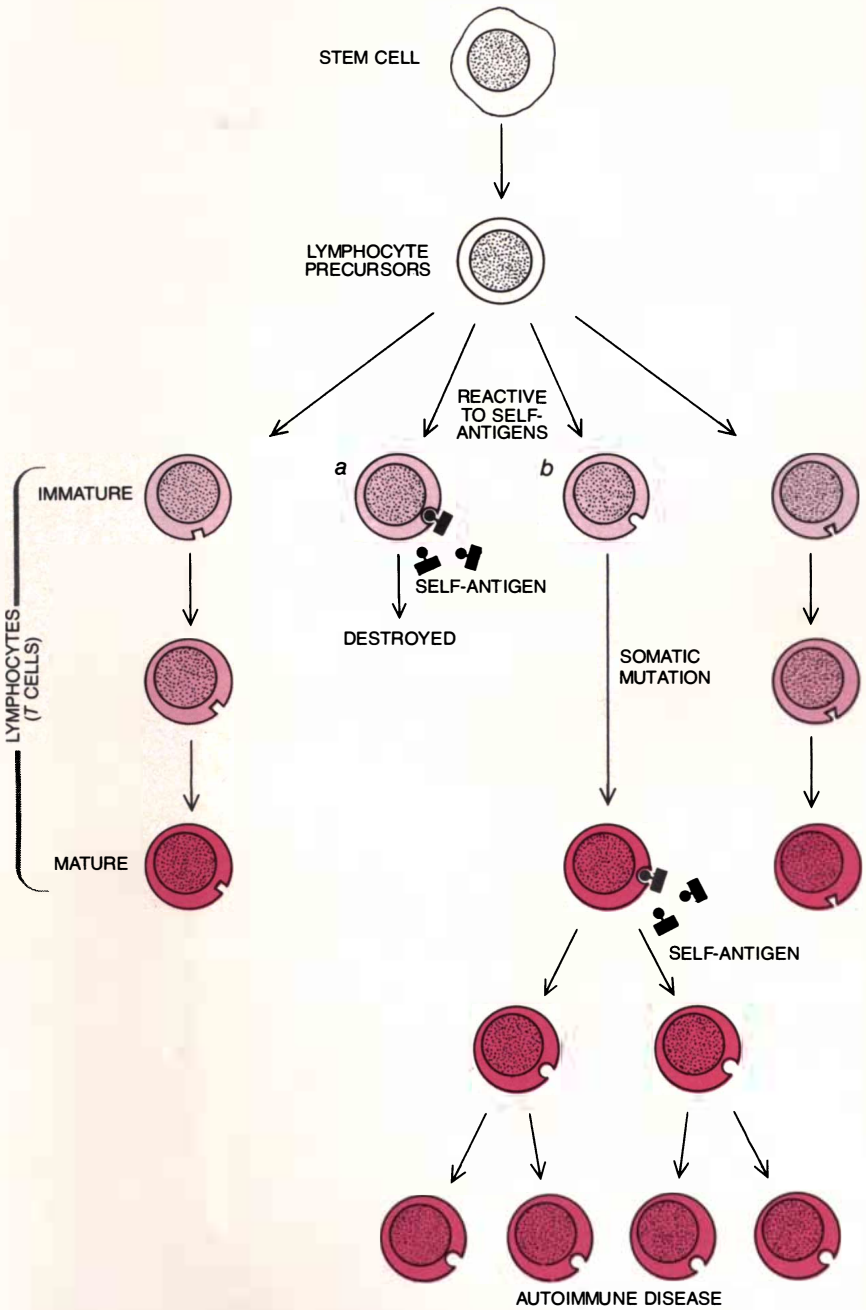
Myelin consists of layers of fatty material interlaced with proteins, one of which is a small basic protein that is the actual autoantigen. Basic protein has been isolated from myelin in a highly purified form and found to consist of a single chain of 170 amino acids. Nine amino acids, Nos. 114 through 122 of the basic protein chain, constitute the encephalitogenic determinant, that is, this sequence can induce autoimmune encephalomyelitis in guinea pigs. Robert H. Swanborg of the Wayne State University School of Medicine discovered, on the other hand, that a separate grouping on the same molecule (amino acids Nos. 44 through 89) renders guinea pigs resistant to encephalomyelitis. Here, then, is what seems to be an important mechanism for maintaining tolerance to the encephalitogenic component of myelin basic protein in the normal animal.

Myelin, like sperm cells, is formed relatively late in embryonic development, so that tolerance to it does not develop. In addition a free exchange between the central nervous system and the rest of the body is impeded by what is known as the blood-brain barrier. These special properties have been cited to account for the autoantigenic potential of myelin basic protein.

In the early 1950's I joined the late Ernest Witebsky at the University of Buffalo School of Medicine in beginning a systematic study of the factors that prevent an autoimmune response to the self-antigens that, unlike sperm cells and myelin, are not isolated in the body. As a model for the study we chose thyroglobulin, a large protein made and stored in the thyroid gland. Witebsky knew from his earlier experiments in Germany before World War II that thyroglobulin was unique to the thyroid, so that if the gland was removed, essentially all the animal's own thyroglobulin would be depleted. It was possible, then, to ask a simple question: Does the body maintain self-tolerance even after the autologous antigen has been eliminated? We tested the question by injecting rabbit thyroglobulin into rabbits from which the thyroid had been removed (and also into normal rabbits that served as controls). The answer was unambiguous: there was no immune response. Self-tolerance persisted even in the absence of the appropriate antigen.

A surprise was in store for us, however. When thyroglobulin was injected together with Freund's adjuvant, autoantibodies to thyroglobulin appeared. The antibodies even reacted with thyroglobulin from the immunized animal. In fact, we could remove a rabbit's thyroid and then immunize the animal with its own thyroglobulin together with Freund's adjuvant. The most startling outcome of the experiment was that the thyroid glands of immunized rabbits were infiltrated by lymphocytes, macrophages and other cells indicative of an inflammatory immune response.

The appearance of the infiltrated thyroids resembled what is seen in some cases of human chronic thyroiditis. We therefore collected serum from a few patients with that disease and tested the material for antibodies to human thyroglobulin. The results were positive. Working independently and with a larger number of patients, Ivan Roitt and Deborah Doniach of the Middlesex Hospital Medical School in London reported exactly the same findings: most patients with chronic thyroiditis and re-



CONCEPT OF AUTOIMMUNITY was formulated in the late 1950's by F. M. Burnet. The development of *T* lymphocytes from stem cells is portrayed in a scheme in which increasing maturity is represented by darkening color. In the normal situation (*a*) an embryonic *T* cell that is reactive to a self-antigen, that is, one of the body's own tissues, is destroyed when it comes in contact with such an antigen. In this way self-reactive lymphocytes are eliminated. Other lymphocytes (*b*), however, may change by mutation so that when they subsequently come in contact with self-antigen, they proliferate. The "forbidden clones" created by this process can give rise to autoimmune disease. Burnet thought *B* cells behaved in a similar way.

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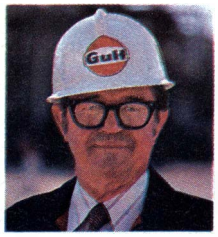

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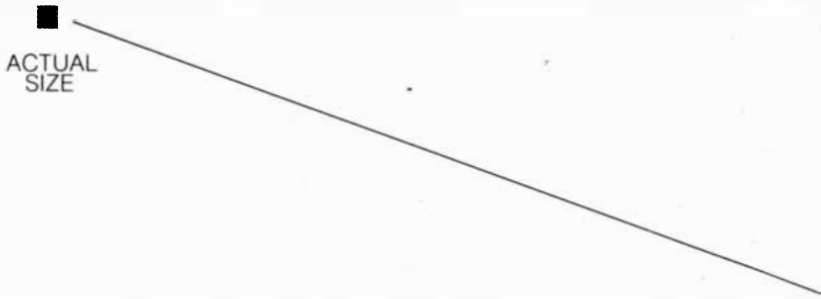

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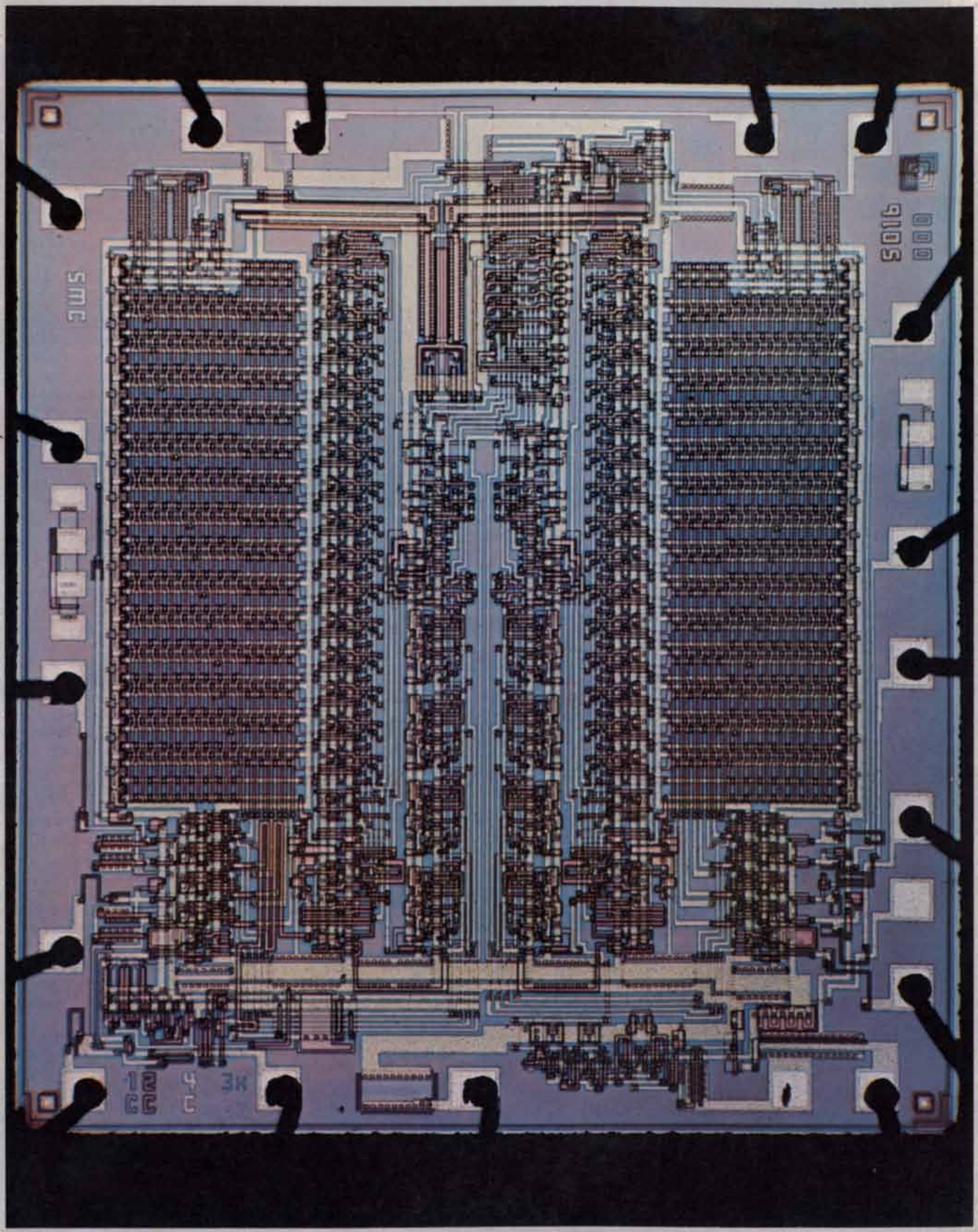

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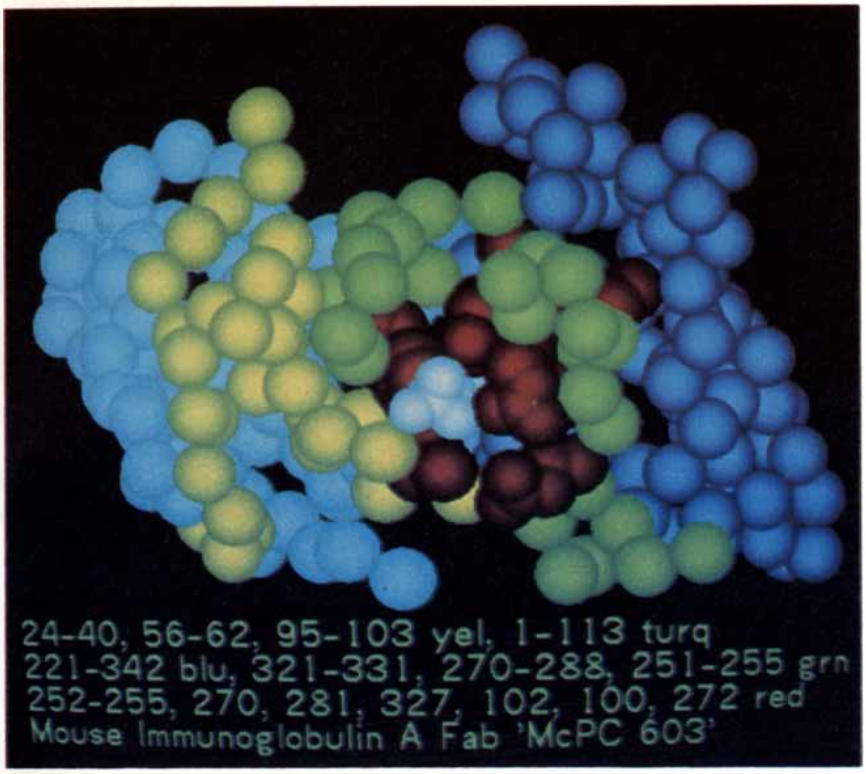
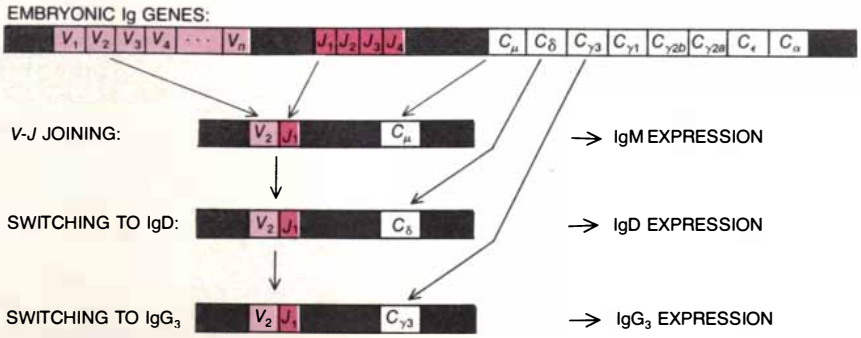


ANTIBODY COMBINING SITE of the antibody (or immunoglobulin) molecule determines the specificity of a *B* lymphocyte because of its unique fit with a particular antigenic determinant. The receptor molecules of *B* lymphocytes are made up of constant and variable regions; the actual combining site is on the variable region and is made up of segments of heavy (*H*) and light (*L*) amino acid chains of the receptor molecule. This model of the combining site of a mouse antibody that binds phosphocholine was presented by a molecular graphics system developed at the National Institutes of Health by Richard Feldmann. Blue corresponds to *L*-chain framework amino acids, turquoise to *H*-chain framework amino acids, yellow and green respectively to *L*- and *H*-chain hypervariable amino acids and red to side chains in contact with phosphocholine. White is the phosphocholine; only the phosphate is visible because the choline is below the surface in a pocket. The structure was determined by David R. Davies and his colleagues at the National Institute of Arthritis, Metabolism, and Digestive Diseases.

lated thyroid disorders are found to have antibodies to thyroglobulin in their bloodstream.

The demonstration of autoantibodies to thyroglobulin in human thyroid disease was followed by demonstrations of highly specific autoantibodies in a number of other human diseases, including juvenile diabetes, myasthenia gravis and Graves' disease. Often these antibodies have proved to be of great help in the diagnosis of the particular disease. An entire new field of clinical immunology has now developed around the demonstration of various autoantibodies for diagnostic purposes.



SYNTHESIS OF IMMUNOGLOBULIN MOLECULE entails the selection by the *B* lymphocyte of a particular *V* gene, here V_2, from a large number of *V* genes. The *V* gene is then joined through one of the *J* genes, here J_1, to one of the small number of *C* genes (C_μ), instructing the cell to make the appropriate amino acid chain to form a particular antigen-specific receptor. This *V*-region segment consists of about 110 amino acids. Later the cell switches to a different *C* gene, C_δ, which instructs it to synthesize immunoglobulin molecules with a constant segment characteristic of the IgD class of immunoglobulins. This new segment is joined to the same variable segment. Switching continues as the C_γ gene is substituted to form IgG.

The finding that rabbits can readily be immunized to their own thyroglobulin was difficult to reconcile with the original clonal-deletion hypothesis. Unlike sperm cells and myelin, thyroglobulin is formed early in fetal life and circulates in small but significant amounts. Even more puzzling was our observation that lymphocytes capable of binding thyroglobulin are present in normal rabbits as well as in immunized ones; according to the clonal-deletion hypothesis, there should be none.

Partial Clonal Deletion

An explanation for these observations seemed at first to be provided by the studies of William O. Weigle of the Scripps Clinic and Research Foundation in La Jolla, Calif. He found that it is generally easier to induce tolerance in *T* cells than it is in *B* cells. Could it be that the levels of circulating thyroglobulin were sufficient to render *T* cells unresponsive but to leave *B* cells reactive?

An affirmative answer to the second part of the question came from the reports by A. C. Allison and his colleagues at the Medical Research Council Clinical Research Centre in London and by Ian Mackay and his associates at the Walter and Eliza Hall Institute of Medical Research in Melbourne that normal human beings have lymphocytes that bind thyroglobulin. These investigators were unable to find thyroglobulin-binding *T* cells in peripheral blood. Perhaps the clonal deletion of *T* but not *B* cells could explain self-tolerance to nonisolated antigens such as thyroglobulin.

Weigle went yet a step further and showed that autoimmunity to thyroglobulin could be caused in rabbits if *T* cells directed to a related antigen were recruited to interact with the thyroglobulin-reactive *B* cells. His ingenious experiments consisted in introducing a foreign determinant into the rabbit thyroglobulin. Simple compounds such as arsanilic or sulfanilic acid served well. Without even requiring Freund's adjuvant these modified molecules were antigenic, probably because *T* cells stimulated by the foreign determinants were able to cooperate with *B* cells that reacted with autologous thyroglobulin.

The concept of *T*-cell deletion has satisfied many of the questions associated with autoimmunity, but some problems remain unsolved by it. One problem revolves around the genetic control of the autoimmune response to thyroglobulin. Working in collaboration with Adrian Vladutiu at the Wayne State University School of Medicine, I showed some years ago that mice of different strains differ greatly in their response to mouse thyroglobulin given with Freund's adjuvant. Mice of some strains produced large amounts of antibody and devel-

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oped severe lesions of the thyroid; other strains made less antibody and had minor lesions.

The genes responsible for this difference are linked to the H2 genes and are within the mouse's major histocompatibility complex. In fact, they meet the definition of *I* genes that regulate the reactions of immunologically competent cells. Moreover, the difference between good and poor responders among mice resides in their *T* cells. We could convert a poor responder into a good one by destroying its own *T* cells and substituting *T* cells from a good responder, even if the *B* cells and macrophages came from poor responders.

T Cells as Regulators

In terms of shedding light on autoimmunity these experiments showed that animals have *T* cells that regulate the response to autologous thyroglobulin. What role might these regulatory *T* cells play? The answer has come from recent studies by Yi-Chi M. Kong, Isao Okayasu and me in which thyroglobulin was injected into mice without an adjuvant. Mice usually show no response to such injections. They are even unresponsive when they are later given mouse thyroglobulin with adjuvant, the standard procedure for provoking autoimmune thyroiditis. We killed some of these unresponsive mice, took *T* cells from their spleen and injected the cells into normal, untreated mice of the same strain. These recipients were then shown to be unresponsive to the standard immunizing dose of mouse thyroglobulin.

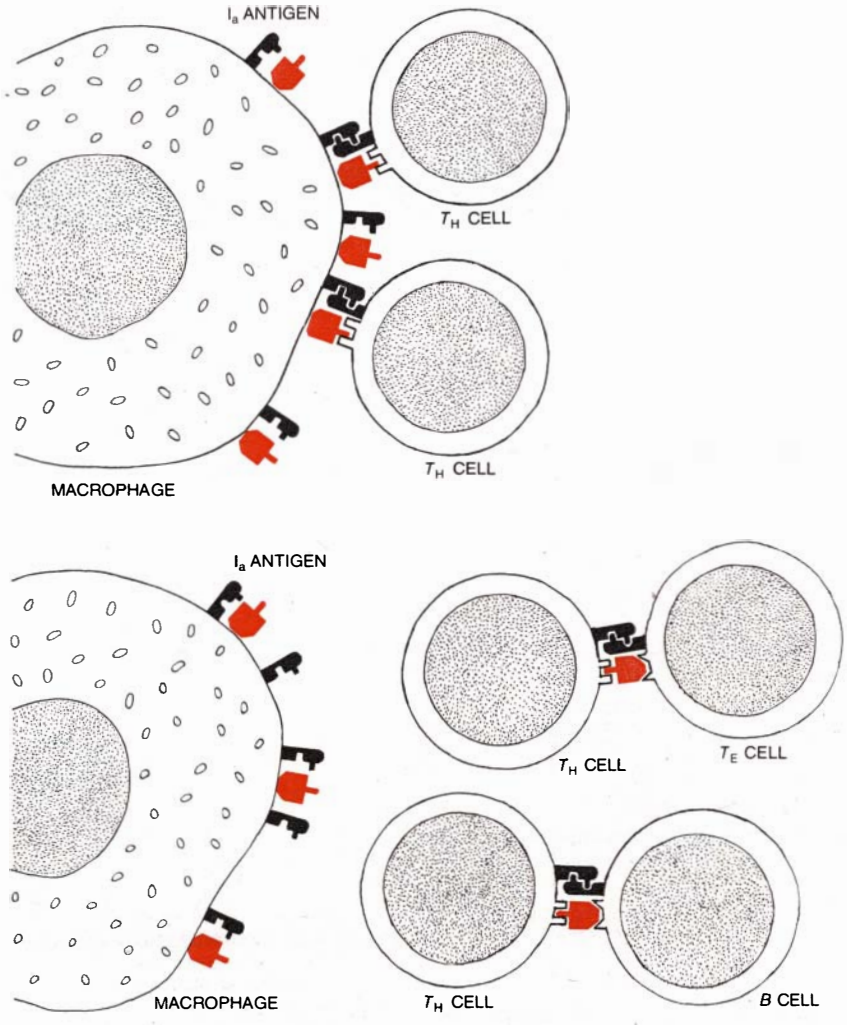
The findings reveal that autologous thyroglobulin, given without an adjuvant, preferentially induces the proliferation of clones of *T* lymphocytes that suppress an autoimmune response to thyroglobulin. The concept of suppressor *T* cells is relatively recent in immunology. It is based on the work of Peter McCullagh at the Australian National University and of Richard K. Gershon and Kazunari Kondo at the Yale University School of Medicine in the early 1970's. They were studying the induction of immunological tolerance in animals with large doses of red blood cells from sheep. Their finding was that the transfer of *T* cells from an animal tolerant to the sheep cells specifically suppressed the response to such sheep cells (but not to other antigens) in a recipient.

At the same time experiments on the induction of autoreactive *T* cells were being done in other laboratories. Work at the Necker Hospital in Paris by Jeannine Charreire and Patrick Yeni (based on a method developed at the Weizmann Institute of Science in Israel by Michael Feldman, Irun Cohen and Hartmut Wekerle) showed that *T* cells removed from the body can be immunized to thyroid cells of the same mouse strain. The degree of immunization, as measured by the proliferation of *T* cells, corresponded to the "responder" status of the particular strain. The stimulated *T* cells can be sustained in a culture medium for two or three weeks. Afterward they can respond specifically if they are confronted with the same stimulating cell. In other words, these *T* cells behave like memory cells with the specific ability to reinitiate autoimmune responses.

It has now become clear that an animal retains both *T* and *B* cells that are reactive with self-antigens such as thyroglobulin. Some *T* cells may act to promote an autoimmune response; others act to suppress it. The outcome of an encounter between an antigen and the immunological system depends on the balance of these positive and negative factors. The important point that has been learned is that self-reactive precursor lymphocytes need not be entirely eliminated to maintain self-tolerance, but it is necessary that suppression be predominant.

The balance between helper and suppressor forces can be shifted by a variety of internal or external events. The presentation of an antigen, with or without an adjuvant, is decisive, and so is the genetic status of the host. Other factors, including endocrine functions and viral infections, also alter the immunological balance.

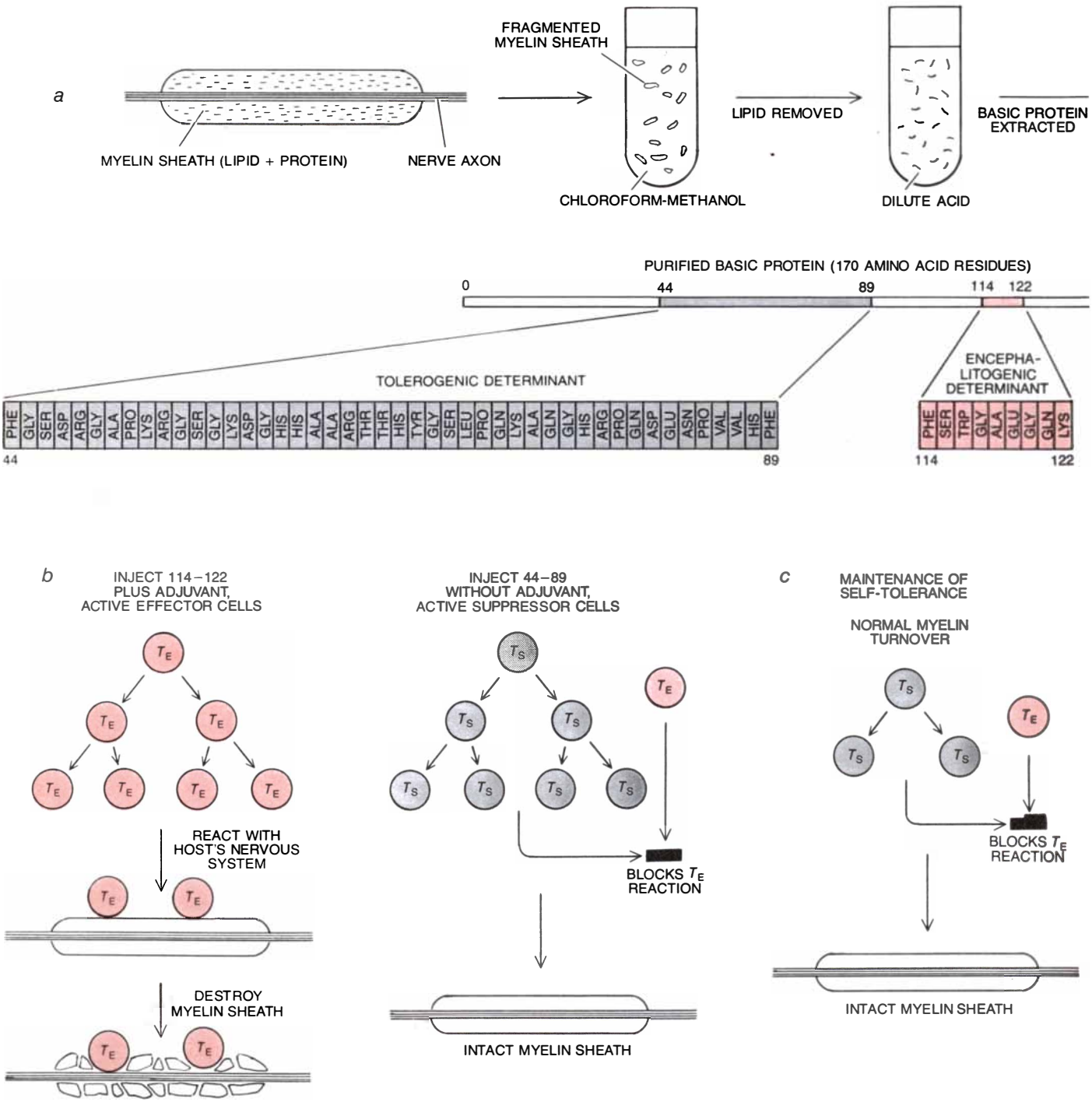
Marianne Bielschowsky of the University of Otago medical school in New Zealand originated a New Zealand black (NZB) strain of mice that is remarkable for the many autoimmune phenomena the animals develop during their short



ROLE OF MACROPHAGE in its interaction with *T* and *B* cells is crucial for an effective immune response. The ability of a T_H cell to recognize an antigen depends on the proper presentation of the antigen (*color*) by a presenting cell, here the macrophage. It must be presented in conjunction with a compatible I_a antigen, that is, a structure coded for by one of the *I* (immune response) genes. These genes control the formation of specialized complementary structures on the surface of a macrophage and a T_H cell that make the proper presentation of the antigen possible. The macrophage and the T_H cell interact either directly on the macrophage surface or indirectly through an antigen-I_a complex shed from the macrophage surface. T_H cells may interact with T_E or *B* cells provided that each cell shares I_a structures and recognizes either the same antigenic determinant or a different determinant on the same antigenic molecule.

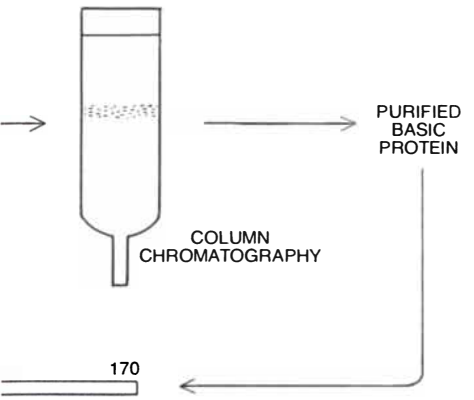
life span. At three months of age they start to show hemolytic anemia from the autoimmune destruction of their blood cells. Later they develop an enlarged spleen and lymph nodes and multiple autoantibodies, sometimes including the kind that react with the nuclei of various cells. Antibodies to nuclei are also found in the human autoimmune disease systemic lupus erythematosus. The premature death of these NZB mice is usually due to kidney failure caused by antigen-antibody deposits in the glomeruli of the kidney. If the mice live long enough, many of them develop cancers of the lymphocyte system.

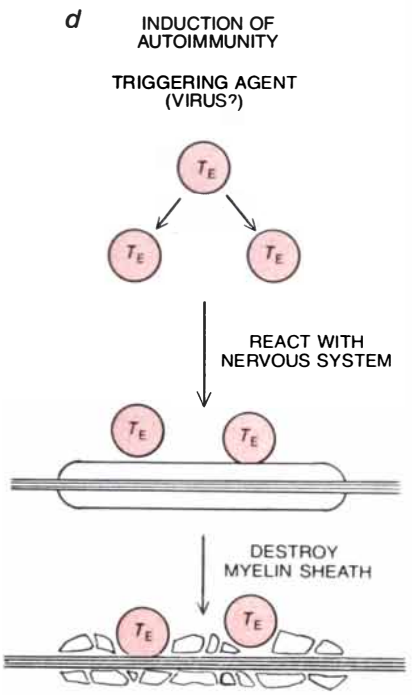
The New Zealand white (NZW) mouse develops no autoimmune disease and has a normal life span. When the NZB and NZW strains are crossed, however, the hybrids show severe autoim-



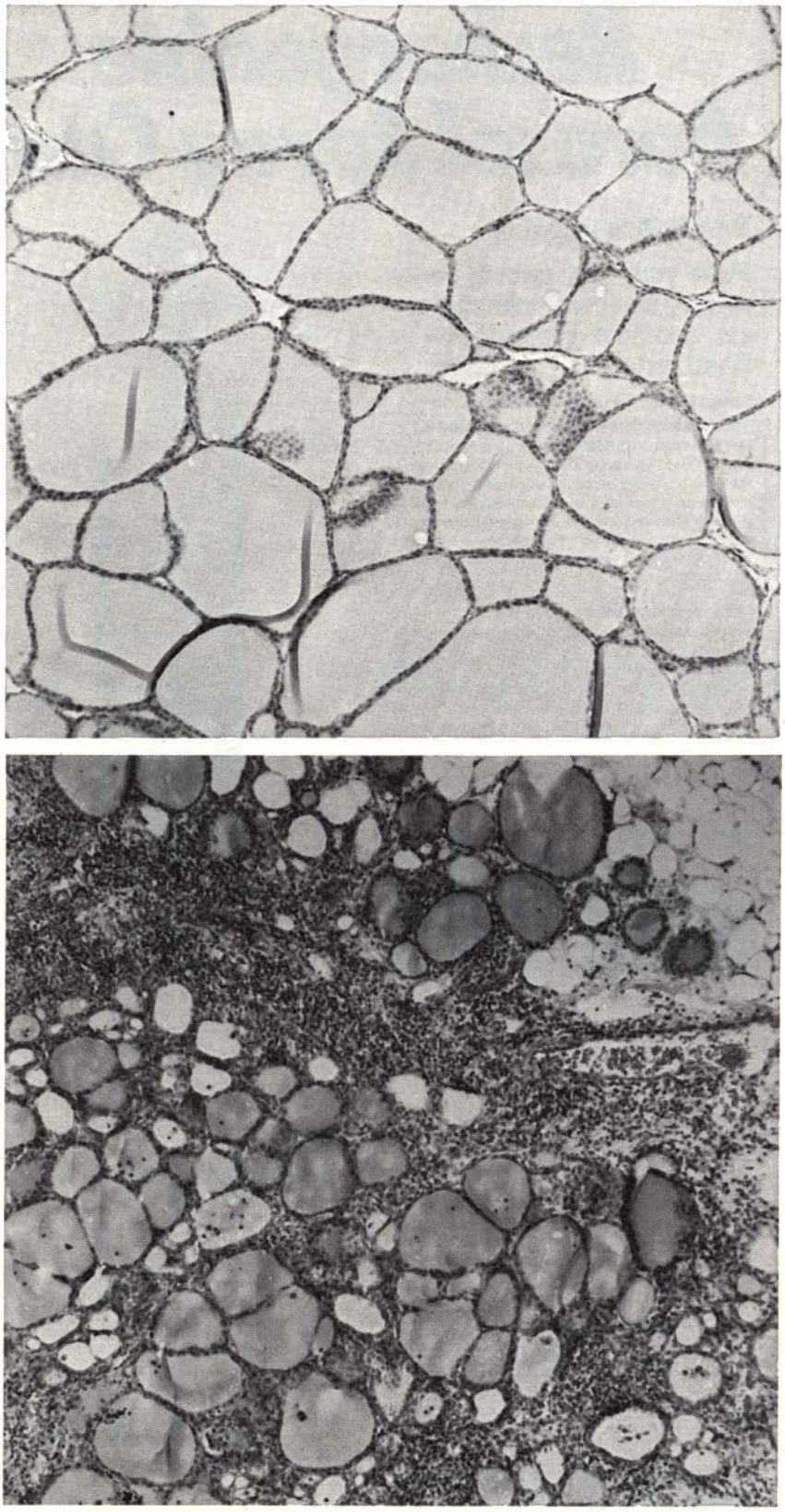
AUTOIMMUNE DISEASE was induced experimentally in animals by injections of basic protein extracted from myelin, the membranous sheath that surrounds and insulates nerve fibers. When the basic protein is extracted (*a*), it is found to consist of a single chain of 170 amino acids. Two regions affect autoimmunity in some species. Amino acids 114 through 122 constitute an encephalitogenic determinant, that is, this segment of the amino acid chain can induce autoimmune encephalomyelitis. Within amino acids 44 through 89 is a determinant that makes the animals unresponsive to the antigen, that is, it maintains self-tolerance. If the encephalitogenic determinant is injected with an adjuvant (*b*), it stimulates effector *T* lymphocytes (T_E) that react with the animal's nervous system and destroy normal myelin sheaths. If before such an injection the animal is treated with segment 44–89 lacking an adjuvant, the disease can be suppressed. Several studies have shown that suppressor *T* cells (T_S) are stimulated and the autoimmune response is blocked. It is probable (*c*) that nat-

mune disease. The hemolytic anemia is less prominent than it is in the NZB parent but the kidney lesions are worse. Antinuclear antibodies eventually appear in almost all the animals. The disease is a close facsimile of systemic lupus erythematosus.





ural self-tolerance to basic protein is maintained by the release of small amounts of segment 44–89 in the normal turnover of myelin. In nature a triggering agent such as a virus may mimic the effect of an adjuvant. The scheme of this illustration is derived from one prepared by Robert H. Swanborg of the Wayne State University School of Medicine.



AUTOIMMUNE THYROIDITIS is a disease that appears naturally and can also be induced experimentally by injecting tbyroglobulin plus Freund's complete adjuvant. The micrograph at the top shows a section of a normal thyroid gland of a rabbit. The micrograph at the bottom shows a thyroid section from a rabbit injected with rabbit thyroglobulin plus adjuvant. The thyroid is infiltrated with lymphocytes and macrophages. Human chronic thyroiditis is similar.

The origin of the autoimmune disease in New Zealand mice has long been a subject of controversy. Clearly there is a basic genetic component. Some investigators say they have isolated viruses that cause the lupus-like symptoms, but more recent evidence puts this finding in question. The immune system of New Zealand mice is abnormal in its development, as is shown by the fact that young animals are made tolerant only with difficulty. Perhaps the thymus is at fault; there is evidence of a deficiency of *T* cells at the beginning of disease.

Focus on Genetics

More recently attention has shifted to the *B* cells of the mice, which have proved to be hyperactive long before the onset of any autoimmune disorder. The proportion of large *B* cells with immunoglobulin on their surface is increased, a change characteristic of *B* cells that are close to the stage of making antibody. Since abnormalities are present even in mice that lack a thymus, they do not result from stimulation by *T* cells. It is quite likely that the ancestors of *B* cells in the bone marrow are abnormal, because it is possible to transfer autoimmune manifestations to normal mice by means of bone-marrow stem cells from New Zealand mice. In their autonomous behavior, which includes the secretion of immunoglobulins without instructions from *T* cells, the *B* cells of New Zealand mice behave much like malignant cells. Although the intrinsic impulse that drives these *B* cells is poorly understood, they are responding to a genetic program. This inborn error in the developmental program of immunological control results in multiple autoimmune diseases.

Additional lessons can be learned from the study of a genetically determined disease in which the autoimmune response assails a single organ. The chickens of a selected flock designated OS suffer from a thyroid deficiency because of severe thyroiditis. The flock was established by Randall K. Cole of Cornell University and was studied in detail by Witebsky and his colleagues Joseph H. Kite, Jr., and George Wick. By demonstrating the presence of autoantibodies to thyroglobulin in the blood serum of OS chickens Witebsky was able to prove that the disease was due to autoimmunity.

With my associates Larry Bacon and Roy Sundick I have been able to identify several genetic defects in the OS flock that predispose the chickens to the spontaneous development of autoimmune thyroiditis. First, the birds respond vigorously to chicken thyroglobulin. The trait is inherited in conjunction with their major histocompatibility complex. Second, the chickens were found to have

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a generalized defect in the maturation of their thymus. *T* cells with the ability to effect cell-mediated immunological reactions leave the thymus at an earlier age than they do in comparable normal chickens and take up their residence in peripheral tissues.

This abnormality in thymic development makes it likely that a self-antigen such as thyroglobulin would reach effector *T* cells before the equivalent suppressor cells were in place. Finally, the OS chickens have an intrinsic aberration of thyroid function, so that their thyroidal uptake of iodide (a unique constituent of thyroid hormone) is greater during embryonic life but their production of thyroid hormones is normal or reduced. Their thyroids are also resistant to the normal physiological regulation exerted by the pituitary gland. These thyroid changes are present well before any autoimmune damage is apparent.

Thus the spontaneous appearance of autoimmune disease in the OS chicken depends on the conjunction in this selected flock of three independent genetic lesions. They include a gene creating a strong response to thyroglobulin, a generalized thymic abnormality reducing the effect of suppressors in relation to effectors and a defect in the thyroid gland.

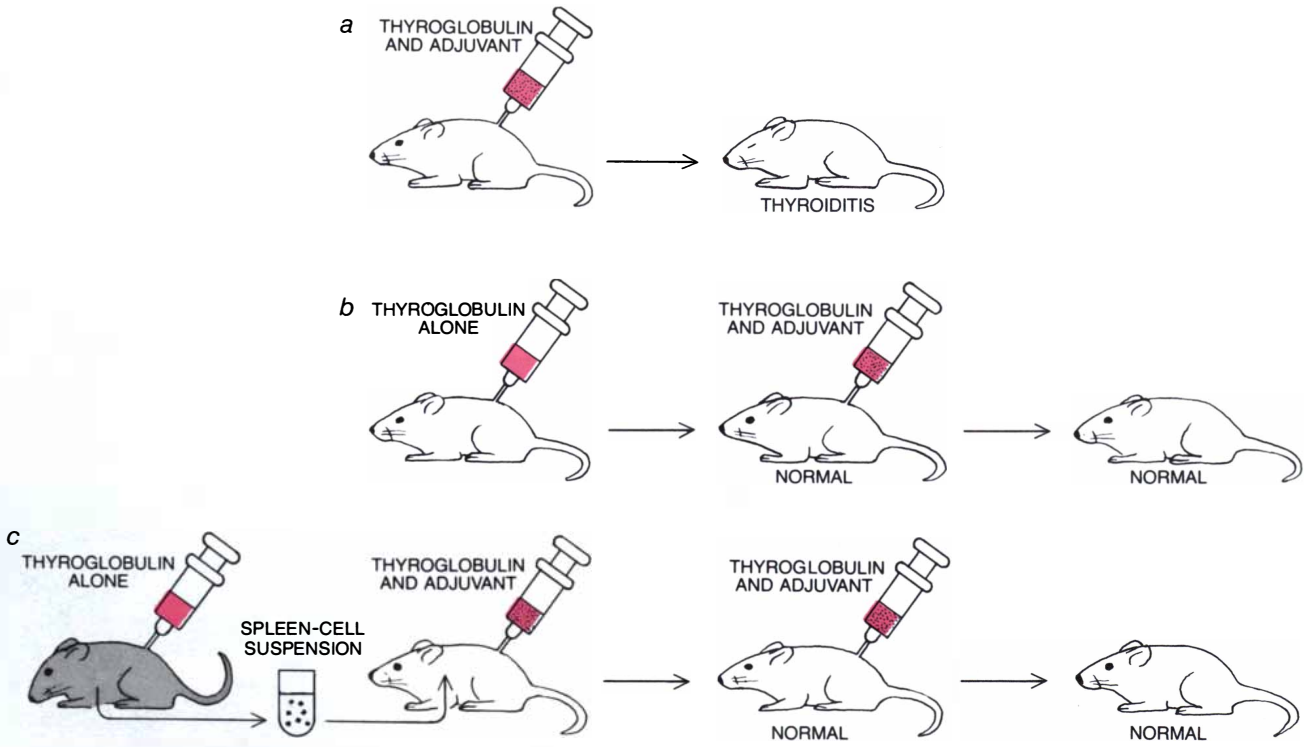
The lessons learned from the study of autoimmune disease in experimental animals are applicable to the problems of autoimmune disease in human beings. Clinical investigations have shown that an extraordinarily high proportion of human patients with autoimmune disease have particular HLA types. Occasionally this association of HLA type with disease is close enough to be of some practical value. For example, the patients with the autoimmune form of diabetes often fall into certain HLA types. Because this form of diabetes usually requires lifetime treatment with insulin the information is potentially of considerable value.

Human Autoimmune Diseases

Clinical studies also have shown that autoimmune phenomena cluster in certain families. For example, the incidence of autoantibodies to thyroglobulin is much higher in people who have a close relative with some disorder of the thyroid gland. Such patients may also have a greater than expected frequency of autoantibodies to such tissue as the adrenal cortex or the gastric lining. The adrenal antibodies are often found in patients with an unexplained failure of adrenal function, and the gastric antibodies are common in pernicious anemia, a disease resulting from the failure of the stomach to secrete a factor required for the absorption of vitamin B-12. The finding of such diverse autoimmune diseases clustered in certain families suggests a fundamental disorder of immunological control of the kind usually exerted by the thymus.

Most of the human autoimmune diseases are much commoner in women than they are in men. This uneven sex ratio suggests that the endocrine system, through its output of sex hormones, plays some role in the regulation of immune responses. Recently Norman Talal and his associates at the University of California Medical Center in San Francisco and Alfred D. Steinberg of the National Institute of Arthritis, Metabolism, and Digestive Diseases have found that they can delay the onset of autoimmune disease in hybrid female NZB-NZW mice by removing their ovaries and treating them with male hormones. These results open new approaches to the treatment of human autoimmune diseases such as systemic lupus erythematosus.

Most autoimmune diseases can affect people of any age, but autoantibodies to one or another human tissue are commoner in old age, even if no disease is evident. With the passing of time genetic errors tend to accumulate in cells, including the populations of lymphocytes that regulate the immune response. Age-related changes in the immune system strongly suggest that an active effort by



EXPERIMENTS WITH THYROGLOBULIN show varying results depending on the injection. If a mouse is injected with thyroglobulin and Freund's complete adjuvant (*a*), experimental thyroiditis is induced. A mouse injected with thyroglobulin alone shows no response (*b*) and does not develop thyroiditis even if it is later given thyroglobulin plus adjuvant. If that mouse's spleen is removed and a suspension of spleen cells is injected into a normal mouse (*c*), there is no response. The living spleen cells transfer the unresponsiveness.

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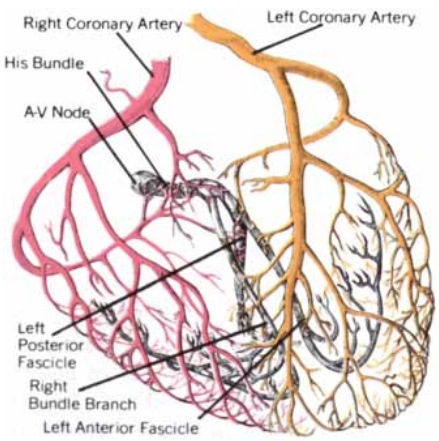

Branches of the right and left coronary arteries supply blood to the AV node and intraventricular conduction system.

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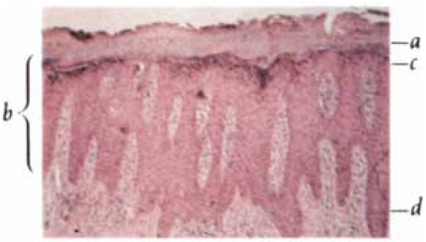
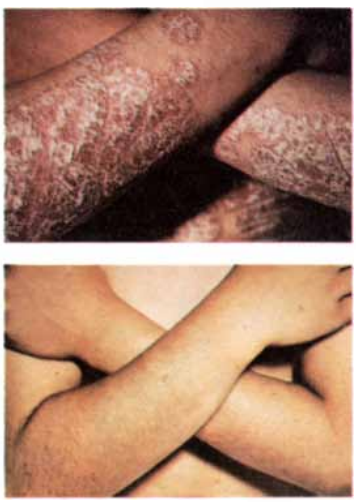


Histopathologic changes in psoriasis.



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

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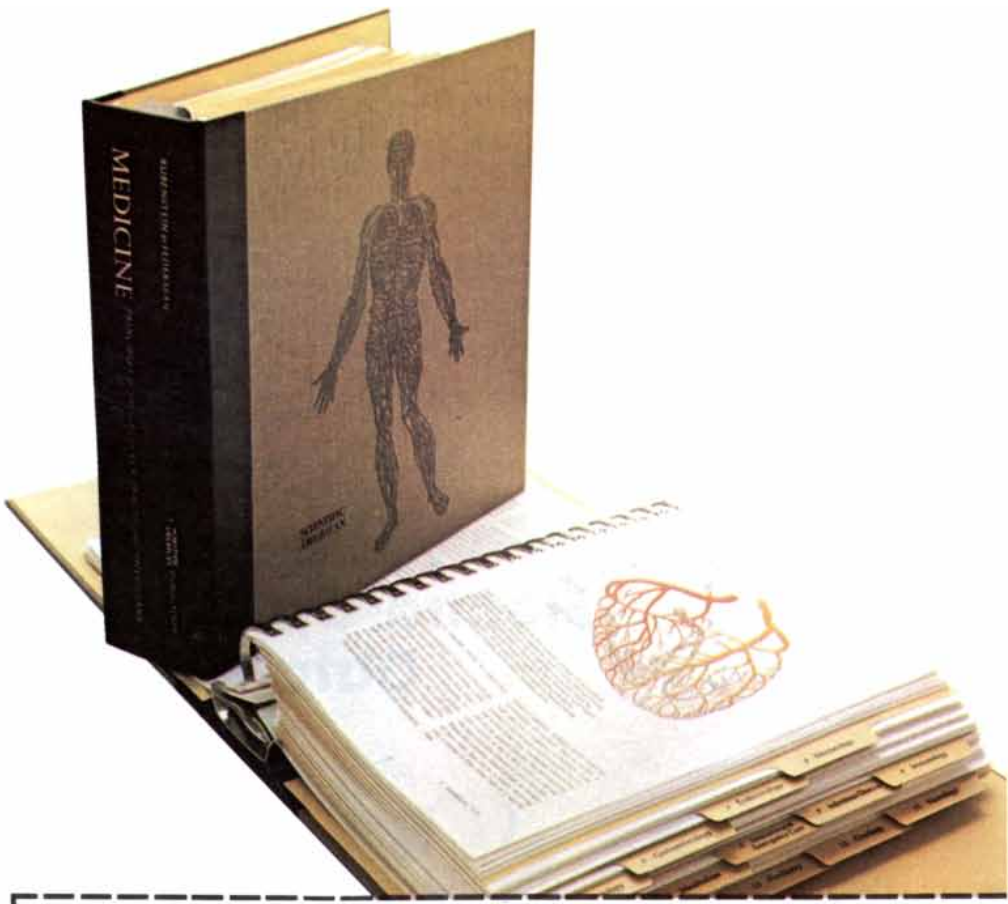

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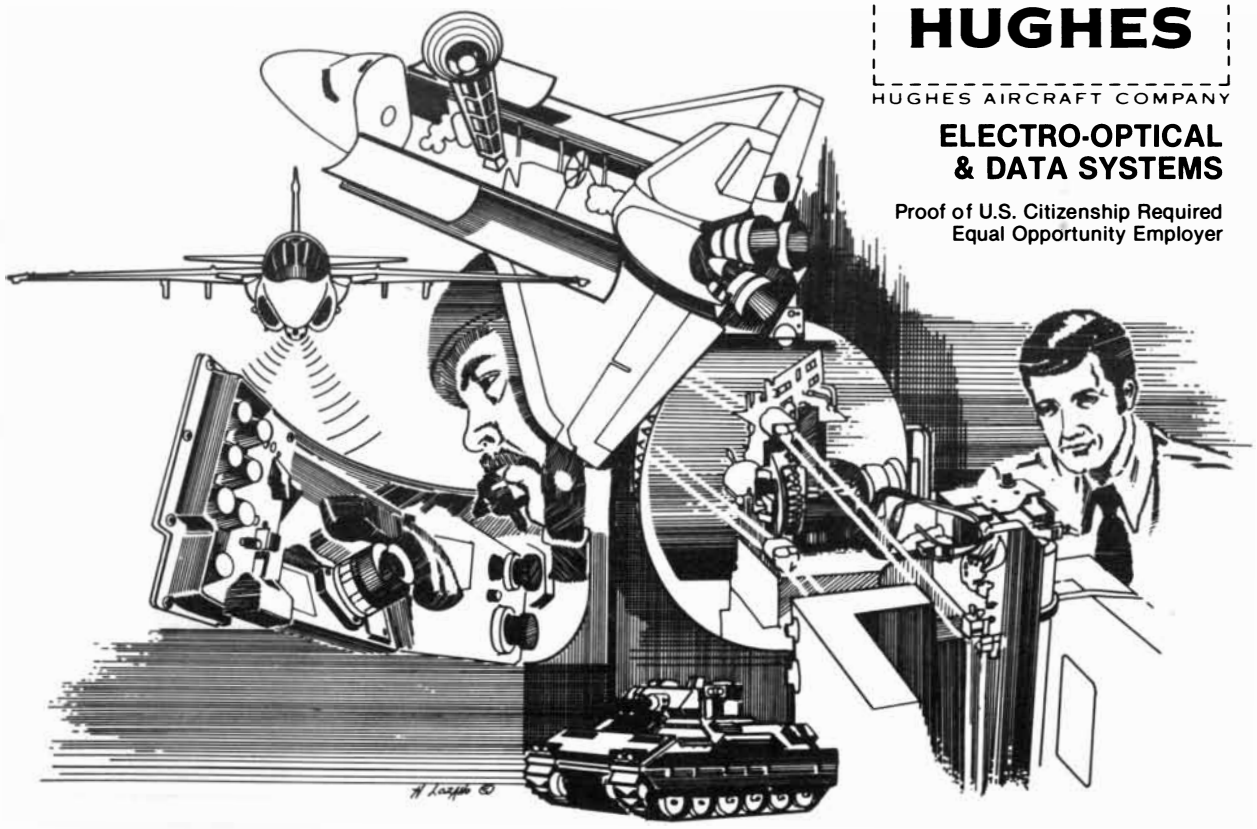


suppressor cells is needed to maintain immunological self-control.

The possible role of viruses in autoimmune disease continues to attract the attention of many investigators. There are several ways viral infections might disrupt the delicate equilibrium that prevents autoimmune responses. Viruses persisting in certain cells may cause the expression of novel antigens related to self-antigens on the cell surface. Alternatively, viruses may injure the *T* cells regulating immune reactions. As yet these possibilities have not been clearly established in human disease.

Future Directions

Autoimmunity is now accepted as being important in human disease. A survey at a large university hospital showed that some 18 percent of the patients suffer from a disease with significant immunological features. The understanding of some of these diseases has already been greatly strengthened by the detailed experimental studies of autoimmunity. For example, the realization that autoimmunity plays a role in systemic lupus erythematosus has led to the use of immunosuppressive drugs as an effective treatment of the disease, arresting what was once thought to be an inexorable and fatal process. Even myasthenia gravis is sometimes improved by measures designed to lower the level of circulating autoantibodies.

In diagnostic laboratories tests for autoantibodies are now a regular step in identifying many diseases, including systemic lupus erythematosus, thyroiditis, rheumatoid arthritis, some forms of progressive liver disease and even pemphigus, a severe and formerly fatal skin disorder. Thus it is evident that the experimental efforts devoted to the understanding of autoimmunity have been rewarded with practical advances in medical care, including both treatment and diagnosis.

It is no less important that studies of autoimmunity have opened new pathways to a deeper understanding of the immune response itself. Although the clonal-deletion theory of Burnet is still useful in broad outline, it has been much modified. From newer knowledge of the different roles of specialized cell populations and their positive and negative interactions has emerged the view that the immune system is a complex, integrated network requiring a continuous exchange of information among cells. Perturbation at any point of the network may affect all these dynamic interactions. The search for insight into the several ways the body can distinguish self from nonself has made it possible to begin sorting out the language by which the cells of the immune system communicate among themselves and with other cells of the body.

The Activity Cycles of Stars

Variations in activity similar to the sun's 11-year sunspot cycle have been followed in 91 nearby stars. The study may reveal why the cycle arises and why it sometimes disappears, as the sun's cycle has in the past

by Olin C. Wilson, Arthur H. Vaughan and Dimitri Mihalas

In 1610 Galileo discovered that the luminous surface of the sun exhibits dark spots. From their movement across the surface he inferred that the sun rotates about every 27 days. The spots on the sun's surface have since been shown to be associated with a rich variety of complex solar phenomena: magnetic fields, the violent eruptions of solar flares, fluctuations in the "wind" of electrified particles that flow outward from the sun and the entire cycle of solar activity. As astronomers learned more about the sun's activity they began looking for evidence of similar activity in nearby stars that resemble the sun in mass, age and other characteristics. As a result of a study begun in 1966 by one of us (Wilson) at the Mount Wilson Observatory one can now say that many other sunlike stars do in fact exhibit activity cycles analogous to the cycles of the sun.

The sun is about 4.5 billion years old, less than half the age of the oldest stars in our galaxy. It is classified as a dwarf star lying on the main sequence of the Hertzsprung-Russell diagram, in which the absolute magnitude of stars is plotted against their temperature. The sun is one of many middle-aged stars that have not yet exhausted their initial supply of hydrogen fuel. The energy released in the sun's core by the thermonuclear fusion of hydrogen into helium is transported to the surface by a combination of radiation and convection, with convection dominating in the outer quarter of the sun's radius. Convection is the transport of heat energy by the physical movement of material. It terminates just below the photosphere, the sun's deepest visible layer, where radiation takes over entirely. The roiling of hot masses of gas below the photosphere in combination with the sun's rotation forces the surface material at different latitudes and depths to rotate at appreciably different rates.

This differential rotation is now thought to be a principal cause of solar activity and of its cyclic character. All main-sequence stars whose mass is less than 1.5 times the mass of the sun should have similar strong convection currents in their outer layers. There are several hundred such stars close enough to the solar system to make feasible a search for analogues of solar activity in their radiation.

Such stars are not close enough, however, to allow direct observation of sunspots or, one should say, starspots. How, then, does one proceed? As we shall see, success has come through the precise measurement of the strength of the emission "core" in two spectral lines of singly ionized calcium atoms (calcium atoms stripped of one electron) in the chromosphere of stars. The solar chromosphere is the magnetically dominated outer atmosphere of the sun that shows up as a brilliantly colored flash just before and just after a total solar eclipse. Roughly speaking, it is the atmospheric layer between the photosphere and the corona, that is, between the sun's visible surface and the extremely hot outermost extension of its atmosphere.

The emission cores in the two calcium emission lines (the Fraunhofer *H* and *K* lines with wavelengths of 3,968.470 and 3,933.664 angstrom units in the near-ultraviolet part of the spectrum) are known to be enhanced in regions of high magnetic flux on the sun. It was therefore reasonable to expect that similar enhancement might be detected in the radiation flux of nearby dwarf stars if the *H* and *K* lines were isolated and observed over a period of time. The successful observation of fluctuations in the *H* and *K* lines of sunlike stars, begun 14 years ago at Mount Wilson, is providing theorists with samples of stellar activity cycles that in some stars are markedly different from the single example previously available: the sun. As a result theoretical models of stellar activity can be tested against objects with masses, compositions and ages different from those of the sun. This effort, which is still very much in its infancy, should ultimately yield a detailed picture of the mechanism responsible for the sun's own cyclic activity.

The significance of the activity cycles we have observed in other stars will be better appreciated if we review briefly what is known about the solar cycle, its manifestations and its likely causes and consequences. Except for some early gaps the record of sunspot activity can be traced back to Galileo's discovery of 1610. In 1843 Heinrich Schwabe showed that the average number of sunspots observed per year varies with a pronounced cycle of about 11 years. Soon thereafter Rudolf Wolf reconstructed the cycle back to about 1700 with the aid of old observatory records.

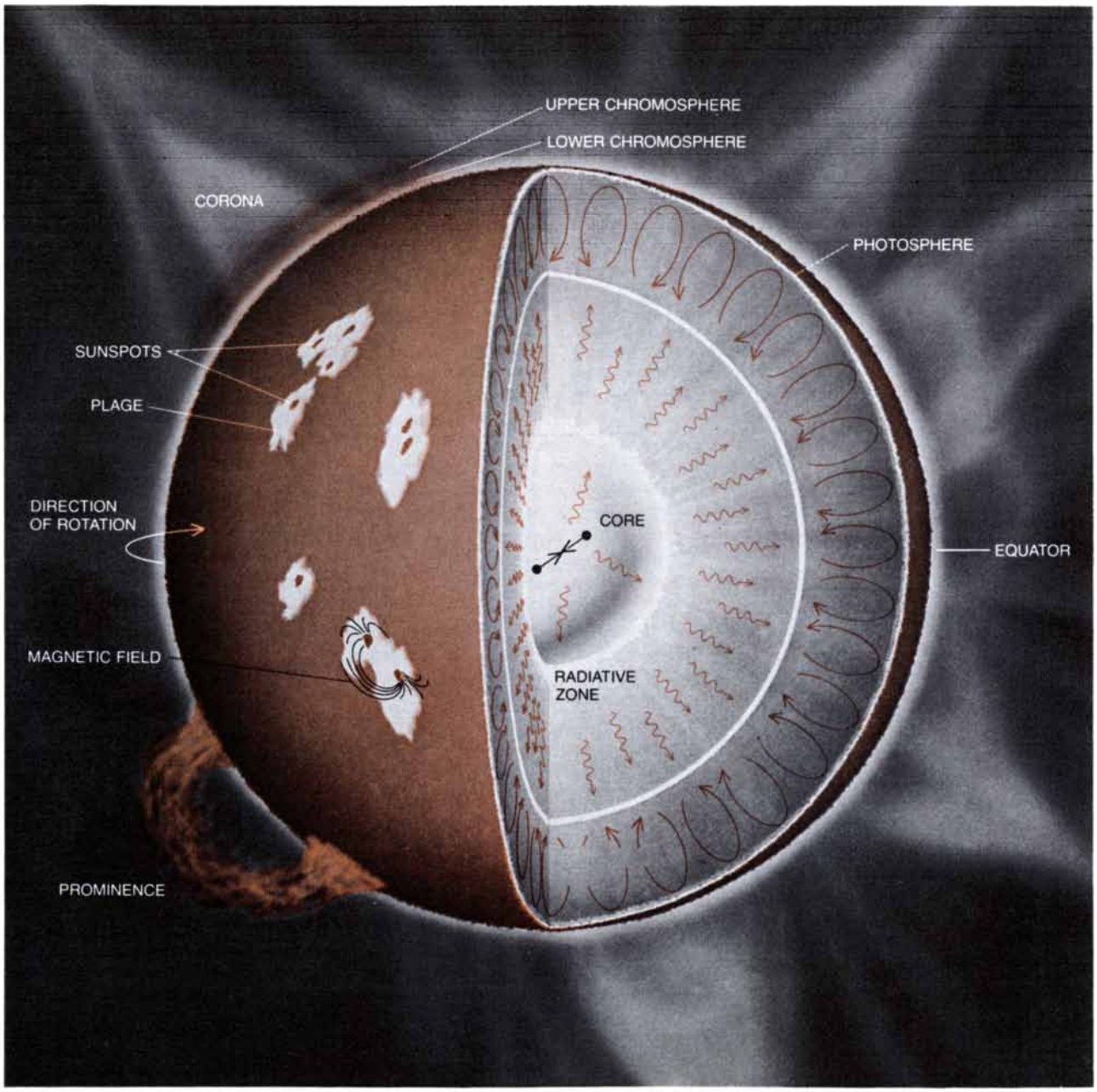
The sunspot cycle might have been discovered much earlier if it had not been for the almost total absence of sunspots over the 70-year period from 1645 to 1715. Twentieth-century astronomers did not accept the existence of this anomalous period until long after it had been described by E. Walter Maunder in 1894. The sunspot deficiency had been brought to Maunder's attention by Gustav Spörer, who had referred to it in a paper five years earlier. In recognition of Maunder's lifelong effort to establish the reality of the 70-year period of sunspot deficiency it is now known as the Maunder minimum. Its reality is no longer questioned.

In the middle of the 19th century Richard Carrington made two important observations about the sun and its activity. He showed that in the course of each cycle sunspots tend initially to appear at high solar latitudes and then to appear progressively nearer the solar equator. Carrington also pointed out that the sun does not rotate as a solid body: sunspots at the equator travel faster than sunspots at higher latitudes. When the locations of sunspots are plotted for a full cycle, the migration of spots toward the equator gives rise to a "butterfly" pattern. The first diagram of this type was published by Maunder in 1922.

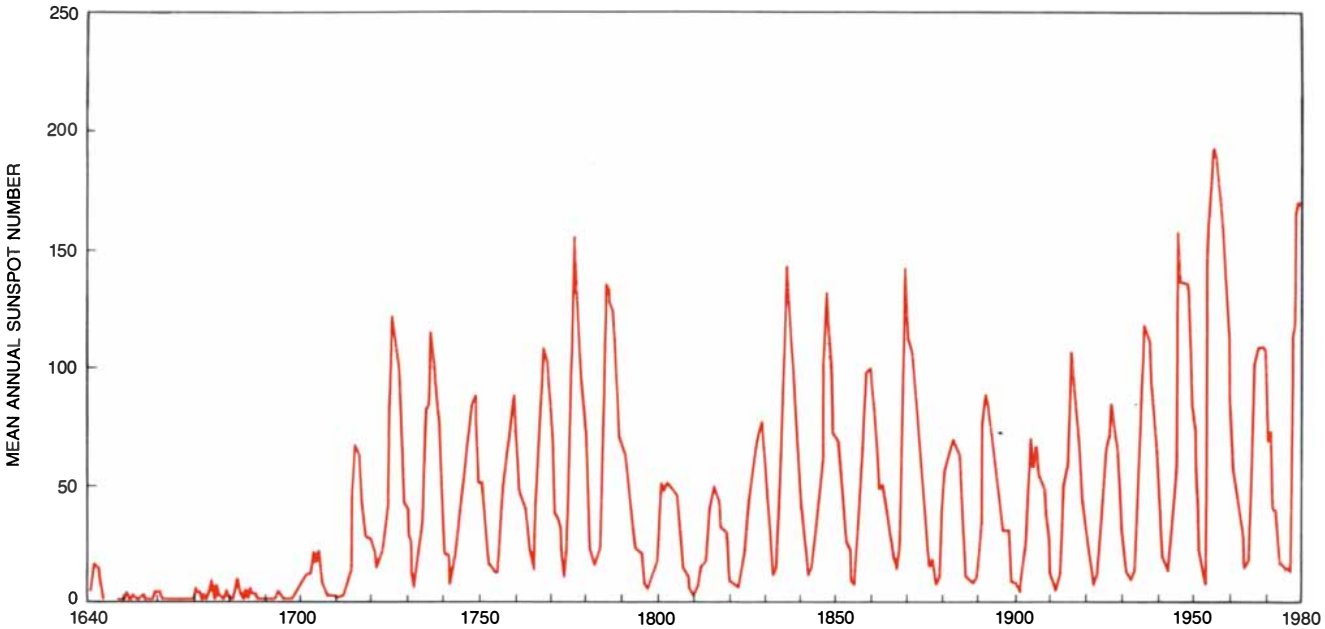
The full physical significance of sunspots began to emerge when George El-

lery Hale of the Mount Wilson Observatory demonstrated in 1908 that all sunspots are associated with strong magnetic fields, typically a few thousand times stronger than the magnetic field at the surface of the earth. From his study of sunspots he was able to deduce a number of remarkable laws. He found that the spots usually arise in pairs of opposite magnetic polarity. He showed that in each solar hemisphere the leading spot in such bipolar pairs nearly always has the same polarity and that in the other hemisphere the leading spot of the pairs nearly always has the opposite polarity. Moreover, Hale found that in successive sunspot cycles the polarities of the leading spots are interchanged, so that the true solar cycle is a magnetic cycle with a period of 22 years, not 11. More recent work has demonstrated that there are similar periodic reversals in the sun's overall magnetic field.

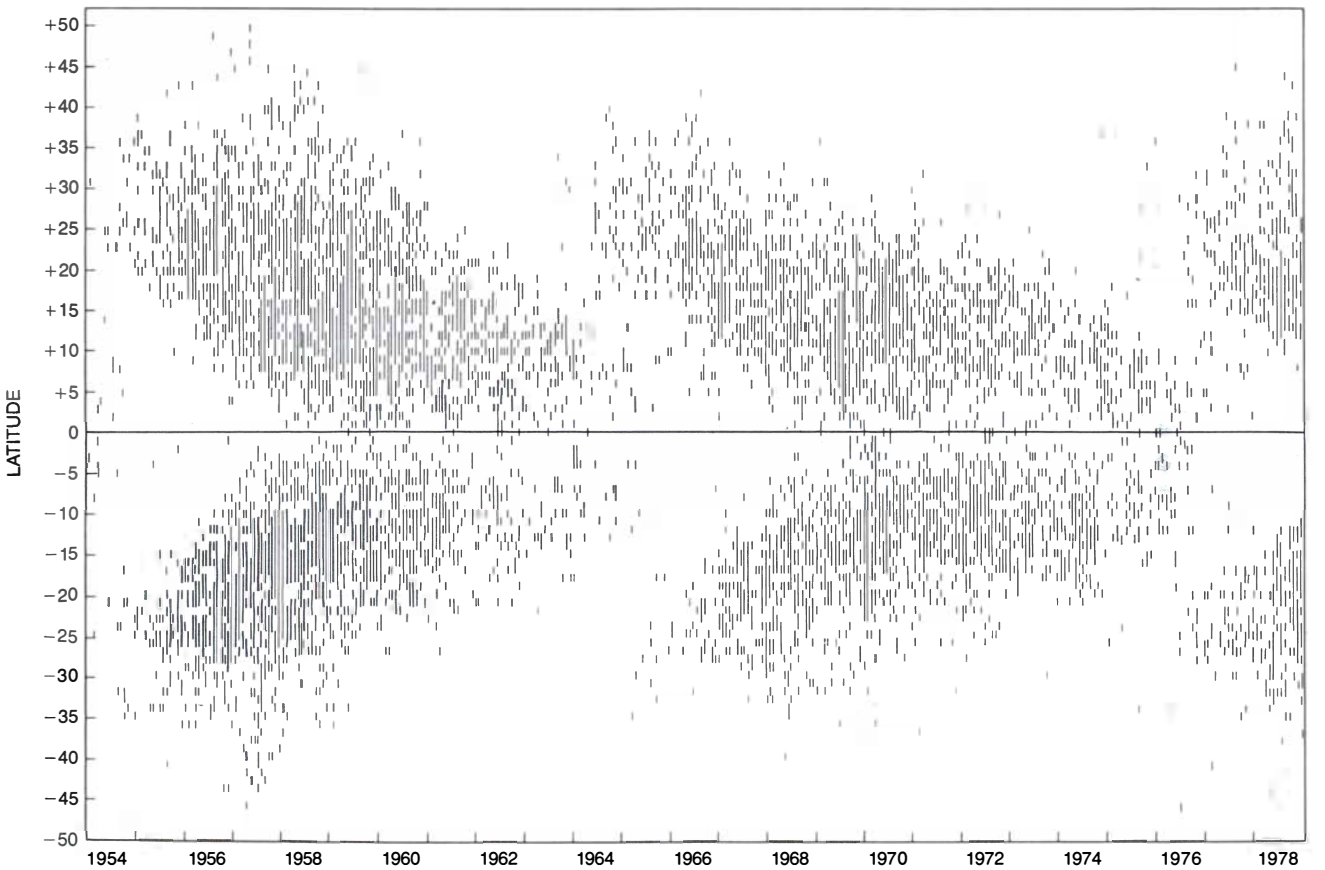
The widely, although not universally, accepted theoretical explanation of this cyclic behavior begins with the amplification of "seed" magnetic fields near the



ACTIVITY AND STRUCTURE OF THE SUN, depicted schematically, are based partly on observations and partly on theoretical models. The sun's features are presumably shared by all stars with a mass less than 1.5 times the sun's and with an absolute magnitude and a temperature that put them on the main sequence of the Hertzsprung-Russell diagram. Such stars obtain their energy from thermonuclear reactions in their core that convert hydrogen into helium. The energy so released is initially conveyed outward by photons, that is, by radiation. In roughly the outer third of the sun's radius energy is transported by convection: the "boiling" of gases. At the photosphere (the visible surface of the sun) energy is again radiated outward by photons. The temperature of the photosphere is 5,730 degrees Kelvin. In the chromosphere temperatures rise progressively until they reach about a million degrees in the corona. Occasionally giant prominences erupt from the solar surface. The sun also exhibits a cycle of activity, typically 11 years long, marked by a rapid rise in the number of sunspots followed by a slower decline. The sunspots, which mark regions of magnetic activity, usually erupt in pairs of opposite magnetic polarity. During the solar cycle the fraction of the sun's surface covered by plages, or hot spots, can vary from zero to more than 20 percent.



IRREGULARITY OF SUNSPOT CYCLE is evident from the historical record. The mean sunspot number represents the annual incidence of spots and spot groups seen on the solar surface. Following Galileo's telescopic discovery of sunspots in 1610, observations remained sporadic until about 1640. From 1645 to 1715, a span now called the Maunder minimum, sunspots were so scarce that the sun's cyclic activity was not evident. Following the first sizable peak in solar activity in 1715 peaks of irregular amplitude have been observed at roughly 11-year intervals. Over two cycles, about 22 years, the sun's magnetic field reverses, transposing north and south magnetic poles.



"BUTTERFLY" PATTERN of sunspot activity emerges when the latitudes at which sunspot groups make their first appearance are plotted month by month over the full 22-year solar cycle. The pattern shows that at the beginning of each 11-year half of the cycle sunspots erupt first at latitudes well away from the equator but then progressively nearer the equator as the cycle continues. As each sunspot group arises it is represented in the diagram by a vertical line one degree long at the appropriate latitude. Longer lines represent the emergence of two or more groups at adjacent latitudes. Some groups from the old cycle are still present (as in 1964 and 1976) when the new cycle begins. The butterfly pattern was first recognized in 1922 by E. Walter Maunder, who had earlier drawn attention to the 70-year sunspot minimum. This diagram was prepared from observations made by Robert F. Howard at the Mount Wilson Observatory.

surface of the sun by a complex interaction of convection and differential rotation sketched out in 1961 by Horace W. Babcock of Mount Wilson. Since the sun is rotating faster at the equator than it is nearer the poles, the lines of magnetic force tend to stretch and wrap around the sun parallel to the direction of rotation. Eventually, perhaps as a result of convection, some of the closely spaced lines develop a kink, so that the lines of force break the surface. A pair of bipolar spots would therefore represent two closely spaced regions where the field lines emerge from the surface and plunge back again. The opposite polarity of the spots is thereby accounted for. The hypothesis can be extended to explain how the overall magnetic field of the sun periodically reverses. Many important details of this theoretical picture remain to be developed, however, and recent evidence suggests that processes deeper in the sun than those visualized in the model may have to be invoked.

Some 15 years ago E. N. Parker of the University of Chicago argued on theoretical grounds that the outermost extension of the sun's atmosphere, the corona, is not bound by the sun's gravitational field. The coronal layers escape from the sun and give rise to the solar wind. The nature of the flow is strongly affected by magnetic fields. In regions where the magnetic-field lines are closed the wind is suppressed. In the recently identified regions known as coronal holes, however, the magnetic-field lines open out into interplanetary space. Here the solar wind, consisting of highly ionized gas, escapes freely, carrying with it trapped magnetic fields to great distances among the planets and beyond. Such coronal holes arise over regions of low magnetic activity on the sun's surface. Occasionally the holes form sufficiently close to the sun's equator for the ionized particles and trapped magnetic fields to stream out into the solar system along the plane of the earth's orbit. The particles and fields then interact strongly with the earth's ionosphere, the electrified region of the upper atmosphere, creating auroral displays and disturbing long-distance communications.

The sun's activity also has an important effect on the flux of cosmic rays, the highly energetic ions and electrons of unknown origin that constantly bombard the earth. When the sun is in an active state, its magnetic field and magnetic fields carried by the solar wind bend the trajectories of the incoming cosmic-ray particles and reduce the number of them entering the earth's atmosphere. The reduction in flux also reduces the rate at which cosmic rays transmute nitrogen 14 in the upper atmosphere into the radioactive isotope carbon 14.

In the course of photosynthesis grow-

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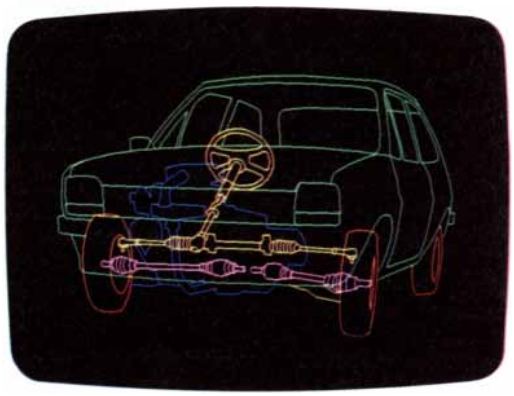

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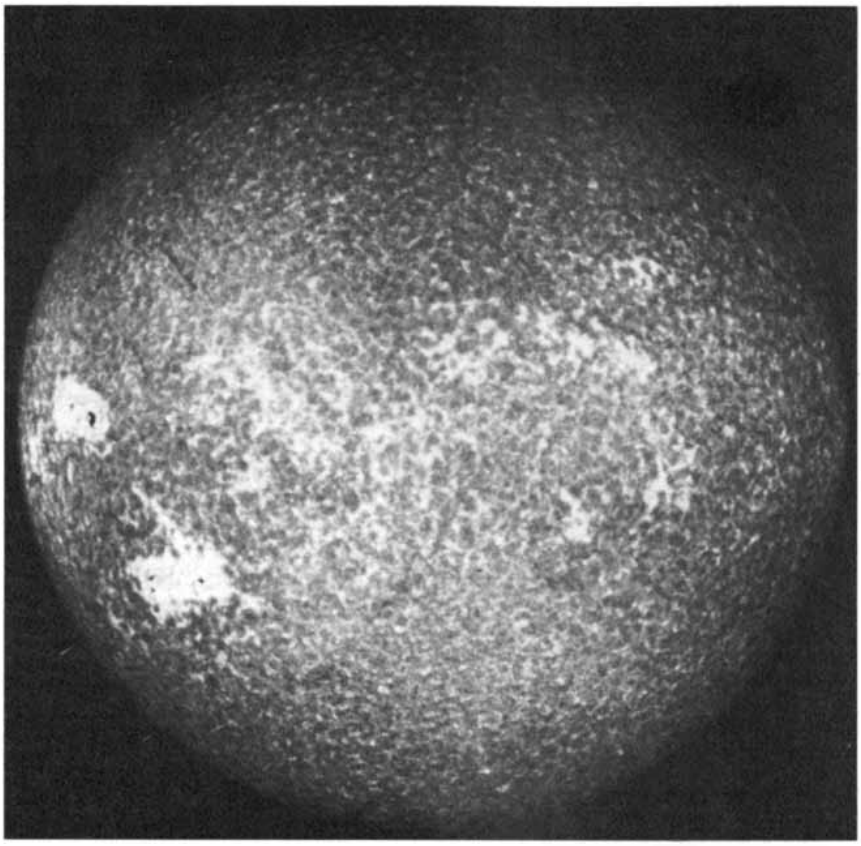
ing plants incorporate small amounts of carbon 14 (which has a half-life of 5,730 years) into their tissues along with the common isotope carbon 12. By measuring the carbon-14 content of the rings of ancient but well-preserved trees investigators have been able to reconstruct the history of carbon-14 abundance in the atmosphere going back more than 7,000 years. This remarkable record, which was one of the things that convinced scientists of the reality of the Maunder minimum, indicates that similar long-term deviations in the sunspot cycle also occurred in earlier epochs. The Maunder minimum coincided closely with a succession of unusually cold years in Europe, sometimes called the Little Ice Age, so that renewed interest has arisen in the possibility that through mechanisms as yet unknown solar activity may have far-reaching effects on the earth's climate. This possibility remains highly controversial, however. The lessons of the Maunder minimum are clear: astronomers do not yet understand the solar cycle, and their wanting to learn more about it is not mere idle curiosity.



SPECTROHELIOGRAM records the radiation emitted by the sun at a single wavelength, in this case 3,933.664 angstrom units, at the "core" of one of two strong absorption lines, the *K* line, of calcium atoms stripped of one electron. The picture shows the sun on September 11, 1961, toward the close of the most active sunspot cycle ever recorded. The image was made by T. Cragg with the 60-foot tower telescope on Mount Wilson. (North is at the top; east is at the left.) The image is dominated by a coarse reticulated network of "supergranulation" cells, roughly 30,000 kilometers across, that make sunspots difficult to perceive. A sunspot can be seen, however, within the large plage near the east limb. The supergranulation cells are driven by convection currents that rise vertically at the cell center and spread horizontally outward. The horizontal flows appear to sweep magnetic-field elements to the cell boundaries, where they accumulate to form the network. The cells seem to have individual lifetimes of about 20 hours. In solar magnetograms, which show the distribution and strength of magnetic fields on the sun, one can see that the cell network is intimately associated with magnetic-field lines confined in narrow flux tubes. The tubes in turn give rise to most of the *K*-line emission recorded in the spectroheliogram. In the authors' study of activity cycles in other stars they look for variations in emission at the wavelength of the *K* line and of the *H* line at 3,968.470 angstroms.

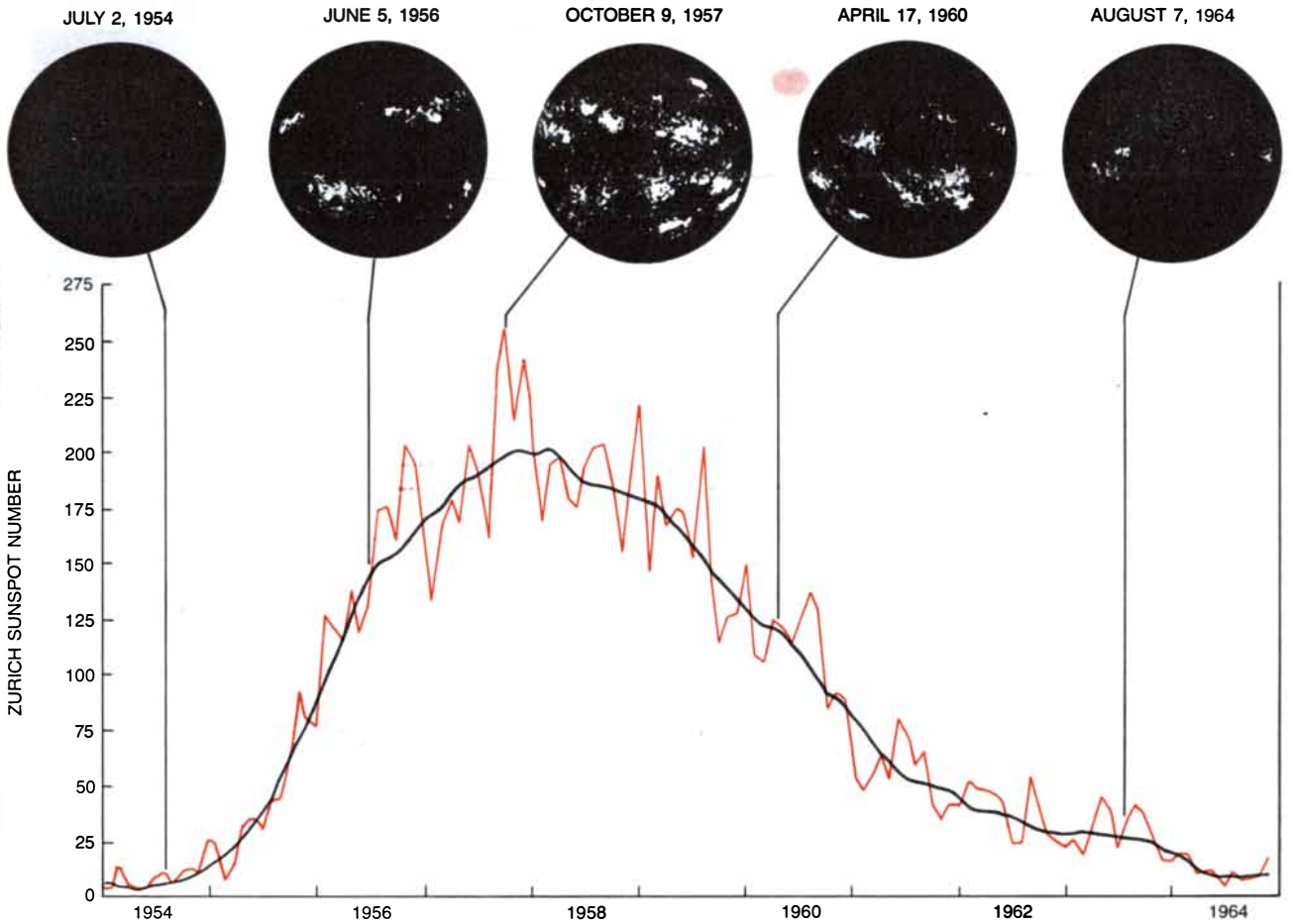
It was reasonable to hope that if cyclic activity could be detected in nearby stars one might gain deeper insights into the cyclic mechanisms at work in our own star. In the sun the enhancement of the *H* and *K* lines of calcium in regions of high magnetic-flux density is best observed in spectroheliograms, photographs taken in monochromatic light that exclude all wavelengths except those including the *H* or *K* lines. In a calcium spectroheliogram magnetically active regions show up as the bright, extended patches called plages (from the French for "beaches") connected by a mottled network of much fainter emission, representing the quiet chromosphere. In the monochromatic images active regions are so bright that they almost completely mask the dark sunspots with which they are associated.

Many fascinating details can be seen in the spectroheliograms that have been recorded daily for many years at solar observatories around the world. For example, the fraction of the sun's surface occupied by bright active regions is found to vary from zero at the minimum of the solar cycle to 20 percent or more at the maximum. If variations of that magnitude occurred in the strength of *H* and *K* lines from nearby stars, it should be possible to observe them with suitably sensitive detectors.

Even before an effort was made to record such variations the *H* and *K* emission lines of many normal stars had been intensively studied photographically by one of us (Wilson) and by others. Such studies had shown, for example, that the intrinsic widths of the *H* and *K* emission components are closely correlated with the absolute luminosity of a star: the wider the two lines are, the brighter the star is. This correlation (known as the Wilson-Bappu effect) is good enough to provide reasonably accurate intrinsic stellar luminosities and thus can serve as a new scale for stellar distances. Moreover, for dwarf stars such as the sun the strengths of the *H* and *K* emission lines are correlated with the age of the star. The weaker the emission in the core of these lines, the older the star. The theoretical explanation of these two types of correlation is still a lively topic among astrophysicists.

The search for time variations in the *H* and *K* lines did not become feasible until the early 1960's, when a high-resolution spectrum scanner was installed on the 100-inch Mount Wilson reflector in combination with a highly stable electronic system for counting photons. The new instrumentation was developed largely by Edwin W. Dennison, Guido Münch and J. Beverley Oke of the California Institute of Technology and Arthur D. Code of the University of Wisconsin at Madison. In 1966 one of us (Wilson) began using the new equipment to search for variable chromospheric activity in a sample of about 70 candidate stars. As part of the calibration procedure, to ensure constancy of measurement, another sample of about 20 very old and inactive stars was selected to serve as a control group. The first phase of the investigation was successfully completed in 1977.

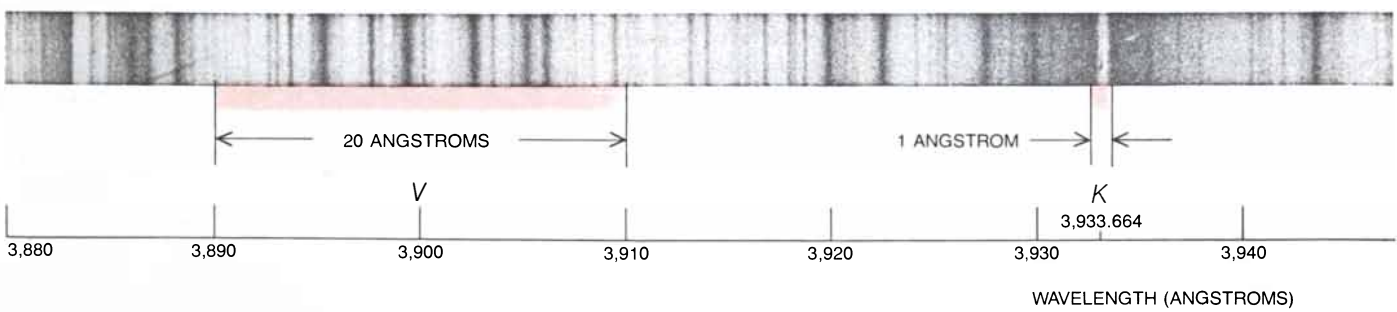
Since that year the study has been continued with a new instrument expressly designed for observing chromo-



CHANGES IN SPECTROHELIOGRAMS made at the wavelength of the calcium *K* line are depicted for five representative points during solar activity cycle No. 19, which ran from 1954 to 1964. During this cycle the "Zurich" sunspot numbers reached a record peak of 200 on a smoothed curve of monthly means. The jagged curve depicts the month-to-month changes in the number of sunspots. The rapid rise time and slower decay time are characteristic of solar activity cycles. The spectroheliograms show how the sun's active regions, visible as bright plages, vary in area and migrate toward the equator in the course of the cycle, as is depicted in detail in the butterfly diagrams.

spheric variability in stars by another of us (Vaughan), originally with the sponsorship of the National Aeronautics and Space Administration. The instrument is still being improved with the support of the National Science Foundation. The new instrument, the "*H-K* photometer," is considerably stabler and somewhat more sensitive than the original one and is routinely used in conjunction with the 60-inch Mount Wilson reflector. (The light-gathering power of the 100-inch mirror is not needed.) With this apparatus one of us (Vaughan) and George W. Preston of Mount Wilson have extended the original survey without interruption, and the continuation of the survey into the future seems reasonably ensured.

The *H-K* photometer works as follows. The stellar radiation collected by the 60-inch mirror strikes a diffraction grating and is dispersed into a spectrum. The spectrum is refocused and strikes a plate perforated with four slits. Two of the slits are very narrow and pass only the *H* and *K* emission lines; the narrow slits are bracketed by two other slits about 20 times wider. A rotating "chopper" wheel allows radiation to pass through only one slit at a time but through all of them in sequence. In this way a single detector of high stability



ENLARGED SPECTROGRAM of a nearby star, HD 22049, shows the *H* and *K* emission lines of calcium measured by the authors in monitoring stellar activity cycles. Their *H-K* photometer compares the strength of the *H* and *K* emission lines with the strength of bands of continuum emission 20 times wider that are either more violet (*V*) or redder (*R*) than the *H* and *K* lines. The measurements yield the "mean

monitors the flux of photons through the slits. The photon count for each slit is accumulated in a counter.

At the end of the observing period (usually less than 10 minutes per star) a "mean *H-K* flux" is computed by adding the number of photons that passed through the slits aligned with the *H* and *K* emission lines and dividing the total by the sum of the photon fluxes measured in the wider slits on each side of the narrower slits. The flux ratio so obtained is an index of the prevalence of active regions on the star being examined. We find that such measurements are reproducible with an accuracy of 1 or 2 percent in spite of the effects of the earth's atmosphere: haze, clouds and small motions of the star's image. The accuracy has proved to be both necessary and sufficient to detect significant variations in stellar activity.

When one examines the record of *H-K* flux variations in a stellar sample extending back as far as 1966, one can draw a number of conclusions about the chromospheric variations in main-sequence stars. A sizable fraction exhibit definite or probable cyclic behavior comparable to the sun's. Among stars of similar mass and similar *H-K* flux some are cyclic; others, within observational limits, remain constant. Even stars that appear to have an essentially constant average flux over a number of years can exhibit a substantial variation in *H-K* flux, sometimes a very large one, on shorter time scales. In some instances the flux changes significantly from one night to the next. Among the cyclic stars there is a marked tendency for the time interval from minimum flux to maximum to be shorter than the interval from maximum to minimum, as is the case with the solar cycle.

From all the data in hand we estimate that perhaps half of the main-sequence stars less massive than about 1.5 solar masses may show cyclic behavior. The fraction of cyclic stars could, however, considerably exceed this estimate, for two reasons. Some of the stars in our sample may well have cycles much longer than the observing period of 14 years. Other stars in the sample, which like the sun have a fairly low photon flux, have not been observed often enough to rule out cycles of very small amplitude. A convenient way to monitor the *H-K* flux of the sun is to measure the sunlight reflected from the moon. Fifty-one measurements made during the maximum of the last solar cycle (from February, 1968, to October, 1970) gave a mean *H-K* flux for the sun of .178 $\pm$ .0008 Wilson flux unit. Another sequence of 35 measurements made during the minimum (from January, 1976, to April, 1977) yielded a mean flux of .164 $\pm$ .0006 unit. The small mean increase of .014 unit (8.5 percent) from solar minimum to solar maximum could easily be missed if it occurred in a star for which many fewer observations were made in corresponding time intervals.

Furthermore, it seems likely that in any observing period as brief as 14 years not all main-sequence stars will be in a cyclic mode, as can be inferred from the Maunder minimum of the sun. For the 15 or so stars in our sample that have so far exhibited definite or probable cycles the period of the cycle ranges from about seven years to at least twice that long. In other words, the observed stellar cycles bracket the solar cycle of 11 years.

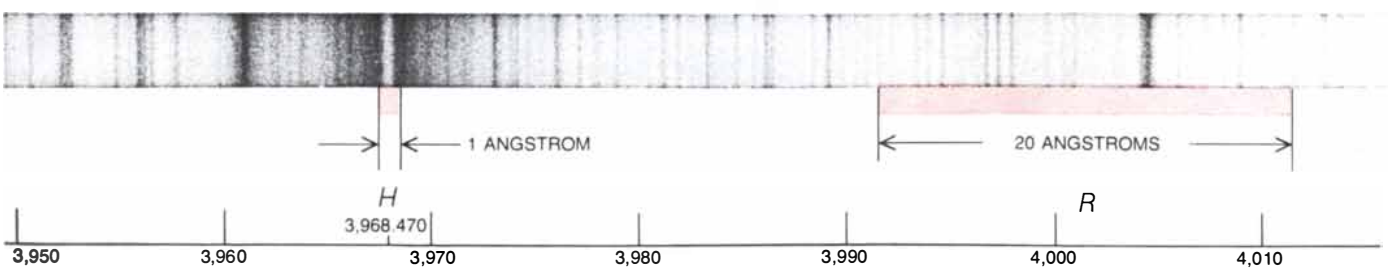
A useful way to organize stellar observations is to plot the value of the newly observed feature against the value of some standard classification feature such as the color index. The color index represents the difference in the star's magnitude when it is measured in two selected wavelength regions, such as blue (*B*) minus "visual" (*V*), or yellow. As the color index is normally plotted the hottest, bluest stars fall at the left and the coolest, reddest stars at the right.

When the *H-K* flux indexes of the 91 main-sequence stars in the original sample are plotted against their color index, the overall trend is clear: the index of *H-K* flux increases to the right as stellar temperatures decrease and stars get redder. The general upward slope does not necessarily signify an absolute increase in the strength of the *H* and *K* emission lines; most of it is caused by a decrease in the continuum emission (the denominator in the *H-K* index) per unit of stellar surface and per unit of wavelength interval as the star's photospheric temperature decreases.

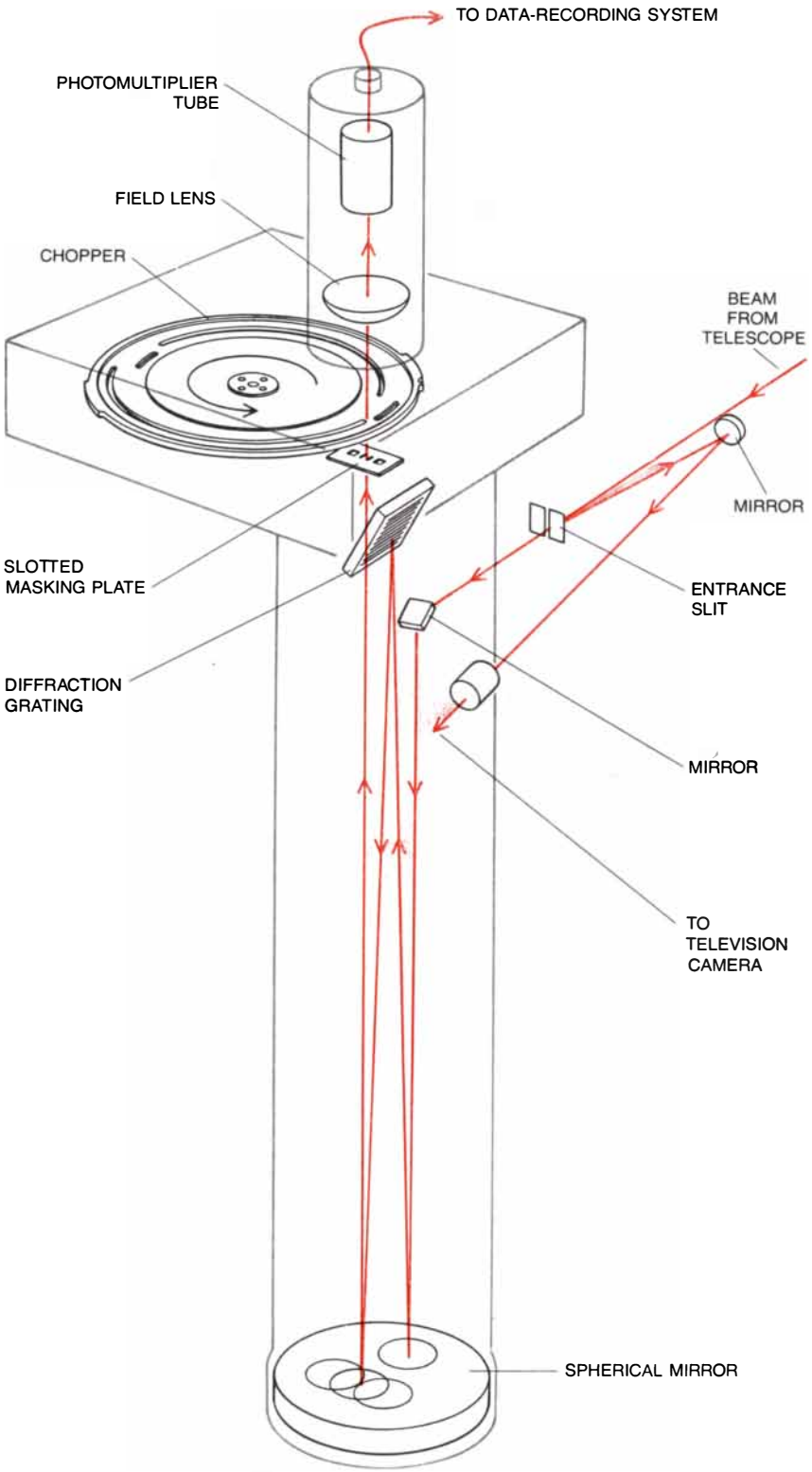
An unexpected feature of such a plot is that the upward trend in the *H-K* flux index divides into two roughly parallel branches. This bifurcation is evident not only for the 91-star sample but also for a much larger sample of 396 stars representing a large fraction of all the sunlike stars in the northern celestial hemisphere within a distance of 25 parsecs (about 80 light-years). The 91 stars are represented by vertical bars of various lengths according to the range of variation observed over an 11-year period; the other 396 stars are represented by dots because in most instances they have been observed only once [*see illustration on page 116*].

It has been known for some time that chromospheric activity for main-sequence stars decreases slowly with the star's age. In the plot of *H-K* flux v. color index a vertical cut anywhere through the plotted points identifies a group of stars of similar mass but of different ages, with the youngest stars at the top of the cut and the oldest at the bottom. One would expect the stars along such a cut to exhibit a smooth distribution. In the diagram of *H-K* fluxes, however, there is a distinctly noticeable gap, particularly toward the left-hand side. One explanation is that for a period in the past there was a hiatus in the birth of new stars and hence a present-day shortage of stars in that particular range of ages. Although this is a conceivable explanation for the bifurcation in the diagram, we do not consider it a very likely one. Rather we suspect that at some age, and for reasons still not known, the mechanism that gives rise to the chromospheric phenomena shifts abruptly from one mode to another mode with a markedly reduced output.

The precision of measurement in the *H-K* flux study is such that nearly all deviations of 3 percent or more must be regarded as intrinsic to the stars and not



***H-K* flux": the sum of the fluxes at *H* and *K* divided by the sum of the fluxes at *V* and *R*. The two strong *H* and *K* lines carry away about 10 percent of all the radiant energy emitted by the star's chromosphere and therefore are a reliable index of chromospheric activity in stars. Since 1968 HD 22049 has exhibited rapid excursions in *H-K* flux but has shown no sign of periodicity (*see illustration on page 118*).**



H-K PHOTOMETER designed by one of the authors (Vaughan) analyzes starlight collected by the 60-inch telescope on Mount Wilson. The device filters out all light except the light in four narrow regions of the spectrum, as is shown in the illustration at the bottom of the preceding two pages. Light from the telescope is focused on an entrance slit at the upper right and continues along the path shown in color. The spherical mirror at the bottom serves both to collimate the light it directs to the diffraction grating and to refocus the light dispersed by the grating, thus forming an image of the spectrum. A section of the spectrum falls on a masking plate perforated by two slits that pass the *H* and *K* lines and two wider slits that pass spectral bands 20 times wider on each side. A rotating "chopper" wheel allows light from only one slit at a time to reach a photodetector tube. The photons that pass through each aperture in sequence are counted separately and summed over exposures of from 30 to 600 seconds to obtain mean *H-K* flux.

as artifacts attributable to equipment or procedure. Accordingly a large part of the scatter seen in our plots of *H-K* flux must be considered real and must be accounted for if possible. Some of the scatter may be a modulation in flux that arises from the rotation of the star. Such a modulation of *H-K* flux from the sun was detected more than a decade ago by solar observers in Czechoslovakia. It is known that the sun's magnetic field and its accompanying chromospheric activity is not uniformly distributed around the sun's equator. The activity is patchy and often detectably stronger on one side of the sun than on the other, and this asymmetry often persists for a considerable length of time (up to many rotations). As the sun rotates, a fixed observer sees a roughly periodic variation in chromospheric emission that coincides with the rotation. It is reasonable to expect other stars to exhibit similar flux changes modulated by rotation.

To uncover such an effect unambiguously would call for continuous and intensive daily observation of stars extending over periods of several weeks or months. A trial effort of this kind was in fact begun last summer by investigators from the Carnegie Institution of Washington, Harvard University, the Sacramento Peak Observatory and the Astronomical Institute in Utrecht, all working as a group at the Mount Wilson Observatory. Although the results of the effort are too new to have been published, they are encouraging.

It seems likely that periods of stellar rotation can be measured with high precision from observations of the modulation in *H-K* fluxes, even for stars turning so slowly that their rotation cannot be detected in any other way. The classical means of determining rotation has been based on the broadening of photospheric absorption lines by the Doppler shift in the observed wavelength of light emanating from the approaching and receding areas of the rotating stellar surface. This method is feasible if the star rotates fast enough; with the currently most sensitive methods of detection the equatorial velocity must exceed two kilometers per second to be discernible. The observed line broadening depends on the angle between the observer's line of sight and the star's rotation axis. The more closely the rotation axis coincides with the observer's line of sight, the smaller the observed broadening is. The orientation of a star's rotation axis is, of course, an unknown. The method based on the modulation of the *H-K* flux, in principle at least, should yield values independent of the angle between the star's rotation axis and the observer provided that the angle is large enough for the modulation to be observed at all.

Another approach to measuring stellar rotation periods could be based on

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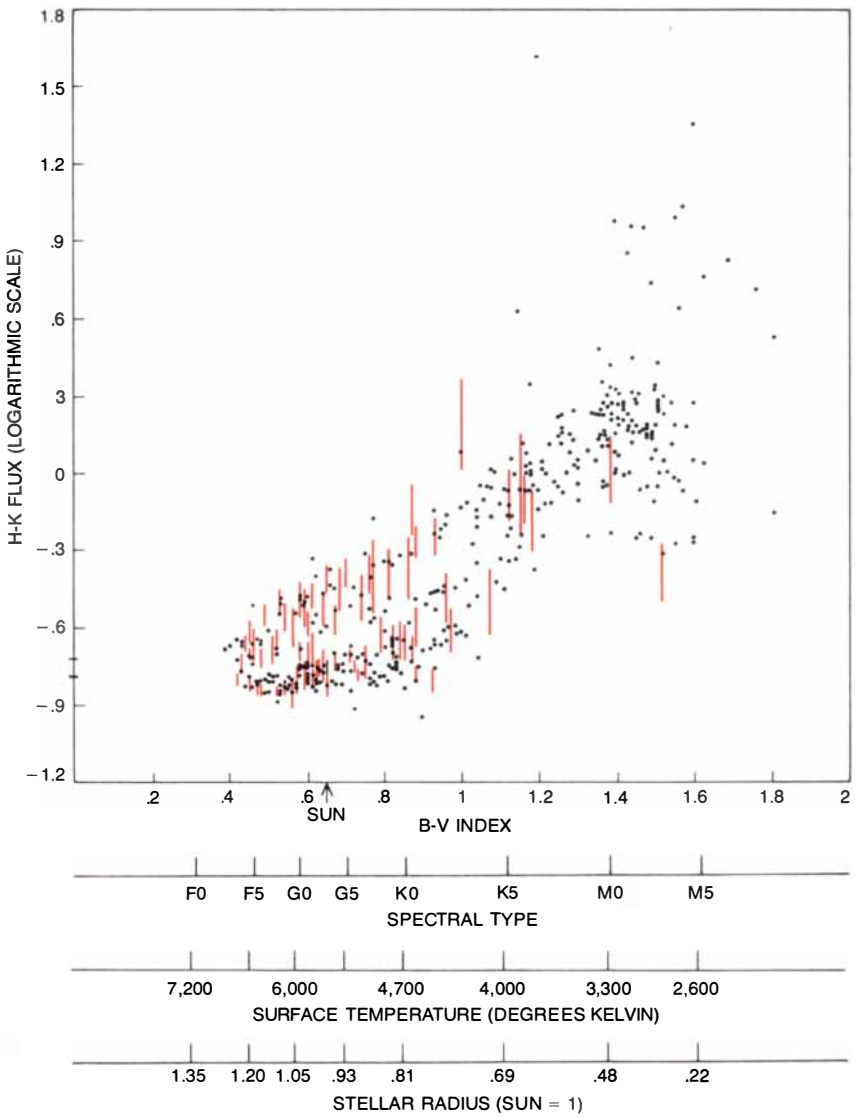
the likelihood that all sunlike stars rotate faster at the equator than they do near the poles. If the stellar activity regions resemble the sun's in progressing from higher to lower latitudes in the course of a cycle, that is, from longer to shorter rotation periods, it should be possible to derive rotation periods from a quickening in the rotation-modulated changes in *H-K* flux observed over one cycle or more.

Stellar rotation would generally be too slow to account for significant changes in the *H-K* flux that take place in the course of a day or two. Such short-term variations most likely indicate the characteristic time scales for the growth and decay of large active regions on the star. Our observations suggest that on many stars changes occur more rapidly than they do on the sun. Another possibility is that whereas solar chromospheric activity is intermittent, some stars may have chromospheres that are



H-K FLUX VARIABILITY for 91 stars in the Mount Wilson stellar activity survey (*vertical bars in color*) is compared with a "snapshot" survey of the *H-K* flux of nearly 400 stars (*black dots*) representing a sizable sample of all the sunlike main-sequence stars within 25 parsecs of the solar system in the northern half of the sky. The *H-K* flux is plotted on a logarithmic scale. Each star is placed on the horizontal scale according to its *B-V* flux index, a classification that is correlated with spectral type, effective surface temperature and stellar radius. The *B-V* flux index represents the difference in a star's magnitude when the magnitude is measured in the blue (*B*) part of the spectrum and in the visual (*V*), or yellow, part. The hotter, bluer stars lie at the left, the cooler, redder stars at the right. The vertical bars indicate the maximum range of variation in *H-K* flux for the 91 survey stars. The single bar in black is the range in variation in the sun's *H-K* flux as it is determined by measuring sunlight reflected from the moon. A vertical cut anywhere through the collection identifies stars of similar mass but of widely different ages, with the youngest at the top and the oldest at the bottom. Although the sun is among the oldest stars in the sample, it is only half the age of the oldest stars in our galaxy. The puzzling gap that suggests a paucity of middle-aged stars is discussed in the text of this article.

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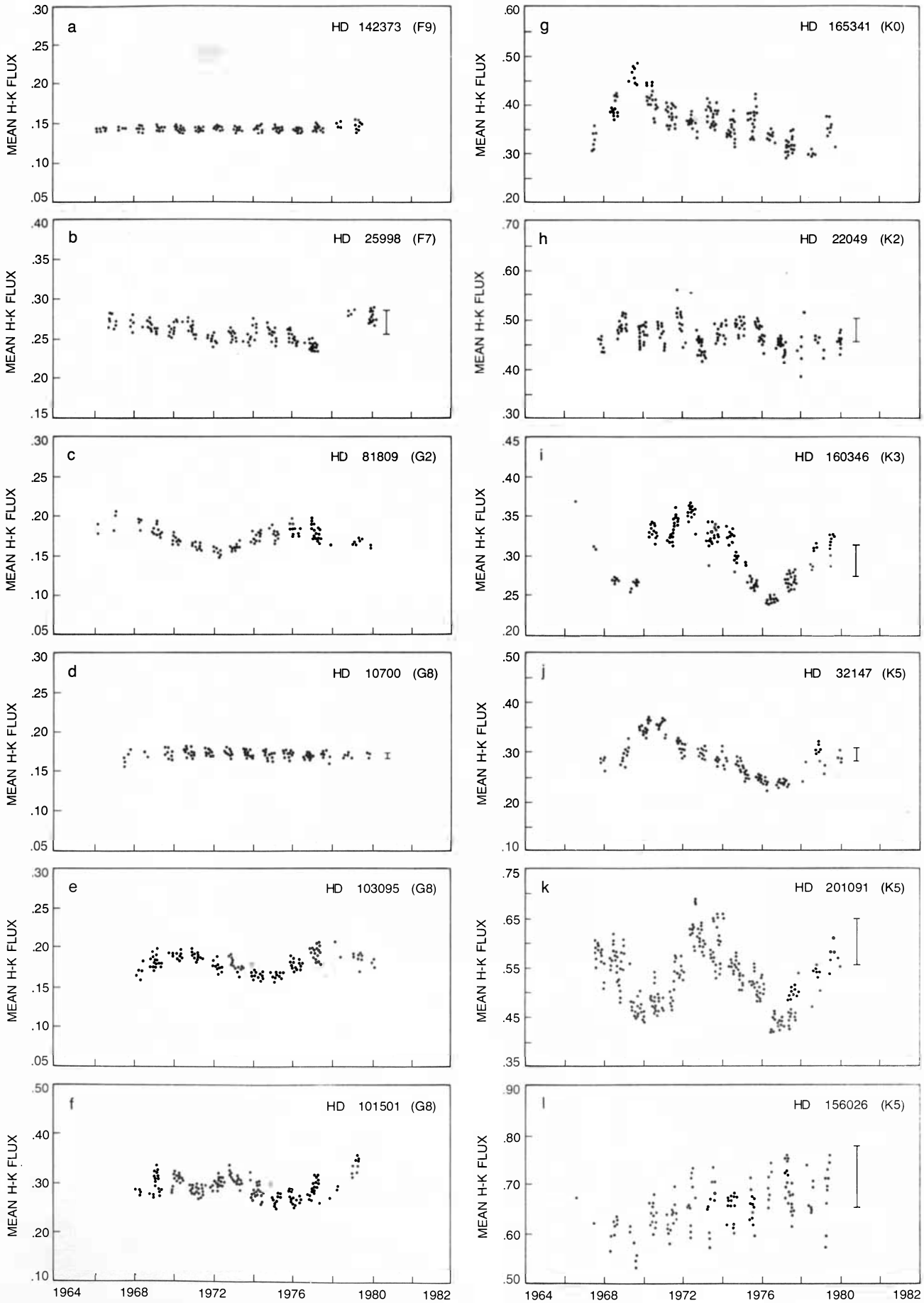

almost continuously active. In such stars flares may occur more often and on a larger scale than they do on the sun. These are tentative suggestions; enlightenment in these matters can come only as a result of future investigations.

It has been recognized for some time that the study of stellar activity cycles would benefit greatly from a parallel and long-term study of the *H* and *K* fluxes of the sun conducted by methods as similar as possible to those devised for the stellar observations. Such a program has been carried out since 1974 by William C. Livingston and O. R. White at the Kitt Peak National Observatory. Similar programs more recently have been initiated by R. L. Stimets of the University of Lowell and by C. Zwaan and his co-workers at the Astronomical Institute in Utrecht. The solar observations by these workers, like a controlled experiment under known conditions, are sure to yield insights that will help investigators to interpret the analogous observations of stars. Even though the sun is only one star, with its own fixed values of age, mass and chemical composition, it has been and must remain the source of detailed information on all the varied phenomena that are associated with activity cycles.

It will be some time before a body of knowledge can be acquired about stellar cycles approaching what has been learned about the solar cycle from several centuries' accumulated observations. What the stellar studies lack in duration can be compensated for in part by the opportunity to take snapshots of a diverse sample of many objects differing in mass, composition and stage of evolution. For example, generations may pass before astronomers have an opportunity to observe the sun during a recurrence of the Maunder minimum. Several of the stars in our observing program may right now be passing through a quiescent period that corresponds closely to such a minimum.

We have mentioned that chromospheric activity in main-sequence stars fades as the star gets older. There are two ways to account for this observation, the simplest being that the magnetic fields in stars are remnants of fields acquired at birth when the prestellar gases were condensing into a protostar. From this point of view the decline of chromospheric activity with age would indicate the initial magnetic fields are gradually transformed into mechanical and thermal energy that in time is radiated away. From the other point of view, which is the more widely accepted one, a star's magnetic field is generated by an internal dynamo that is maintained by the star's rotation. The strength of the magnetic field accordingly declines as the star's rotation is braked by interaction of the ionized particles ejected by the star and the lines of force in the star's magnetic field.

What happens to chromospheric activity after a star has remained on the main sequence long enough for its magnetic activity to fade to a low level? Eventually the star exhausts its hydrogen fuel, begins to burn helium and restructures itself so that both its luminosity and its radius increase; it becomes a subgiant star. As the star's radius grows its rotational speed diminishes in accordance with the conservation of angular momentum. One might therefore expect the strength of the star's magnetic field to decline still more and its chromospheric activity to fall to a correspondingly low level. Yet it is known that many subgiants have highly active chromospheres: their *H* and *K* emission can be substantial. The curious revival of activity in subgiant stars is additional evidence that the physics underlying stellar magnetic activity is poorly understood. So far no search has been made for activity cycles and rotational modulation in subgiants or in any of the other classes of stars that lie off the main sequence. It is an exciting task for the future.

CHROMOSPHERIC VARIATIONS are shown on the opposite page for a representative sample of 12 stars selected from the group of 91 sunlike stars systematically observed at the Mount Wilson Observatory since 1966. The dots are individual observations of *H-K* flux; the bars show the range observed in 1980. All the stars are within 25 parsecs (about 80 light-years) of the solar system and lie on the main sequence. Each star is identified by its number in the Henry Draper catalogue. The star's spectral type, which is correlated with its surface temperature, follows in parentheses. The type letter (*F, G, K*) specifies a certain temperature range, which is further subdivided into 10 levels by the following digit (0 through 9). (The relations among spectral type, temperature, color and stellar radius are shown in the illustration on page 116.) The stars are arranged in the order of their decreasing surface temperature with one exception: star *a* is slightly cooler than star *b*. Star *a* is put at the head of the group as an example of a star with no evidence of cyclic behavior and very small scatter in *H-K* flux. Star *b* shows a slow decline followed by a sharp rise in 1979 and 1980. Star *c* (of the same spectral type as the sun, *G2*) exhibits a cycle of about 10 years, very close to that of the sun. Stars *d*, *e* and *f*, although they are of the same type, *G8*, show marked differences in behavior. Star *e* is an old star with a content of metallic elements much lower than that of most other stars, including the sun. Star *g* is an example of a star that is probably cyclic but that has not been observed through one cycle. Star *h* exhibits rapid flux variations but no obvious cycle. The next three stars (*i, j, k*) exhibit short, well-defined cycles. Star *l* is another star with no periodicity but large variations.

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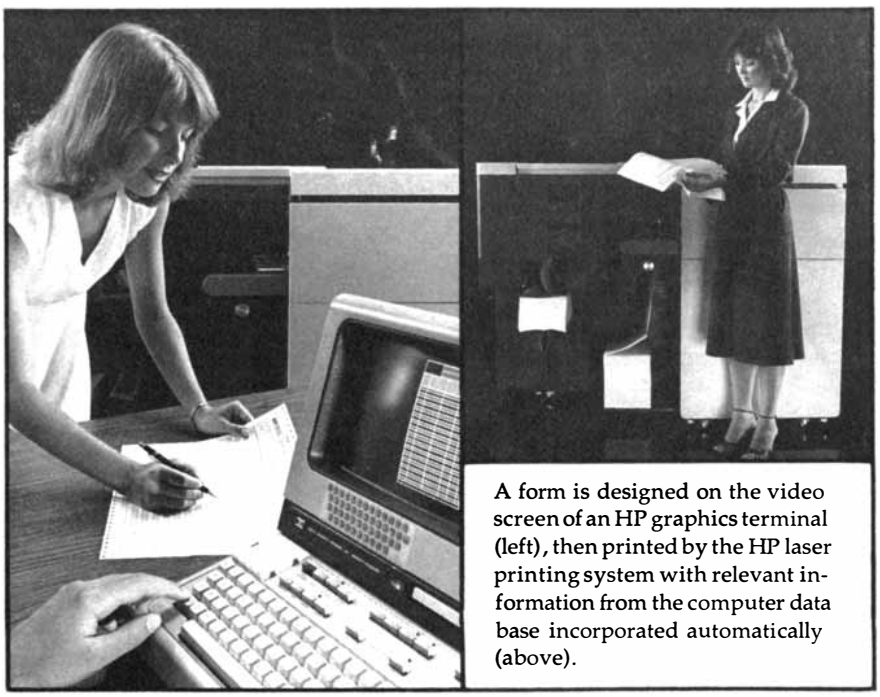

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Pterosaurs

Neither dinosaurs nor birds, these creatures were flying reptiles that endured for 135 million years. The ones with wingspans of 12 meters are thought to have been the largest animals ever to fly

by Wann Langston, Jr.

Few prehistoric animals have captured the imagination so completely as have the flying reptiles known as the pterosaurs. Extinct for the 64 million years that have passed since the end of the Mesozoic era, these dragons of the air have nonetheless figured prominently in man's view of the earth's distant past ever since Arthur Conan Doyle made them part of *The Lost World*. For almost two centuries paleontologists have been puzzling over the fossil remains of the pterosaurs, and surely others have wondered how the pterosaurs solved the problems of powered flight. Hang-gliding enthusiasts might well be curious, because the larger pterosaurs weighed about as much as a human hang-glider pilot.

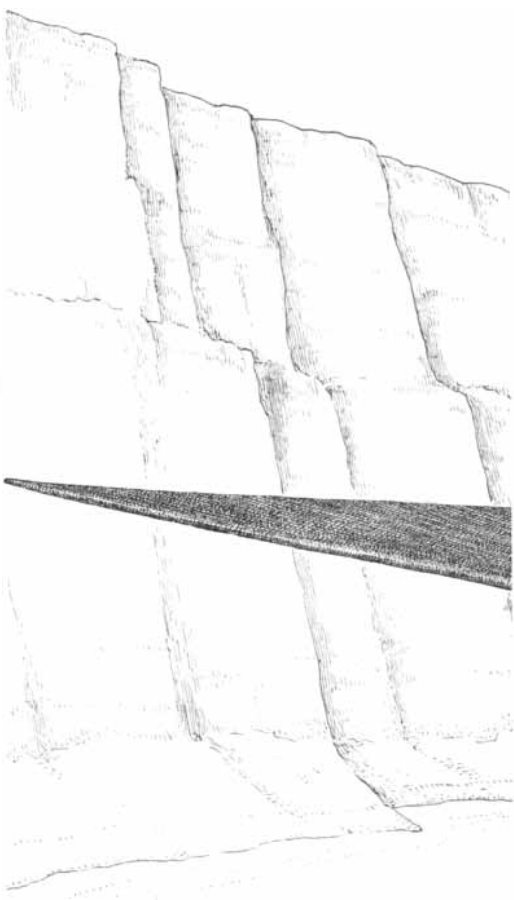
Until recently it was thought that pterosaurs with wingspans as great as eight meters represented the maximum size for flying animals. Nine years ago, however, Douglas A. Lawson, then a student at the University of Texas at Austin, discovered a number of wing bones from an unknown species of pterosaur in the Big Bend National Park in West Texas. The bones were surprisingly large. The radius, a forearm bone, was almost complete. It was nearly three-quarters of a meter long. No additional remains of this animal, named *Quetzalcoatlus northropi* after the Aztec god who took the form of a feathered serpent, have come to light since then, but bones of smaller, quite similar pterosaurs have been found in another part of the park. These further discoveries allow a hypothetical reconstruction of *Quetzalcoatlus* that gives it a wingspan of 11 to 12 meters. *Quetzalcoatlus* may thus have been the largest creature ever to fly. Although the Texas pterosaurs are still imperfectly understood, I shall review here what is known about them today. The subject can best be approached in the context of what is known (or suspected) about the pterosaurs in general.

Perhaps the least controversial assertion about the pterosaurs is that they were reptiles. For one thing, their skull is reptilian, including the shape of the teeth. For another, the pelvis and hind feet are those of a reptile. It seems clear, however, that in their adaptations to flight the pterosaurs departed so far from the reptiles popularly known as the dinosaurs that no investigator would now confuse them with either of the two dinosaurian orders. The pterosaurs and the dinosaurs appear to have evolved on divergent paths from earlier forms of reptilian life.

It also seems clear that the pterosaurs did not evolve into the birds. In this regard the telltale anatomy is that of the wing. In a pterosaur the fourth finger of each forelimb was greatly elongated. It supported the front edge of a membrane that stretched from the flank of the body to the farthest tip of that finger. The other fingers were short and reptilian, with a sharp claw at the end of each one. In a bird it is the second finger that is the principal strut of the wing, and in the bird much of the extent of the wing consists of course of feathers.

Although the fossilized remains of pterosaurs have been found on every continent except Antarctica, most pterosaur fossils come from the chalk deposits of western Kansas, from certain sedimentary strata in England and particularly from the Solnhofen limestone of Bavaria, a fine-grained rock laid down in a quiet lagoon during the Mesozoic era and used by man for lithography throughout the past few hundred years. The first pterosaur fossils were found in a limestone quarry near the Bavarian village of Eichstätt. Their discovery was reported in 1784 by Cosimo Collini, a former secretary to Voltaire. The fossils plainly included a winglike structure. Nevertheless, Collini conceived them to represent an amphibious mammal. Similar misconceptions persisted. Indeed, even after Georges Cuvier, the 19th century master of comparative anatomy, pronounced what he called the "ptero-dactyle" (literally wing-finger) to be a flying reptile, some of his contemporaries continued to regard the pterosaurs as bats, birds or flying marsupials. In 1830 Johann Wagler, a German zoologist, linked the pterosaurs to extinct marine reptiles. He considered them intermediate between mammals and birds. His reconstruction showed a swimming creature with penguinlike wings and rudder-shaped feet.

The modern consensus that the pterosaurs are flying reptiles was established by the turn of the century, and the pterosaurs are now regarded by most investi-



PTERANODON, a pterosaur of the Cretaceous period, which lasted from 135 through 64 million years ago, is depicted in flight. The

gators as making up an order of reptiles: the Pterosauria. Roughly 85 species are known. They are arranged in two suborders. The older suborder, the Rhamphorhynchoidea, appears abruptly in the fossil record in 200-million-year-old Triassic limestone in northern Italy. The distinguishing features of the Rhamphorhynchoidea are many. They had a short face and a short neck. In the wing the wrist was short and the fourth finger was long. The animal had a long tail. The Rhamphorhynchoidea included some of the smallest pterosaurs, which were roughly the size of a sparrow.

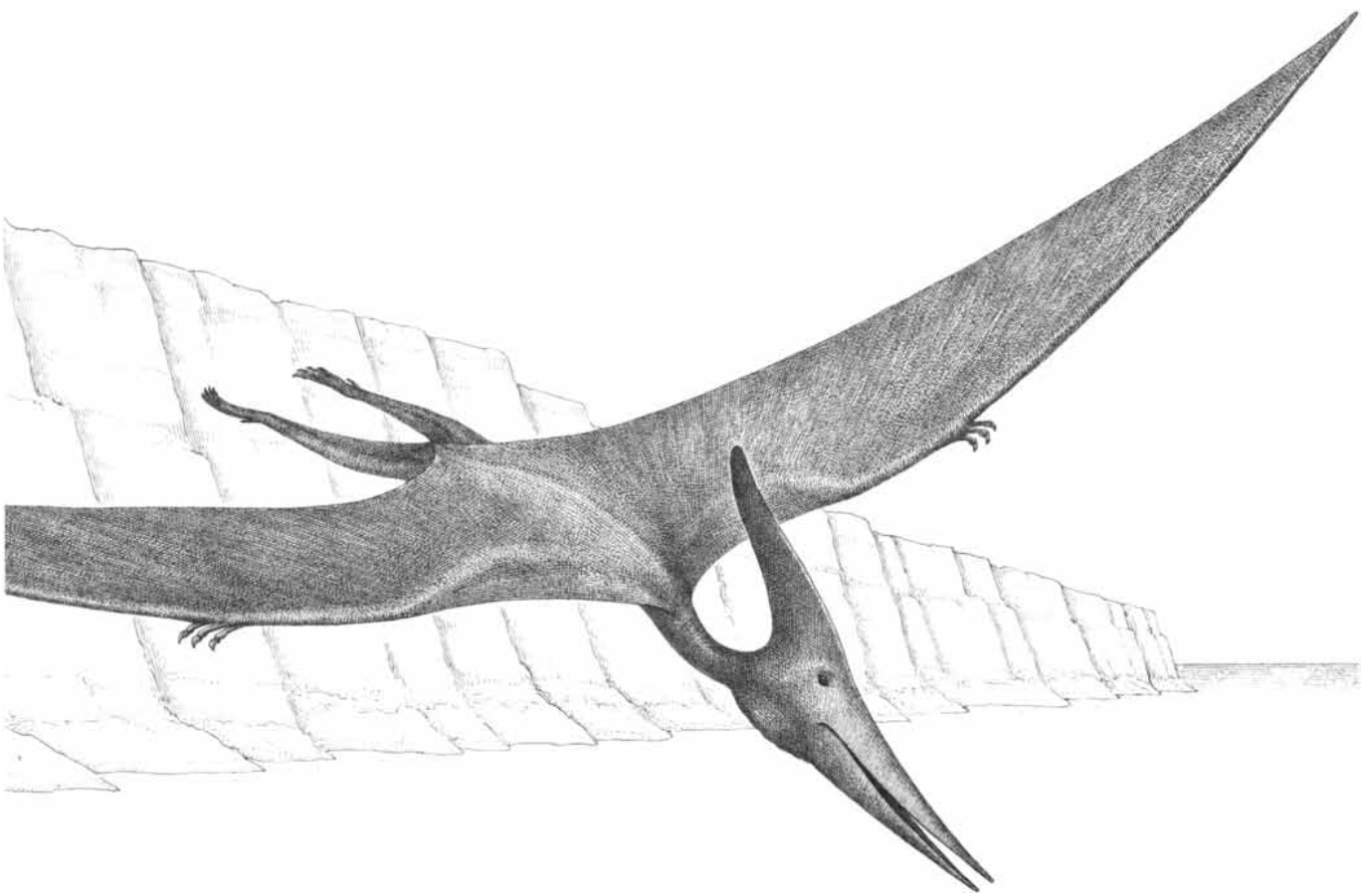
The other suborder, the Pterodactyloidea, appears just as abruptly in the late Jurassic, about 50 million years later. These animals were distinguished by a long face and a long, curved neck. Both the wrist and the fourth finger contributed impressively to the length of the wing, and some of the species were exceptionally big. *Quetzalcoatlus* was a pterodactyloid. The Pterodactyloidea were almost tailless. The sudden appearance of both suborders of the pterosaurs without any obvious antecedents is fairly typical of the fossil record. It emphasizes the random nature of discoveries in paleontology.

The pterosaurs resembled both birds and bats in their overall structure and proportions. In a way this is not surprising. The design of any vertebrate animal that flies is subject to aerodynamic constraints. A more detailed examination reveals both similarities and differences. For one thing the pterosaurs had hollow bones. No doubt this represented a saving in weight. Birds too have hollow bones, but they usually are reinforced more massively by internal struts. In pterosaurs as in birds the fusion of various bones limited the flexibility of the trunk. Movable joints were few, particularly in the wings and the ankles, the places where the stresses on the body were great. The long tail of the rhamphorhynchoids was stiffened by long, overlapping outgrowths of the vertebrae, and other vertebral outgrowths limited the sideward bending and twisting of the neck of the great pterodactyl called *Pteranodon*.

Many pterosaurs had a ridge or crest on their skull. The crest was most extreme in *Pteranodon,* where in some species it doubled the length of the head. The function of the crest is a puzzle. It surely had an effect on the aerodynamics of the animal; experiments with models of the head in a wind tunnel suggest that when it was turned at a right angle to the direction of the animal's flight, it increased the drag. The crest thus may have been an air brake for landing. It also could have served as a front-end rudder to offset the lack of a tail. Further, it may have helped to balance the long beak and in that way allowed a reduction in the mass of the neck muscles.

Other large pterosaurs seem, however, to have managed without a crest. Moreover, the interlocking of the neck vertebrae in *Pteranodon* may have kept the animal from rotating its head to any great degree. Finally, some *Pteranodon* skulls lack a crest. If this is a natural condition and does not merely reflect the imperfect preservation of the fossils, the crest may have been a sexual characteristic. Whether it would then have adorned the male or the female cannot be guessed.

The most remarkable evolutionary adaptation in the structure of the pterosaurs was of course the wing. In its fundamental design it resembled the forelimb of a tetrapod: an animal that goes on all fours. Here, however, the



animal has employed the updraft along a cliff to gain altitude, then turned in a glide toward the sea to search for fish. It is thought to have flapped its wings only slowly and infrequently. The crest on the back of the head could have been an air-control surface; the crest may thus have offset the lack of a tail. The wingspan of a big pteranodon was as much as seven meters, making it large among the pterosaurs.

greatly elongated fourth finger had become a long, slender wing spar. The wing was attached to the trunk of the pterosaur by a massive shoulder girdle: a bony ring consisting of the scapula, or shoulder blade, the sternum, or breastbone, and a third bone, the coracoid. In the smaller pterosaurs the girdle roughly resembled the one in a bird. The main difference was the absence of a fourth bone, the wishbone or furcula. Typically, however, the scapula and the coracoid were fused, and in the larger species the scapula no longer lay loosely embedded in the muscles along the flank of the animal, a position typical of the scapula in all the tetrapods except the turtles. Instead the scapula was a massive rod turned inward. At the midplane of the body the top of the scapula was inserted into the notarium, a bony bar unique to the largest pterodactyls. The notarium was formed by the fusion of several of the vertebrae.

Many of the pterosaur fossils that lie in fine-grained sediments include impressions of the wing membrane, which extended from the tip of the fourth finger to the side of the trunk, at least in the rhamphorhynchoids. The membrane was reinforced internally by long, thin, closely spaced collagenous fibers that probably prevented sharp bending of

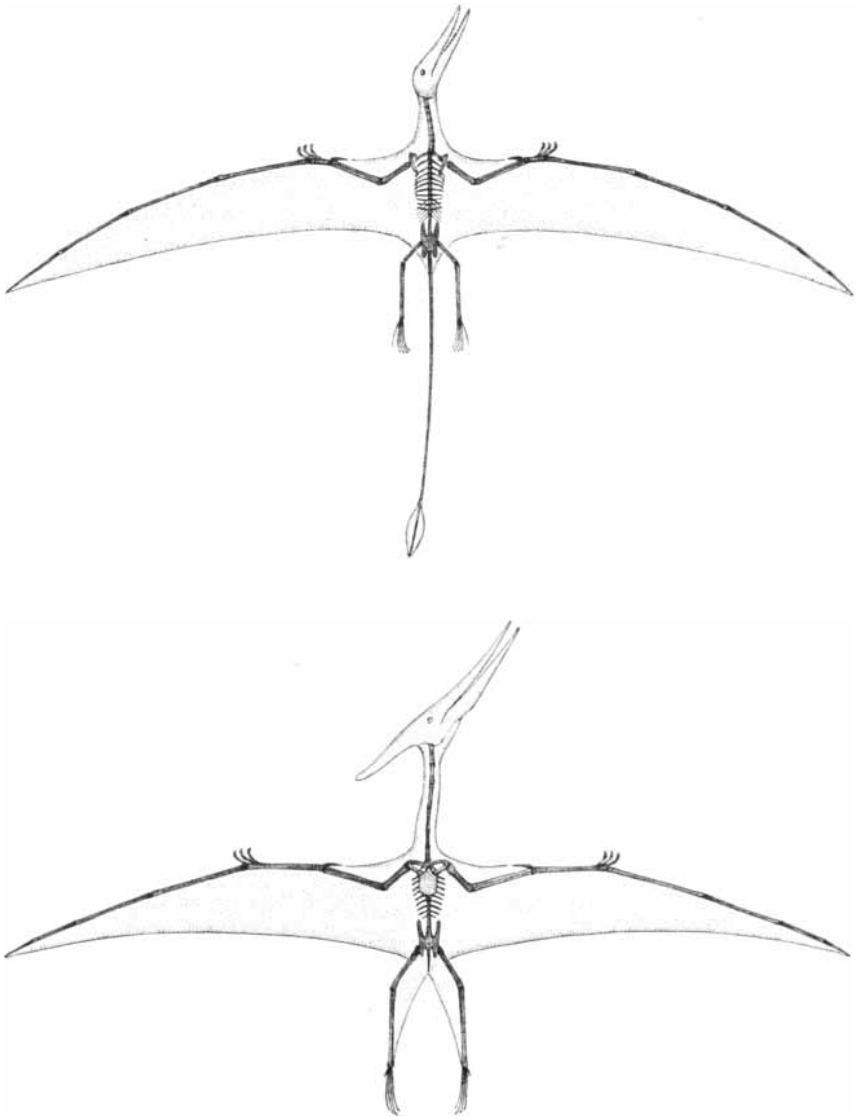
FOSSIL REMAINS of the sparrow-size pterosaur *Pterodactylus elegans* lie in limestone from Solnhofen in West Germany. The limestone solidified from sediment that lay at the bottom of a lagoon some 150 million years ago, in the late Jurassic period. The attitude of the skeleton is unnatural. For example, both wings extend toward the left and then fold under the rib cage. Apparently the carcass of the animal dried out on a beach before it drifted to the place where it finally sank. In addition to fossilized pterosaurs the Solnhofen limestone has yielded fossils of small dinosaurs and of the first known bird, *Archaeopteryx*. The stone has been used for centuries for lithographic printing. The specimen of *Pterodactylus elegans* shown here is from the collection of the American Museum of Natural History.

the outer part of the wing. Additional fibers were arrayed toward the trailing edge of the wing, where they could decrease the wing membrane's fluttering. The fibers were slightly arched in a fore-and-aft direction, thereby contributing to the camber, or upward-directed convexity, of the pterosaur's airfoil. The fourth finger was stretched out by a long, slender tendon running from a muscle in the inner wing (the homologue of a tetrapod's upper arm) to a bony, elbowlike outgrowth on the first segment of the fourth finger.

Adding to the area of the wing was a triangular membrane that stretched forward from the wrist to the base of the neck. The triangle was supported at the wrist by a uniquely pterosaurian innovation, the pteroid bone, which evidently was a place of attachment for a tendon and a muscle that held the membranous triangle taut and braced the wing in front. It is known from well-preserved specimens that some rhamphorhynchoids had a vertical flap of skin at the end of their tail. This was clearly some kind of rudder that must have enhanced the animal's maneuverability in flight. It could also have served in water if the rhamphorhynchoids were swimmers.

Three other aspects of the pterosaur's anatomy deserve separate mention. The first is the pterosaur's hand, or rather the three digits of the hand that projected outward from the wing. If the pterosaurs walked on all four limbs, the hand may have been employed for grasping. Gorillas walk, however, with their fingers folded against the palm of the hand; in other words, they walk on their knuckles. The pterosaur may have done much the same. It may, however, have been a biped. In any case the long fourth finger was folded out of the way by means of a joint at the base of that finger when the pterosaur walked. The joint allowed the fourth finger, and with it the wing, to turn upward along the side of the animal's body.

The second notable aspect of the pterosaur's anatomy is the brain of the animal. In this regard an analysis of endocranial casts is illuminating. The casts form when sediment fills the cranial cavity of a skeleton during its fossilization. They therefore suggest the surface features of the brain. Perhaps the best example of a pterosaur endocast was discovered in Jurassic rock in northern England late in the 19th century. The specimen is only 25 millimeters long. It nonetheless shows that the cerebellum was substantially larger in relation to the size of the animal than it is in reptiles that do not fly. Indeed, the floccular lobes of the cerebellum were larger than they are in birds of comparable size today. This suggests a high level of muscular coordination. More specifically, it suggests maneuverability in flight, takeoff and landing.



TWO SUBORDERS of the order Pterosauria are compared. The Rhamphorhynchoidea (*top*) had wingspans ranging from .4 to 2.2 meters. The face and neck were short; the tail was long. Each hind limb had five long toes. The Pterodactyloidea (*bottom*) had wingspans as great as 12 meters. The face was long; the neck curved. There was almost no tail. Fifth toe was rudimentary.

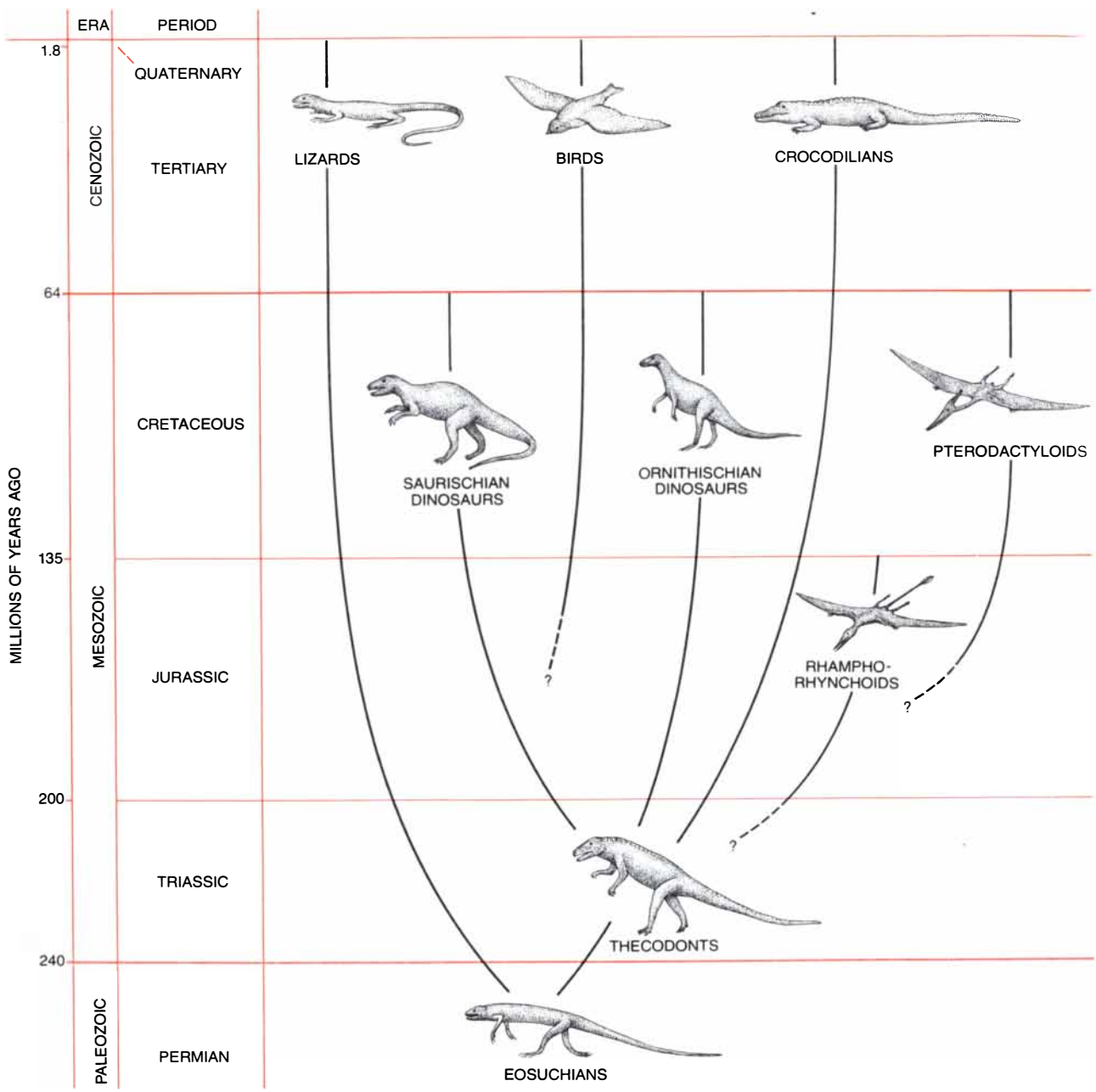
The olfactory bulbs of the brain were small. This suggests that the animal's sense of smell was poor; thus the pterosaurs did not rely on smell for hunting. In contrast, the optic lobes were well developed. Hence the animal's eyesight was good; doubtless the pterosaurs used vision for hunting and navigation. Moreover, they were probably active in daylight. Overall, the encephalization quotient of the pterosaur—the ratio of the volume or weight of its brain to that of the brain of an earthbound reptile of the same size—was relatively large. It indicates that pterosaur brains were large for the brain of a reptile but had not quite attained the relative size achieved by the brain of a bird.

The third notable aspect of the anatomy is the pterosaur's skin. Although reptiles are typically covered by scales and mammals are covered by hair, it has been suggested from time to time that the pterosaurs may have had a hairy coat. The reasoning begins with the hypothesis, offered by T. H. Huxley more than a century ago, that a flying vertebrate such as a pterosaur must have been a warm-blooded animal. After all, flying implies a high rate of metabolism, which in turn implies that the animal must maintain a high internal temperature. A coat of hair would furnish insulation against the loss of body heat. It might also streamline an animal's body to reduce its drag in flight. In 1971 A. G. Sharov, a Russian zoologist, presented the first clear evidence that this reason-

ing is correct. He had discovered in Kazakhstan the fossil skeleton of a pigeon-size rhamphorhynchoid, *Sordes pilosus*. The fossil was clothed in "long, dense and relatively thick" hairlike fossil material. It appeared to Sharov that the entire body (except for the tail) was indeed covered by hair.

Our knowledge of the giant West Texas pterosaur, *Quetzalcoatlus*, comes mostly from two groups of fossils. The first group consists of fragments from the wing of *Quetzalcoatlus northropi*. The remains of other parts of the body have not been found; evidently the wing of the animal was separated from the body before the burial. The second group of fossils consists of the scattered bones of at least a dozen smaller animals. All of them were found in one area, where it appears that all the animals died over a short span of time, perhaps only a few years.

The sites where the two groups of fossils were found are some 50 kilometers apart, and so it cannot be established that all the fossils represent a single population. Nor can it be shown that all the animals lived at exactly the same time. Nevertheless, the larger and smaller bones would scarcely be distinguishable if it were not for the disparity in size. The smaller bones might therefore be viewed as representing immature specimens of *Quetzalcoatlus northropi*. Pending new discoveries that may settle the issue definitively, the smaller bones are classified in taxonomic shorthand as rep-



PTEROSAURS EVOLVED in the early part of the Mesozoic era. Their appearance preceded that of the earliest birds by about 50 million years and followed that of the earliest dinosaurs by about 20 million years. It is hypothesized that the precursors of the pterosaurs (and of the birds and of both orders of the dinosaurs, the ornithischians and the saurischians) were the reptiles called the thecodonts, which for their part evolved from the early, lizard-shaped reptiles known as eosuchians. Among the pterosaurs the rhamphorhynchoids first appeared some 50 million years before the pterodactyloids. The last pterodactyls died out with the dinosaurs 64 million years ago.

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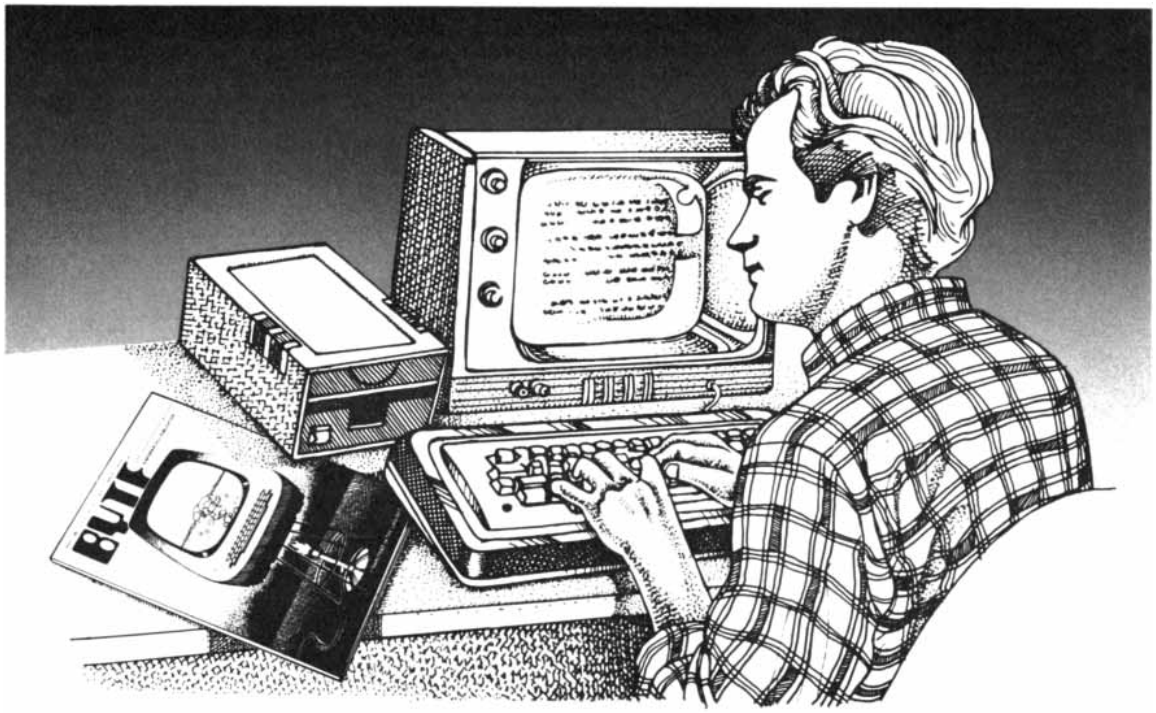

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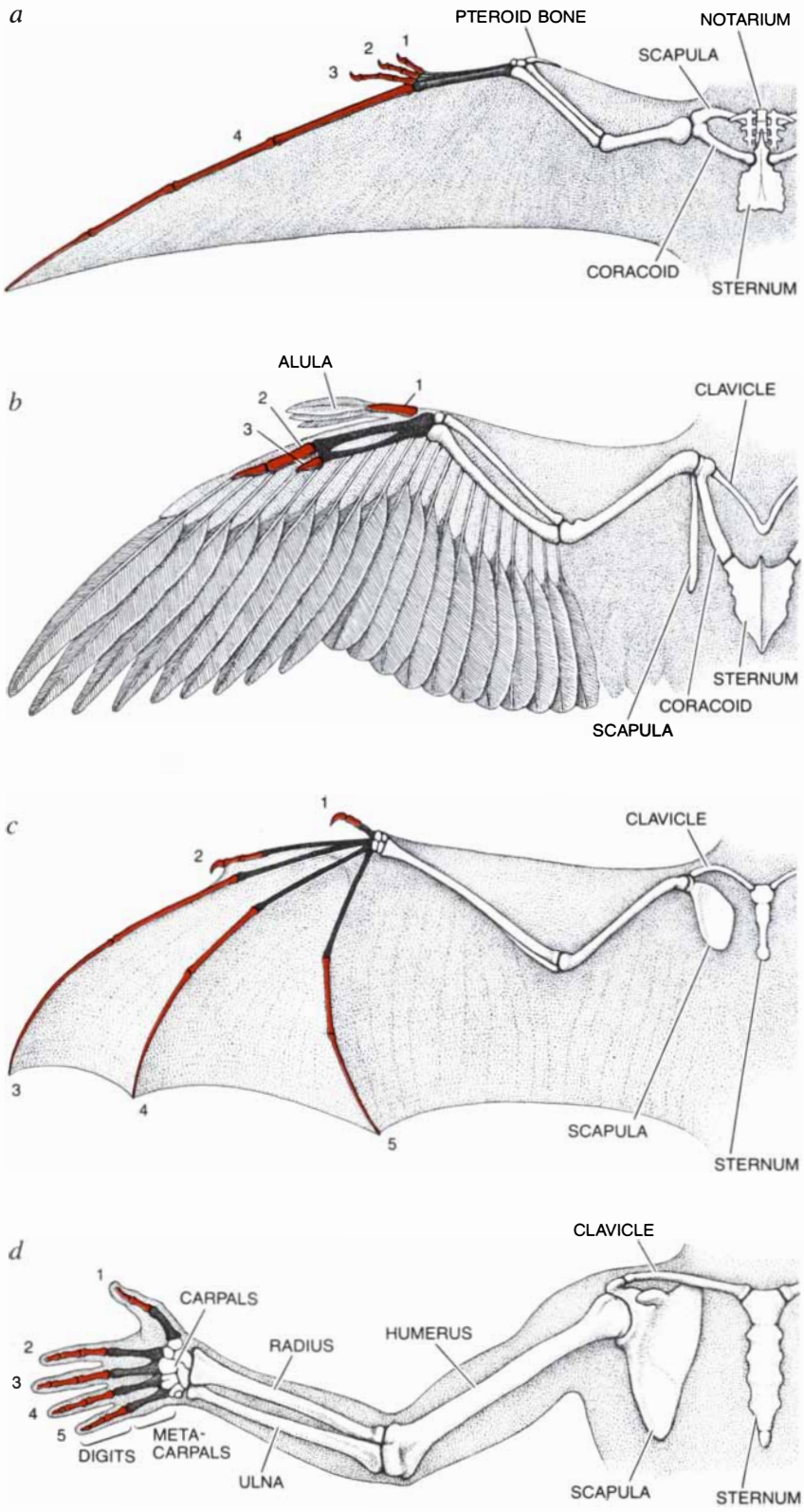


WINGS of a pterosaur (*a*), a bird (*b*) and a bat (*c*) are evolutionary variations on a forelimb that was suitable for an earthbound animal that walked on all fours. The variations are distinctive: in the pterosaur it is the fourth finger that supports the wing; in the bird it is mainly the second, and in the bat it is the second through the fifth. In each animal the wing attaches to the trunk by means of the shoulder girdle, a ring of bones. The girdle of the larger pterodactyls is peculiar in that the scapula, or shoulder blade, turns inward and abuts the notarium, a unique pterosaurian bone, at the midplane of the body. The notarium is several vertebrae fused together. The arrangement provided a base for the action of the wing. The arm of man is shown in *d*.

resenting *Quetzalcoatlus* sp., an undetermined species.

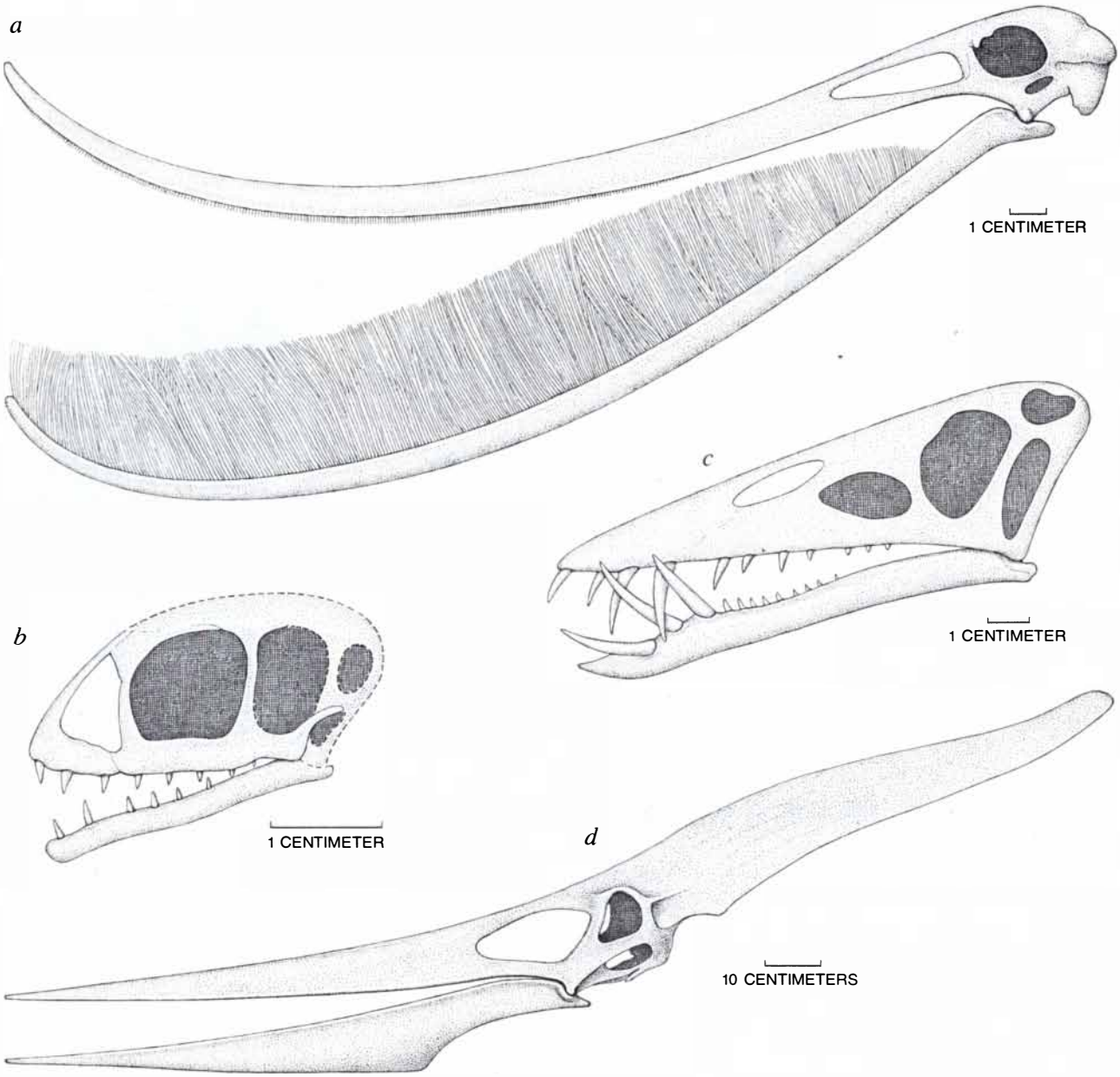
A pterosaur vertebra found in the 1940's in Jordan bears on this problem because it resembles the neck vertebrae of *Quetzalcoatlus* sp. The vertebra was long and slender, and so it was mistaken at first for a wing bone. It clearly represented an animal larger than any pterosaur known at the time. The animal was therefore named *Titanopteryx*. The point is that the vertebra found in Jordan is almost large enough to fit *Q. northropi*. On the other hand, the fossil from Jordan is older than the fossils from Texas. For the present *Titanopteryx* and *Quetzalcoatlus* can be regarded as distinct. If future discoveries demonstrate that they are the same, the International Rules of Zoological Nomenclature stipulate that *Titanopteryx* must replace *Quetzalcoatlus* as the name for the Texas pterosaur.

The preliminary estimates of the size of *Quetzalcoatlus northropi* were based on comparisons between the wing bones of that animal and the wings of some considerably smaller pterosaur species. By this method it was inferred that the wingspan of *Q. northropi* ranged from 11 to 21 meters. Extrapolations from two large pterosaurs, *Quetzalcoatlus* sp. and *Pteranodon*, refined the estimate to 15.5 meters.

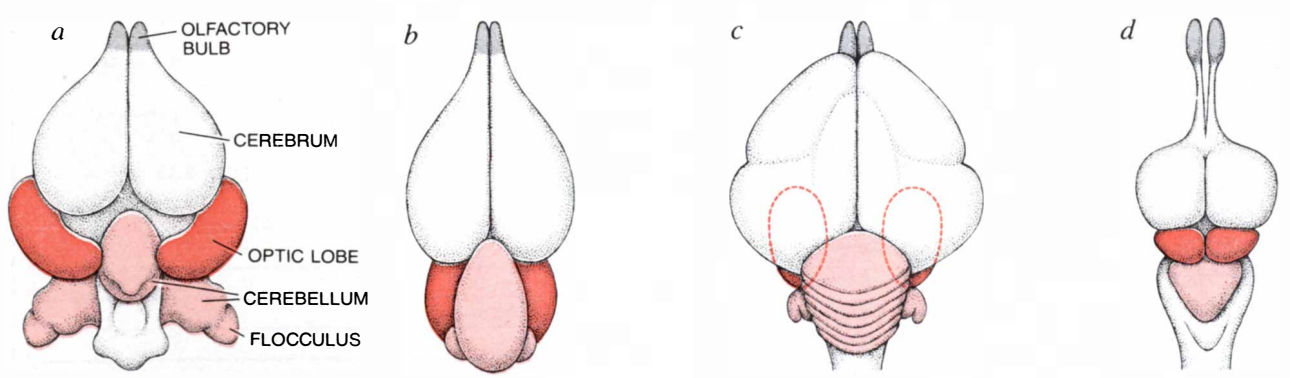
Aeronautical engineers quickly pointed out, however, that a pterosaur with the shape of *Pteranodon* and a wingspan of 15.5 meters might have weighed as much as 136 kilograms. It would then have lacked the muscle power to maintain level flight by flapping its wings. Moreover, the strength of the wing bones would perhaps have been insufficient to bear the stresses the wings would have had to endure. Of course, *Quetzalcoatlus northropi* did not have exactly the proportions of *Pteranodon*. Even so, an animal with a wingspan of 15.5 meters would probably have been at or beyond the engineering limits for a flying machine made of muscles, tendons and delicate hollow bones.

Unfortunately the precise length of the wing of *Quetzalcoatlus northropi* is still uncertain. It is known, however, that the metacarpal bone of the fourth finger was relatively longer in *Quetzalcoatlus* than it was in *Pteranodon* and that some of the other bones of this finger were substantially shorter. These differences suggest an adjusted calculation by which the wingspan of *Quetzalcoatlus* sp. emerges as no less than 5.5 meters, and that of *Q. northropi* as 11 to 12 meters. Such an animal might have weighed 86 kilograms. In spite of the recent discovery in Argentina of an extinct vulture whose wingspan is estimated to have been more than seven meters, *Q. northropi* still would rank as the largest known flying creature.

Few assertions about how the ptero-



SKULLS of four pterosaurs suggest that their diets varied. *Pterodaustro* (*a*) had teeth that resemble the baleen with which some whales strain plankton from seawater. *Anurognathus* (*b*), a tiny pterosaur, had peglike teeth. It may have eaten insects. *Dorygnathus* (*c*) was toothy; *Pteranodon* (*d*) was toothless. It seems that both, however, ate fish, because fossil fish have been found within their rib cage.



BRAIN of the pterosaur (*a*) is reconstructed from endocasts, which formed from sediment that filled the skull during fossilization. The other brains are of *Archaeopteryx* (*b*), a modern bird (*c*) and a modern reptile, the alligator (*d*). The view is from above. In the pterosaur the optic lobes (indicative of vision) and the cerebellum (indicative of muscular coordination) are well developed for a reptile's brain.

saurs lived are well supported. The difficulty is that vertebrate animals in general are seldom buried immediately in the precise place where they lived. Instead the carcass lies exposed to scavengers, decay, weathering and transport by flowing water. The Kansas pteranodons, for example, are found at sites that were at least 160 kilometers out to sea in the Mesozoic. Almost surely the animals had died in or over water far from home. The Solnhofen pterosaurs are in stone that was laid down as limy sediment in lagoons. The attitudes of many of the skeletons suggest that the carcasses had dried out on a beach and then had floated to where they sank.

Efforts to imagine how the pterosaurs became airborne have led to suggestions that they launched themselves by jumping or falling off a cliff, by dropping from their roosting place in a tree or even by rising into a light wind from the crest of a wave. Each hypothesis has its difficulties. The first one rests in part on the assertion that the hind feet of the pterosaur resembled those of a bat and therefore could serve as hooks by which the animal hung from a cliff in preparation for flight. A recent study by Kevin Padian of the University of California at Berkeley suggests, however, that the hind limbs and the feet of pterosaurs were much more like those of birds and dinosaurs than has generally been assumed. None of these animals is thought to have been much of a cliff-hanger.

As for the second hypothesis, it seems unlikely that large pterosaurs could have landed in trees without damaging their wings. It is conceivable, however, that the pterosaurs climbed the trees. The hooves of the billy goat seem to make the animal suitable only for walking, and yet billy goats can climb into the low branches of trees by clinging to them with other parts of their limbs. The third hypothesis calls for high waves to channel the updrafts the animal would have employed to soar. The wind that made such waves, however, might well have been too strong for the animal to control its flight once it was airborne.

The setting of the Texas pterosaurs presents a special problem for imagining how the animal left the ground. The fossils were found in siltstones and sandstones that were deposited in a broad alluvial fan some 400 kilometers inland from the nearest seacoast of the time. Although highlands extended to the west, there is no indication in the geology of the region that any mountains or cliffs were nearby. It appears, then, that *Quetzalcoatlus* may have lived on fairly flat, low-lying ground. There, as is the habit of a vulture, it may well have had to wait each morning until the sun warmed the ground and strong thermal updrafts developed. In the larger pterosaurs the musculature that animated the wing was not impressively massive, and

the hind limbs were long but weak. All things considered, it seems unlikely that *Quetzalcoatlus* could have run on its hind legs and flapped its wings energetically. Still, if the animal could stand up on its hind legs and catch the appropriate breeze, a single flap of the wings and a kick with the legs may have been all it needed for takeoff.

Landing would have been less problematic. Evidently the air speed at which a flying pterosaur stalled was less for a pterosaur than it is for a bird of the same weight. Hence the pterosaur could touch down gently on its hind limbs. The animal's body would pitch slowly onto its hands as the animal folded its wings. How did it move on the ground? Some investigators suspect that the hindquarters of *Pteranodon,* at least, were too weak to support the body at all. They suggest instead that the animal rested on its breast, which they assume was well padded. The animal would then have dragged and pushed itself in the manner of certain bats. Padian suggests, to the contrary, that the pterosaur had a two-legged stance. Finally, certain fossil tracks from a Jurassic sandstone in Arizona are attributed (perhaps erroneously) to a pterosaur. They were made by an animal that was walking on all fours.

The mechanics of pterosaur flight is a subject also fraught with uncertainties. Yet it too sheds light on how the pterosaurs may have lived. Cherrie D. Bramwell and George R. Whitfield of the University of Reading have made a detailed examination of *Pteranodon* as a flying machine. They conclude that a pteranodon with a wingspan of 6.9 meters and a weight of 16.6 kilograms could have flown only in light to moderate winds. A light wind is one that blows at eight to 12 miles per hour; it will lift loose paper off the ground and make a flag stand out by a third of its length from its staff. The aerodynamic properties of the pterosaur in a glide would give it only a small tendency to sink. Thus it could easily rise in an updraft. All these calculations are based, however, on a model of *Pteranodon* in which the wing membrane stretches from the tip of the fourth finger to the ankle of the hind leg. The fossil record gives no evidence for this. In fact, in some pterosaurs the wing is known to have been narrow at the base.

In general the relation between the area of the wing and the total weight of the pterosaur indicates that the wing bore less weight per unit area than it does in a bird of the same size. Ordinarily this would suggest that the flight of the pterosaur was slow but maneuverable. Pterosaurs, however, lacked many of the control surfaces that are available to the birds. They lacked, for example, an effective horizontal stabilizer. The bird's tail serves such a func-

EVIDENCE OF HAIR on the body of the pterosaurs was provided in 1971, when these fossil impressions of the pigeon-size pterosaur *Sordes pilosus* were found in Kazakhstan in the U.S.S.R. The hairlike marks at the bottom apparently covered the entire body except the tail.

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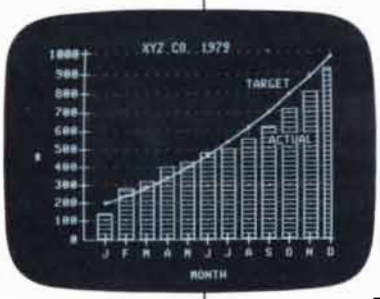

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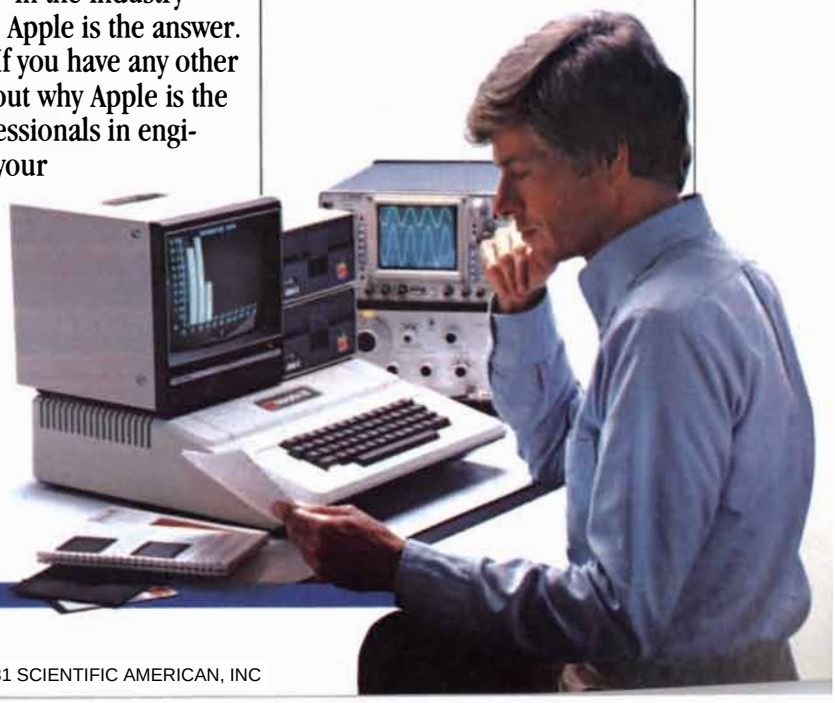

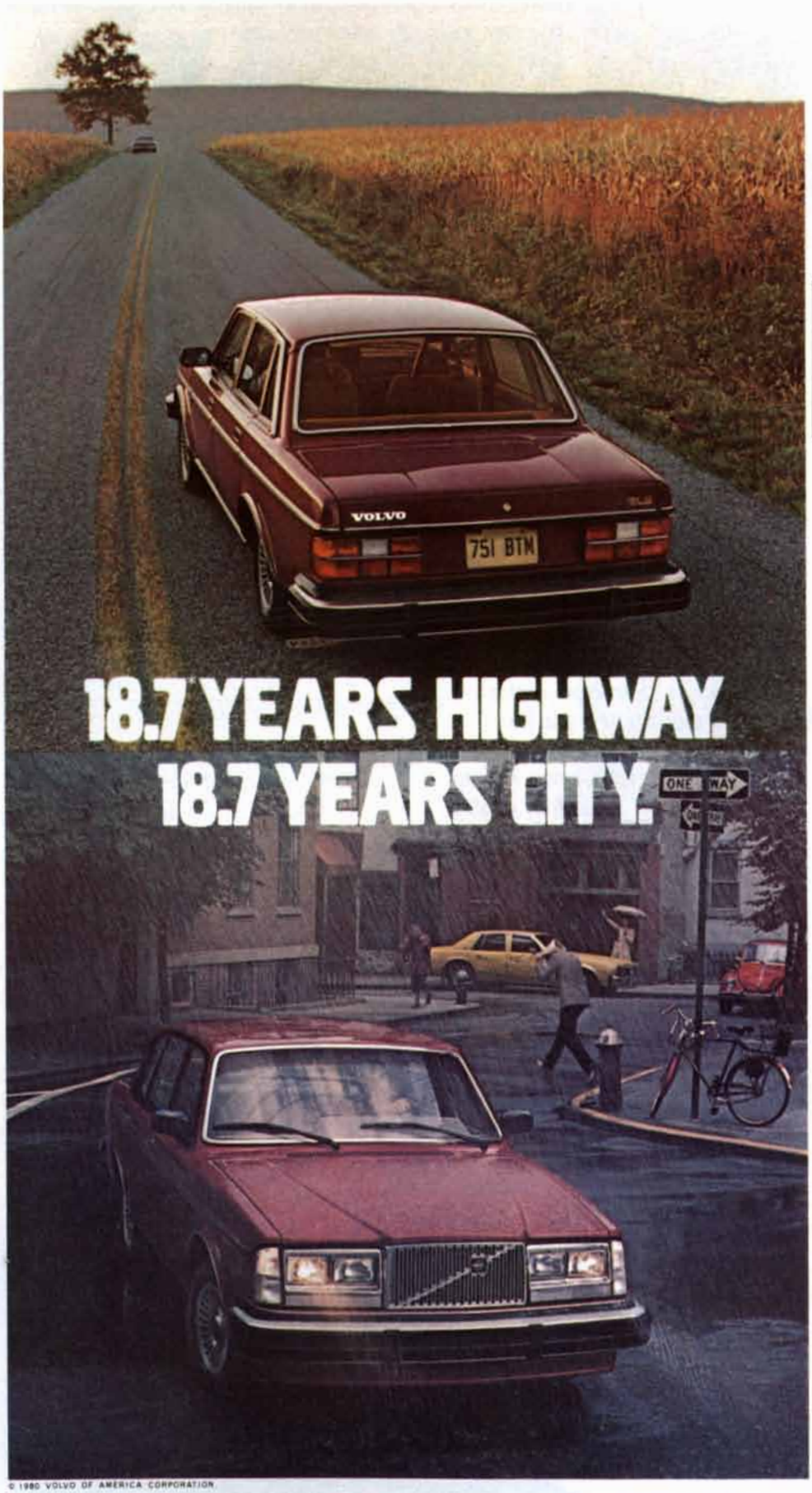

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tion. The pterosaurs therefore should have been less able to maneuver in flight than a bird is. The larger pterodactyls probably flapped their wings slowly at takeoff and for restoring level flight when that was necessary. Once airborne, an animal such as *Pteranodon* may have remained aloft for long periods, rising on updrafts near surface features such as cliffs and then riding weak air currents over land or water.

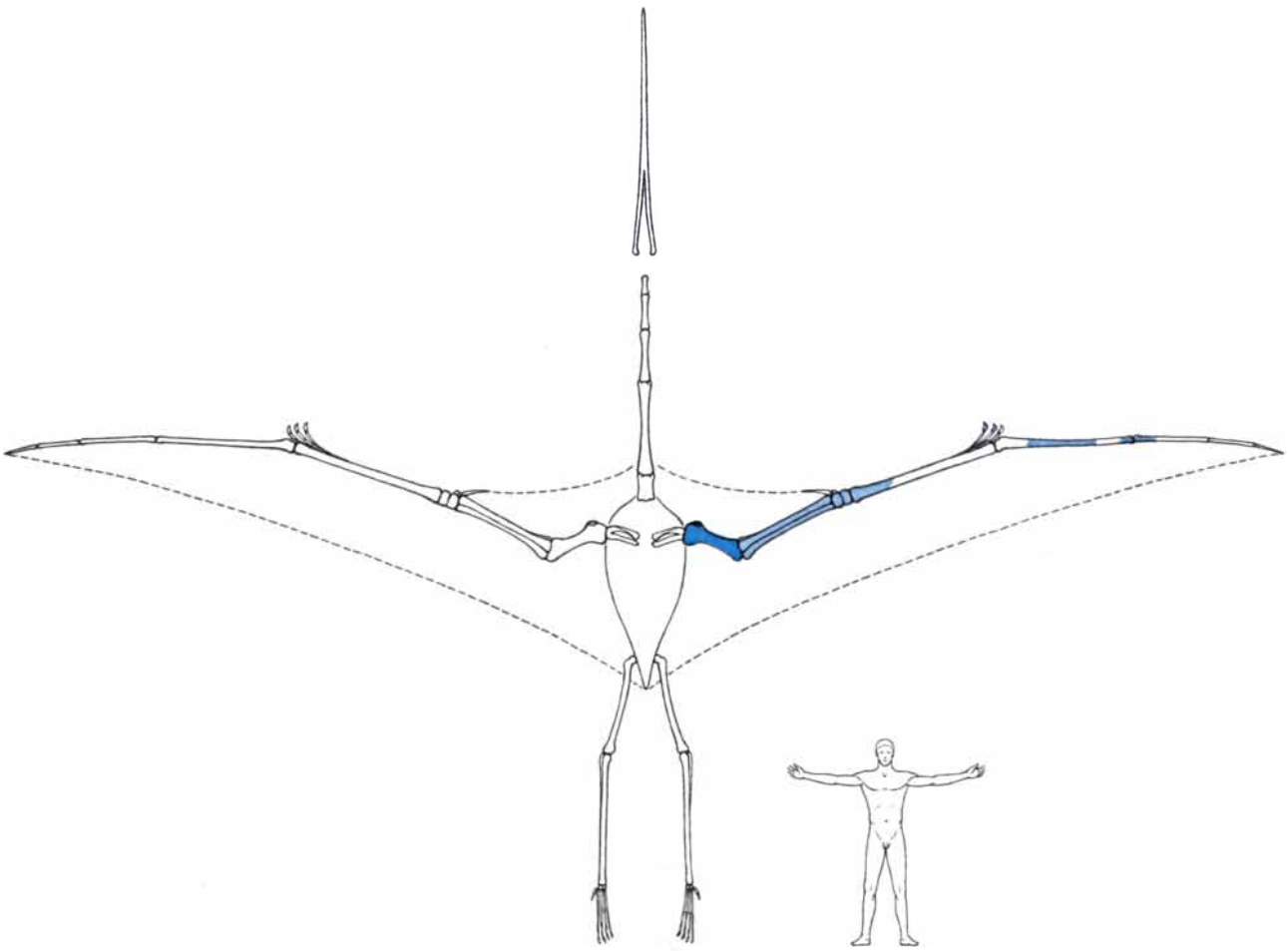
The smaller pterosaurs were probably more active fliers, able to flap their wings more energetically. They nonetheless were probably slower than a bird of similar size. In 1956 Erich von Holst of the Max Planck Institute for Behavioral Physiology at Seewiesen in West Germany constructed a model of a rhamphorhynchoid from rice paper, balsa wood and aluminum. Powered by rubber bands, the model flapped its wings up and down about 40 times with a wingbeat of two to three times per second, then glided to a soft landing. The flight was described as elegant—not at all, for example, like the jerky flight of a bat. The wings of the model were broader, however, than those of a pterosaur, and so it is unlikely that the pterosaur would have flown in the same way. More recent efforts to duplicate pterosaur flight have been disappointing.

The fossilized contents of the stomach of the pterosaur (or at least the fossils found inside the fossilized rib cage) show that several species of pterosaur ate fish. How the fish were caught is not clear. The skeleton of the pterosaur probably could not have withstood the stresses of diving into water, and the body of the pterosaur makes it about as suitable as an unfolded newspaper for motion underwater.

Pteranodon and some other pterodactyls may have fished on the wing. A pteranodon gliding slowly just above the surface of a body of water could have dipped its beak into the water to pluck out a fish. The narrow profile of the beak would meet with little resistance. The fish could then have been gulped down on the spot. Alternatively *Pteranodon* could have carried the fish in its throat sac, a pouch that resembles the pouch of a pelican. The fossil remains of fish have been found in a fossil impression of the sac. Some investigators believe pterosaurs could land on water and thus could fish from a floating platform.

When stomach contents have not been discovered, the best clue to an animal's diet is usually its dentition and the structure of its jaw. On such evidence it has been suggested that *Anurognathus,* a tiny pterosaur with a short face and peglike teeth, ate insects. Whether the animal was maneuverable enough to catch insects on the wing is debatable. Other species clearly had different diets. The lower jaw of *Pterodaustro* has hundreds of teeth that resemble the baleen of a whale. The animal may therefore have fed on plankton. The fish-eating *Pteranodon* was toothless.

Quetzalcoatlus may also have eaten fish, but where it would have caught them is a problem. There is no evidence to suggest that there were large permanent bodies of water near the habitations of *Quetzalcoatlus.* Moreover, the rock in which the fossils of *Quetzalcoatlus* were found are almost devoid of fish remains. The rocks do, however, bear many traces of burrowing animals. In addition the presence of masses of fossilized logs in the area suggests periodic ancient flooding. Perhaps a monsoon was responsible. All of this raises the



LARGEST FLYING ANIMAL ever to inhabit the earth is thought to have been the pterosaur *Quetzalcoatlus northropi,* whose remains were discovered in Texas in 1971. Only incomplete wing bones (*light color*) were found. It is calculated, however, that the wingspan of the animal must have been 11 to 12 meters. The humerus (*dark color*) is the bone that appears at the top of the photograph on the next page.

possibility that *Quetzalcoatlus* employed its slender beak to probe for mollusks or arthropods living in shallow flood basins. That would mean, of course, that *Quetzalcoatlus* foraged on the ground.

Since the pterosaurs were reptiles, it might be surmised that they were oviparous. Indeed, purported pterosaur eggs were discovered in England more than a century ago. On the other hand, the pelvis of a pterosaur is not similar to that of a bird. In particular the passageway for eggs would have been relatively constricted. The problem would have been worsened because a pterosaur egg would no doubt have been large to accommodate the folded wings of the developing animal. It also seems likely that the mother would have had to fly to search for food throughout the gestation, in spite of her additional weight. Perhaps the young were born alive in an immature state of development. Prolonged nurture would then have been necessary. Masses of fossil conifer needles found with the remains of *Quetzalcoatlus* sp. may be the remnants of nests.

From the geographical distribution of the fossils and the age of the rocks in which the fossils are found one may suppose the pterosaurs first appeared in what is now southern Europe. From there they spread into Asia, Africa, India and North America by the end of the Jurassic and reached South America and Australia in the Cretaceous. Their dispersal was facilitated by the relative lack of geographical barriers. In those times the earth's present land masses were all more or less in contact. Later the sea floors spread and the continents moved apart. The pterosaur populations became isolated and evolution accentuated their diversity. Large species evolved on several continents.

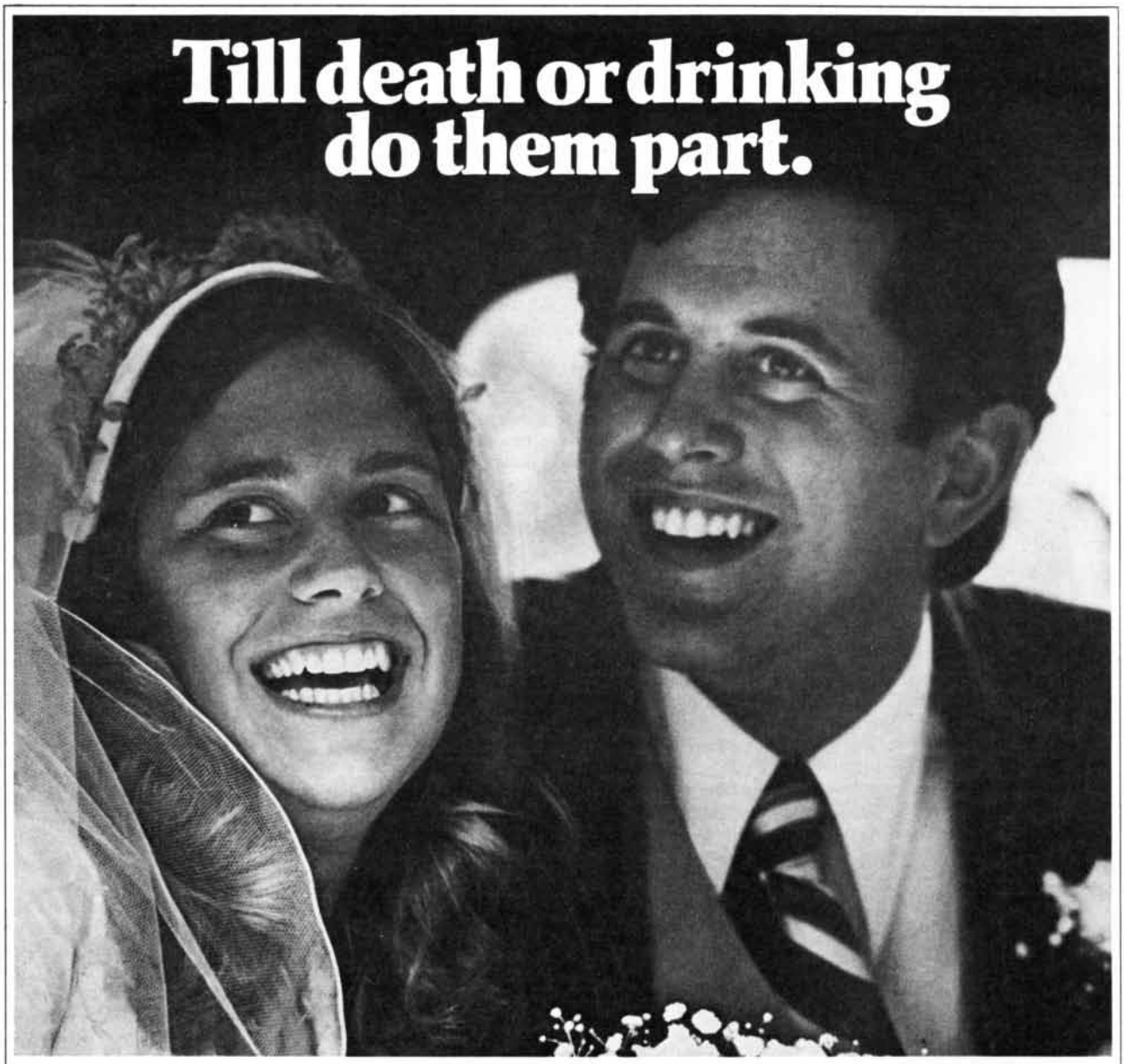
As the Mesozoic drew to a close the land masses of the earth approached the positions they have today. It was a time of widespread flooding in the low-lying areas of the continents. The total land surface was temporarily reduced to perhaps half of what it is at present. For example, a wide inland seaway cut North America in two from north to south. Pterosaurs then achieved their greatest distribution: they extended both north and south of the Equator to latitudes of about 70 degrees. Mountain ranges, however, were rising, and when sea-floor spreading subsided at the very end of the Cretaceous, the ocean basins deepened. The sea level therefore fell, and the flooded land reemerged. These changes altered the climates and the habitats to which the pterosaurs were accustomed. Extinction gradually reduced their numbers until only *Quetzalcoatlus* remained. Then it too died out.

The disappearance of the pterosaurs coincided with that of many forms of marine plankton, mollusks and reptiles. On land the dinosaurs disappeared. Indeed, no animal heavier than about 23 kilograms survived the Cretaceous. The reasons for the mass extinction are widely debated. Early ideas have given way to explanations that sometimes invoke such catastrophes as volcanic explosions or the lethal radiation of a supernova near the solar system. The newest hypothesis is that an asteroid struck the earth at the end of the Mesozoic and gave rise to a dust cloud that enveloped the earth for several years, dimming the light of the sun. The forms of life that survived on land were either small or warm-blooded or both. The mammals, it is imagined, survived by eating seeds. It counts in favor of this hypothesis that the end of the Mesozoic in some places is marked in the geological record by a thin layer of clay in which the concentration of exotic chemical elements such as iridium is curiously high.

The consequences of a collision of an asteroid with the earth would surely have disposed of the last of the pterosaurs. But another, less dramatic explanation also seems possible. The fossil record clearly shows that the pterosaurs were in decline during the last few million years of the Cretaceous. Moreover, it is thought the climatic changes at the end of the Cretaceous included decreasing world temperatures and increasing seasonal variation in the weather. The earth thus would have been stormy. The gusty winds of the storms would have been disastrous for creatures such as *Pteranodon,* which were adapted for soaring in light, steady winds. Their only chance would seem to have been to improve their aerodynamic capabilities by reducing their size. The remains of *Quetzalcoatlus* suggest that the pterosaurs evolved in the opposite direction.

COMPARISON OF BONES of *Quetzalcoatlus northropi* with those of smaller, similar pterosaurs found nearby contributed to the reconstruction of *Quetzalcoatlus*. The bone at the top is the left humerus of *Q. northropi*. It is .54 meter long. The bone below it is the right humerus of an animal designated *Quetzalcoatlus* sp. in the absence of proof that it was the young of the species *northropi*. The bone is .24 meter long. The fossils of *Quetzalcoatlus* sp. are sufficiently complete for it to be said that the wingspan of the smaller animal was six meters.

Till death or drinking do them part.



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A Deep-Sea Neutrino Telescope

High-energy phenomena such as supernovas and X-ray double stars may emit a flood of neutrinos. An array of sensors shielded by five kilometers of water could selectively detect such particles

by John G. Learned and David Eichler

Virtually everything astronomers know about objects outside the solar system is based on the detection of photons: the quanta of electromagnetic radiation. Yet there is another form of radiation that pervades the universe and may even dominate it: neutrinos. With no electric charge and negligible mass, the neutrino is an elementary particle that rarely interacts with other particles, so rarely that a neutrino can cross the entire universe, even traversing substantial aggregations of matter, without being absorbed or even deflected. And neutrinos that have not been absorbed or deflected carry with them information about the site of their production and can escape from regions of space where light and other kinds of electromagnetic radiation are blocked by matter. Therefore the detection of cosmic neutrinos could provide new information about a wide variety of astrophysical phenomena.

The same reluctance to interact with matter that gives the neutrino its long range makes it extraordinarily difficult to detect. Most neutrinos reaching the earth travel all the way through it unperturbed, leaving no sign of their passage. No apparatus can detect neutrinos unless it is extremely massive and sufficiently shielded from the interfering effects of other particles. Great mass is synonymous with huge numbers of nucleons (neutrons and protons), and the more massive the detector, the larger the probability of one of its nucleons' interacting with a neutrino.

A few years ago a group of physicists came up with an ambitious proposal for detecting cosmic and terrestrial neutrinos by harnessing the mass of the ocean. Named DUMAND, for deep underwater muon and neutrino detector, the proposal calls for placing an array of light sensors above the ocean floor at a depth of some five kilometers. The detecting medium is the seawater itself: when a neutrino interacts with a particle in an atom of seawater, it gives rise to a cascade of electrically charged particles and a flash of light that will be detected by the sensors. The five kilometers of seawater above the sensors will shield them from the interfering effects of other high-energy particles raining down through the atmosphere.

The neutrino has a rich intellectual history. In 1931 the particle was introduced as a hypothetical entity to account for a tiny amount of energy that seemed to vanish in the radioactive decay of certain atomic nuclei. Wolfgang Pauli proposed that the missing energy was spirited away by an unobserved particle, which was later named by Enrico Fermi the neutrino ("little neutral one"). It was not until 1956, however, that Frederick Reines and Clyde L. Cowan, Jr., detected the particle. The neutrino is now seen as being a member of the small family of elementary particles known as leptons, which seem to have no measurable size and no constituents. The other species of lepton are the muon, the electron and the tau particle. There are three kinds of neutrino, one associated with the electron (called the electron neutrino), one associated with the muon (the muon neutrino) and one associated with the tau particle (the tau neutrino). And for each kind of neutrino there is a corresponding antineutrino.

Neutrinos created in large particle accelerators are routinely employed to probe the massive members of the other major class of particles: the hadrons (including the proton, the neutron, the pion and the kaon), which seem to have the constituents called quarks. Particle-accelerator experiments in which neutrinos are scattered by hadrons have revealed much about the quark structure of matter. It is testimony to the versatility of the neutrino that it can be exploited both to probe objects as small as quarks and to investigate objects at astronomical distances. Neutrino microscopes, however, have far outpaced neutrino telescopes.

The DUMAND apparatus will not be the first neutrino telescope. In the early 1960's Raymond Davis of the Brookhaven National Laboratory made the initial serious attempt at neutrino astronomy. He set out to detect low-energy neutrinos emitted by the sun, the brightest source in the sky of neutrinos as well as photons. The neutrinos are generated deep within the sun in the thermonuclear reactions that transmute hydrogen into helium with the release of energy. Almost a tenth of the energy is carried away by neutrinos, whose energies range from half a million electron volts to 14 million. The flux of solar neutrinos at the distance of the earth is staggering (more than 100 million million pass through the human body every second), but the particles are nonetheless elusive. Even so, a tiny fraction of them do interact with a sufficient quantity of matter.

With a massive detector and endless patience Davis has apparently detected solar neutrinos. His detector is basically a large tank containing 610 tons of the ordinary cleaning fluid tetrachloroethylene, the molecules of which consist of two atoms of carbon and four of chlorine (C_2Cl_4). A fourth of the chlorine atoms are those of the isotope chlorine 37, and when such an atom captures a neutrino, it is transformed into an atom of argon 37. The argon 37 is radioactive, and so the decay of an atom of it signifies the capture of a neutrino. Davis and his co-workers have spent the past decade trying to record solar neutrinos. The experiment has finally begun to yield a positive signal, although it is not as large as was expected.

Another kind of low-energy neutrino telescope has been developed in the past decade. It consists of a tank of water equipped with light detectors. If a neutrino interacts with an atom of the water, the interaction gives rise to charged particles that recoil with high energy. When such a particle travels through a transparent medium faster than the speed of light in that medium, it emits the characteristic blue light of Cerenkov radiation, and it is the tiny flash of this light that is picked up by the detectors.

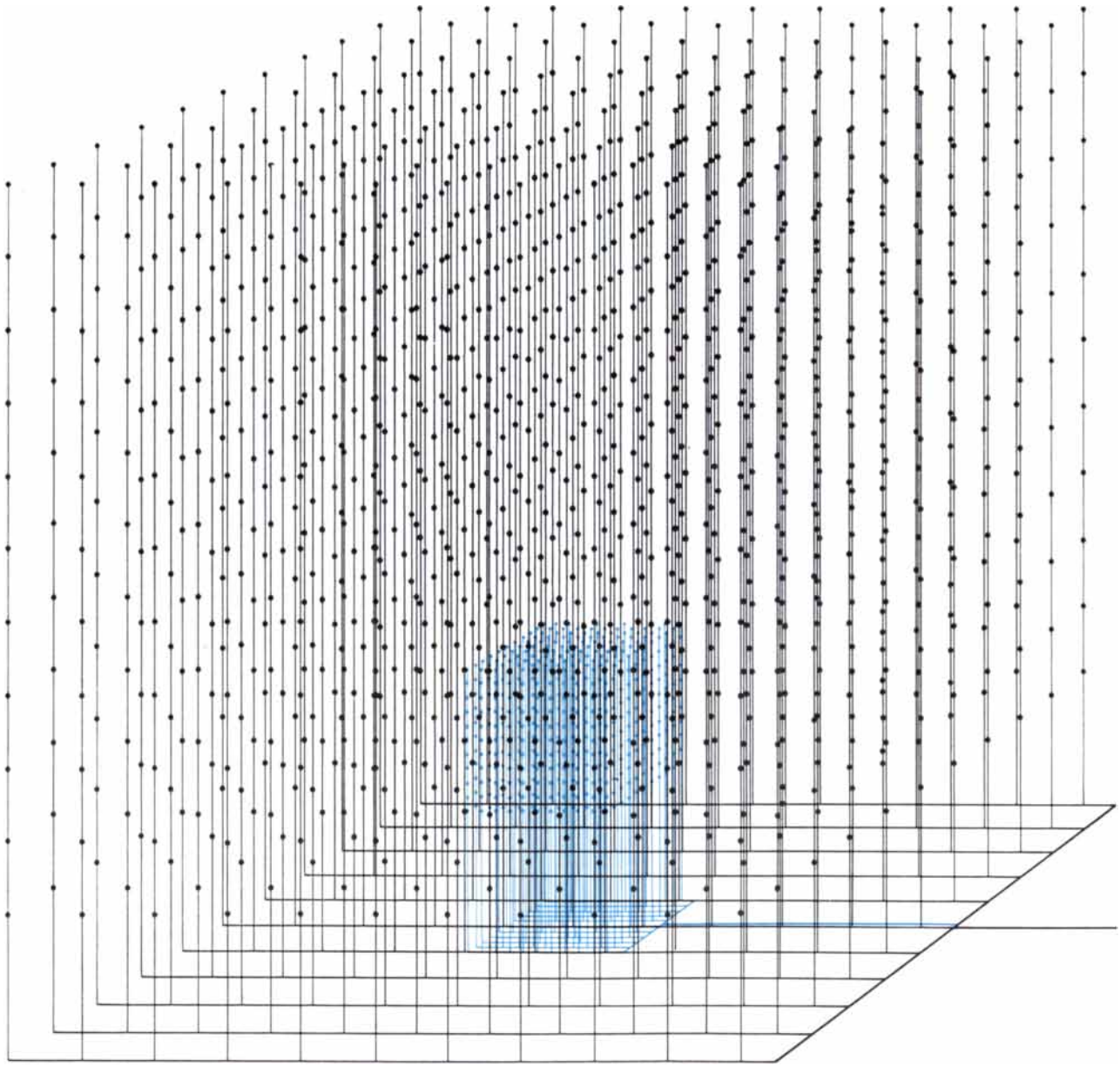
Low-energy neutrino telescopes may be able to record neutrinos from a supernova, a star that is believed to explode after it has exhausted its nuclear fuel and collapsed. More energy is released in the few seconds of the explo-

sion than in the star's entire previous history. Most of this energy escapes in the form of neutrinos, each of which typically has an energy of 15 million electron volts. A detector with a mass of several tons could monitor neutrinos coming from a supernova on the other side of our galaxy. Several low-energy neutrino telescopes are now poised to observe the next such supernova.

Some neutrinos are far more energetic than those produced in supernovas or in the interior of stars such as the sun. In the earth's atmosphere and in many astrophysical systems neutrinos are created with energies in excess of 10^9 electron volts. Such neutrinos are the result of extremely energetic collisions between nucleons. For example, high-energy neutrinos are generated when energetic cosmic-ray protons strike the nuclei of atoms in the earth's atmosphere. DUMAND will be able to detect neutrinos with energies of more than 10^{11} electron volts.

The history of attempts to detect high-energy neutrinos at sites other than particle accelerators is a short one. There have been only four experiments, of which the first and largest was done by Reines and his co-workers. Their detector and the others consist of extensive arrays of sensors deployed in deep mine shafts. When an occasional high-energy neutrino interacts with a nucleon in the surrounding rock, it creates a shower of electrically charged particles that are registered by the sensors.

If the neutrino is a muon neutrino with an energy of more than 10^9 electron volts, the particles emerging from the collision will usually include a muon. Muons have great penetrating power; indeed, an energetic one can penetrate a kilometer of rock. Hence the



ARRAY OF 1,331 LIGHT SENSORS may be anchored to the ocean floor in the Hawaiian Islands at a depth of five kilometers. Called DUMAND, for deep underwater muon and neutrino detector, the proposed array will detect the flash of blue Cerenkov radiation generated by the cascade of particles created when a neutrino collides with a particle in the nucleus of an atom of seawater. If the DUMAND project is approved and funded, the sensors will be placed at intervals of 50 meters throughout 125 million metric tons of seawater. An inner array will also consist of 1,331 sensors spaced at intervals of 10 meters. The outer array will monitor neutrinos whose energy exceeds 10^{12} electron volts; the inner array will detect less energetic neutrinos and multiple muons. The sensors are linked by cable to a computer on the shore. The two arrays are only one of several configurations of sensors that are being considered by the DUMAND organization.

neutrino can be monitored even if it interacts with a nucleon a kilometer from the sensor: the resulting muon will continue roughly along the trajectory of the neutrino and trip the sensor. Therefore the effective size of the detector extends well beyond its physical dimensions.

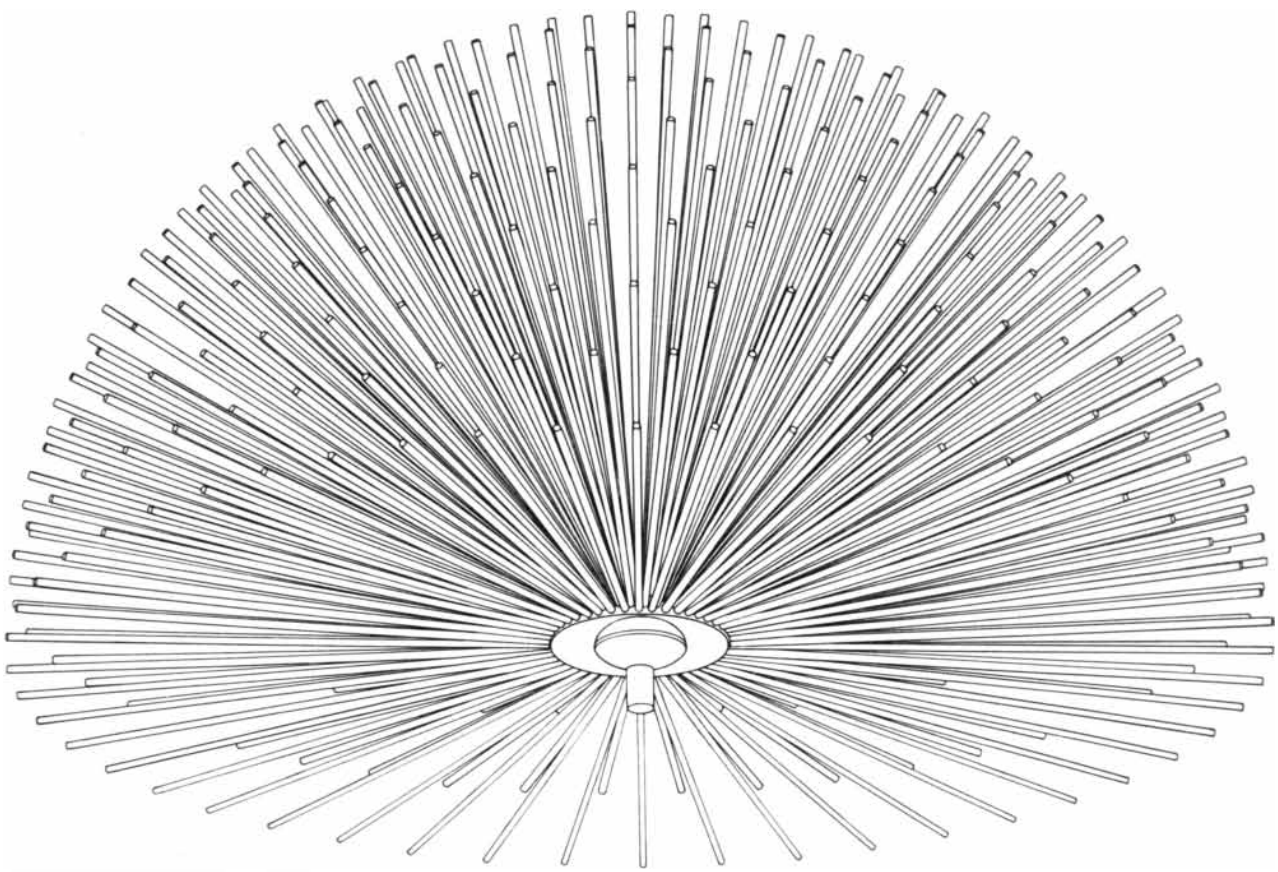
Muons are also created high in the earth's atmosphere in collisions between cosmic rays and the nucleons of air molecules, and the muons will trigger a high-energy neutrino detector if they can reach it. It is to keep atmospheric muons from swamping rarer neutrino-generated muons that the detector must be placed deep below the surface. Reines' detector, which had a total area of 140 square meters, was two miles down in the deepest mine shaft in the world (near Johannesburg in South Africa). The depth and the installation costs put limits on the size of the detector, and it did not reveal any neutrino sources outside the earth's atmosphere. Even so, the negative result has astrophysical significance: it bears on the production in the universe of deuterium (heavy hydrogen), in which nucleons collide and give rise to neutrinos.

The DUMAND apparatus will be much more sensitive than other high-energy neutrino detectors chiefly because it will be better shielded and will be able to detect neutrino interactions in a much larger volume of matter. The current plan is to ultimately distribute at least 2,000 light sensors throughout a cubic kilometer of seawater. Flexible cables will anchor the sensors to one another and to the ocean floor. The entire array will be linked to a computer on the shore.

The DUMAND array will efficiently detect a single neutrino interaction if the energy of the neutrino exceeds 10^{11} electron volts. Neutrinos with less energy will register only if many of them trip the detector simultaneously, as might happen if an astrophysical system gave off a powerful burst of them. An essential feature of the array will be its ability to determine the direction from which a detected neutrino came. The bulk of the charged particles created in the interaction of a neutrino and a nucleon of seawater will continue for some 10 meters in a direction within half a degree of the trajectory of the incident neutrino. The charged particles will collide with other particles in the water, which will in turn collide with still other particles, giving rise to a cascade of perhaps a few million particles. The cascade will be accompanied by billions of tiny flashes of Cerenkov radiation and will trigger light sensors in the immediate vicinity.

A muon among the charged particles, being exceptionally penetrating, will emit light throughout its long path through the seawater. At a neutrino energy of about 10^{12} electron volts the typical muon track is at least a kilometer long. A computer analysis of the sensor responses should fix the direction of the incident neutrino to better than half a degree. According to calculations by Arthur Roberts and Victor J. Stenger of the Hawaii DUMAND Center, a computer analysis of the total number of detected Cerenkov photons should establish the energy of the neutrino fairly accurately.

Although the DUMAND array will have a cross-sectional area of a square kilometer for muon detection, its effective collection area will be far smaller for neutrino detection. For a neutrino with an energy of 10^{12} electron volts each nucleon of seawater in effect provides a target of 10^{-35} square centimeter. A cubic kilometer of seawater holds 6×10^{38} nucleons, and so the total col-



"SEA URCHIN" is a type of light sensor being considered for the DUMAND project. The sensor has 500 "spines," each eight feet long, radiating from a hemispheric photomultiplier tube. The spines are filled with a chemical that fluoresces when it receives a flash of Cerenkov radiation. The fluorescence then travels down the light pipe of the spine and triggers the photomultiplier, signifying the passage of the particle that gave rise to the Cerenkov radiation. Each of the 1,331 sensors in the outer DUMAND array might be a sea urchin.

lecting area for collisions within the DUMAND array comes to 6,000 square centimeters. Unlike telescopes that record photons, the neutrino telescope will look in all directions at once; it will even be detecting neutrinos coming up from below through the earth. Three or more counts per year of high-energy neutrinos from a given direction might constitute a statistically significant result. Such a result would correspond to a minimum energy flux of 15 electron volts per centimeter squared per second. If the distance over which the neutrino-generated muon can travel is taken into account, the effective size of the detector is much larger.

Theodore Bowen of the University of Arizona was the first to suggest another way the ocean could be harnessed to detect neutrinos. The particle cascade triggered by the neutrino collision heats a rod-shaped volume of water. The heat expands the water and launches a small pressure pulse, or sound wave, that can travel as far as 10 kilometers before it is absorbed or lost in the background noise of the ocean. If acoustic sensors could be designed that would "hear" the cascade, they would have a much longer range than the optical sensors have. Nevertheless, for a muon or particle cascade whose energy is less than 10^{16} volts the sound pulse will quickly be lost in the background noise. If there are neutrinos that can trigger a cascade of more than 10^{16} electron volts, the acoustic sensors would be able to determine the trajectory of the neutrinos from the highly directional sound wave of the cascade. Hence the DUMAND array may include an array of acoustic sensors.

It will be no small technological feat to place thousands of optical and acoustic sensors five kilometers deep in the ocean, to keep them operating and to monitor their signals. Over the past six years some 100 physicists, astronomers, engineers and oceanographers headed by Reines have evaluated potential sites on the ocean floor, have studied ways of deploying the apparatus and have investigated different kinds of optical and acoustic sensors. A series of studies and workshops decided on the Hawaiian Islands as the site. Since the islands are steep-sided volcanoes, the ocean floor is quite deep near the shore; as a result the sensors would be more accessible. Above the ocean floor near the islands there are few strong currents and little biological activity that might interfere with the sensors' performance.

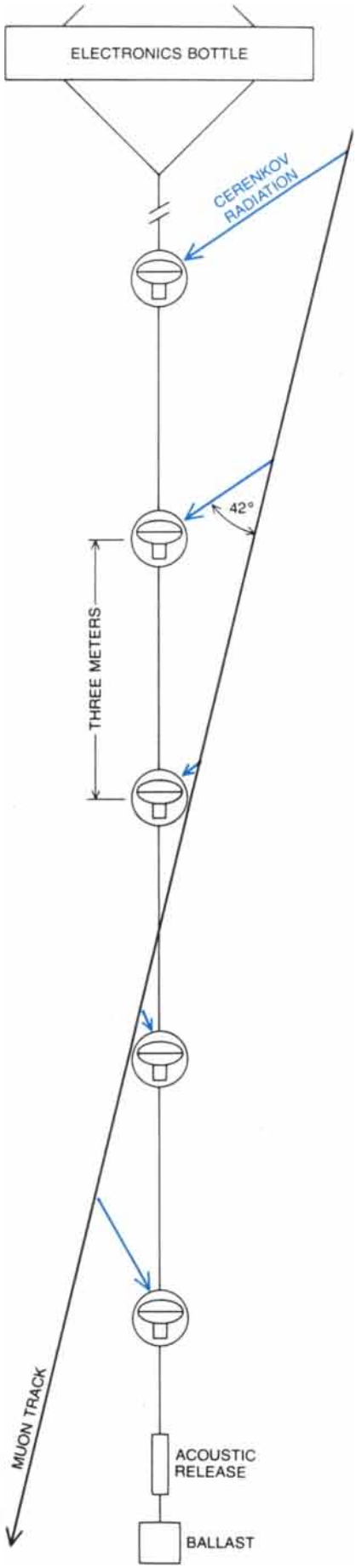
Another advantage of the Hawaiian Islands is that the deep seawater around them is unusually transparent to blue light. Recent tests conducted 20 kilometers west of the island of Hawaii at a depth of 4.5 kilometers showed that a flash of blue light is attenuated by 64 percent only over the surprisingly large distance of 25 meters. As a result the DUMAND sensors can be placed not at intervals of 20 meters, as was originally suggested, but at intervals of more than 50 meters, so that fewer detectors will be needed to monitor the same volume of water.

The cost of the DUMAND project was initially put at about $100 million, but the need for fewer detectors has significantly reduced the figure. Moreover, the DUMAND organization plans to build and install a smaller array of sensors before implementing the full project. That array would cost about $5 million. If the smaller project is approved and the funds are provided, the array could begin gathering data in perhaps three years.

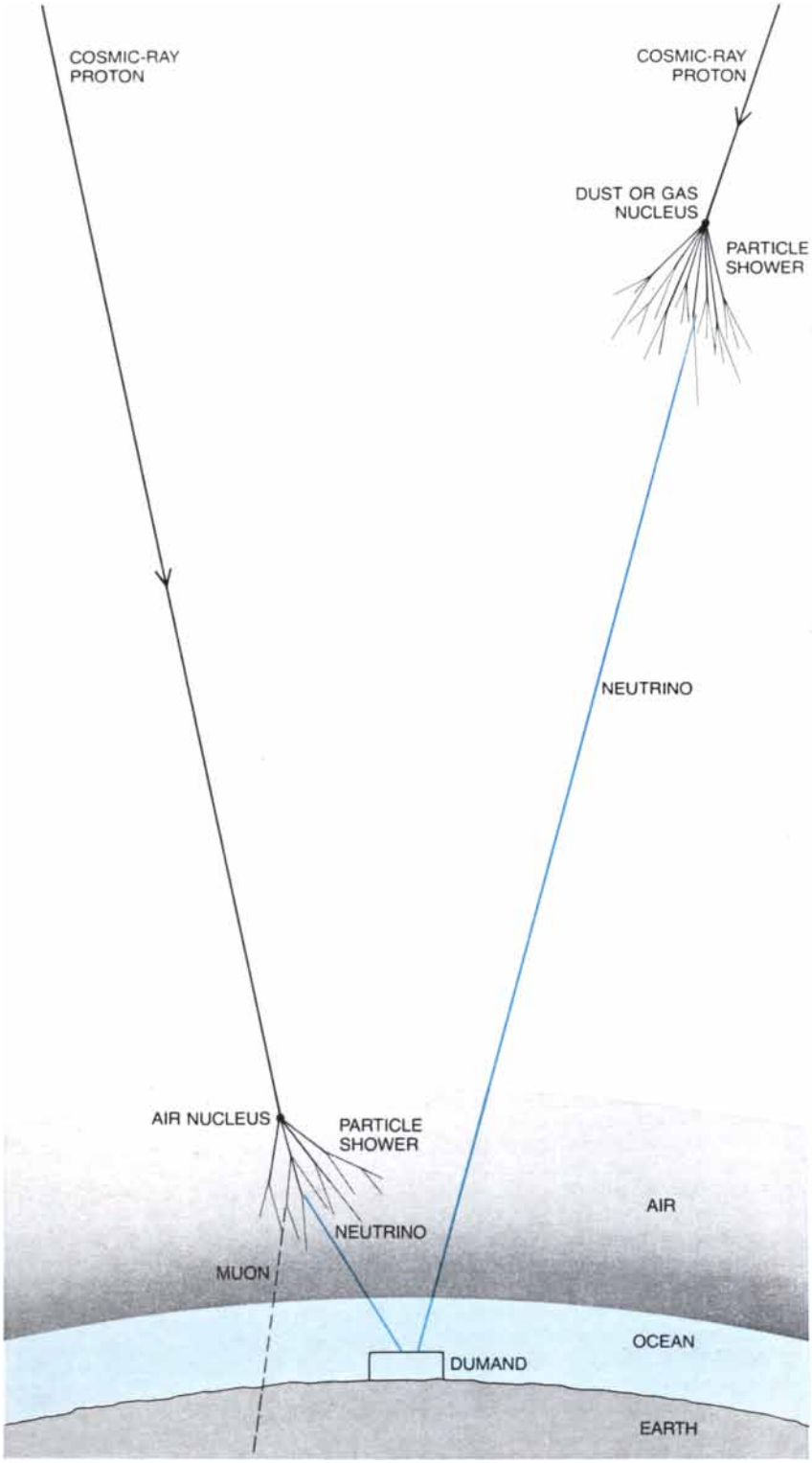
This spring a group of investigators led by Vincent Z. Peterson of the Hawaii DUMAND Center plans to deploy a string of five muon sensors at depths of between one kilometer and five kilometers. The sensors will collect data for two weeks, during which they are expected to record thousands of atmospheric muons and perhaps four neutrino-induced muons. If the detected muons come from below, they will undoubtedly have been generated by neutrinos; the neutrino is the only particle that can pass all the way through the earth. The operation of the string of sensors should help to establish the feasibility of the DUMAND project.

What originally generates the high-energy neutrinos the DUMAND array will detect? The neutrino is a chief decay product of the unstable hadrons the pion and the kaon. Pions and kaons are copiously created when a nucleon is struck by a relativistic proton: a proton moving at nearly the speed of light. About a third of the pions have no electric charge; they decay into gamma rays. The charged pions and most of the kaons decay into neutrinos, muons, electrons and their antiparticles. When a relativistic proton strikes a stationary nucleon, the pions, kaons and the decay products all continue in about the same direction as the proton. In many such collisions one of the decay products (such as the neutrino) inherits a large fraction of the proton's energy.

In short, the production of high-energy neutrinos calls for high-energy pro-



FIVE MUON SENSORS will be emplaced at depths of between one kilometer and five kilometers this spring. Over a two-week period the string of sensors may detect four neutrino-generated muons and numerous atmospheric muons. If detected muon comes from below, it will clearly have been generated by a neutrino because only a neutrino could have traveled all the way through the earth. These sensors are photomultipliers without spines, and they could be employed in the DUMAND project instead of the sea-urchin detectors.



TWO KINDS OF SOURCE (atmospheric and astrophysical) generate the neutrinos that will trigger the DUMAND array. Neutrinos are created when an energetic proton collides with a nucleon (a proton or a neutron). The collision gives rise to pions and kaons that decay into neutrinos, muons and other particles. Pions and kaons created by proton-nucleon collisions in the earth's atmosphere are usually absorbed by the atmosphere or the ground before they have time to decay into neutrinos. In interstellar space the density of matter is so low that the pions and the kaons (as well as the muons) will not be absorbed, hence they will have time to decay into neutrinos. At sufficiently high energies the relativistic phenomenon of time dilation has the effect of prolonging the lifetime of the pions and the kaons to the point where most of the atmospheric pions and kaons will collide with a nucleon in a molecule of air before they are able to decay into neutrinos and other products. Therefore at sufficiently high energies the extraterrestrial neutrinos will dominate the events registered by the DUMAND apparatus.

tons and a target of stationary nucleons for the protons to bombard. With the exception of particle accelerators the main terrestrial source of high-energy neutrinos is the impact of cosmic-ray protons on the nucleons in air molecules in the upper atmosphere. When the pions and kaons created in such collisions are able to decay before being absorbed in the atmosphere or in the ground, they give rise to neutrinos.

The relativistic effect of time dilation prolongs the life of pions and kaons that are particularly energetic. For pions and kaons with energies exceeding 10^{12} electron volts the effect of time dilation is to lengthen their lifetimes to the point where many of them eventually collide with a particle in the air instead of decaying into neutrinos and other products. Cosmic-ray protons entering the earth's atmosphere at shallow angles give rise to secondary particles that skim along the top of the atmosphere, where the density of the air molecules is low. Such particles have a better chance of decaying before undergoing a collision than particles that are heading straight down into the denser regions of the atmosphere, where the probability of a collision is much higher. At energies of about 10^{12} electron volts four times as many atmospheric neutrinos come from the horizontal direction as come from the vertical. This angular dependence is a signature that the neutrinos originated in the atmosphere.

Cosmic-ray protons collide not only with nucleons in the atmosphere but also with protons in the rarefied medium between the stars of our galaxy. In regions of the galaxy where protons have been accelerated to high energies the density of matter is typically so low that all the secondary particles created in a collision decay and yield neutrinos before they lose most of their energy in subsequent collisions. In this sense neutrino production is more efficient in the galaxy at large than it is in the earth's atmosphere. Extraterrestrial neutrinos are likely to dominate those detected by the DUMAND array at the high energies where the production of neutrinos in the atmosphere is the least efficient.

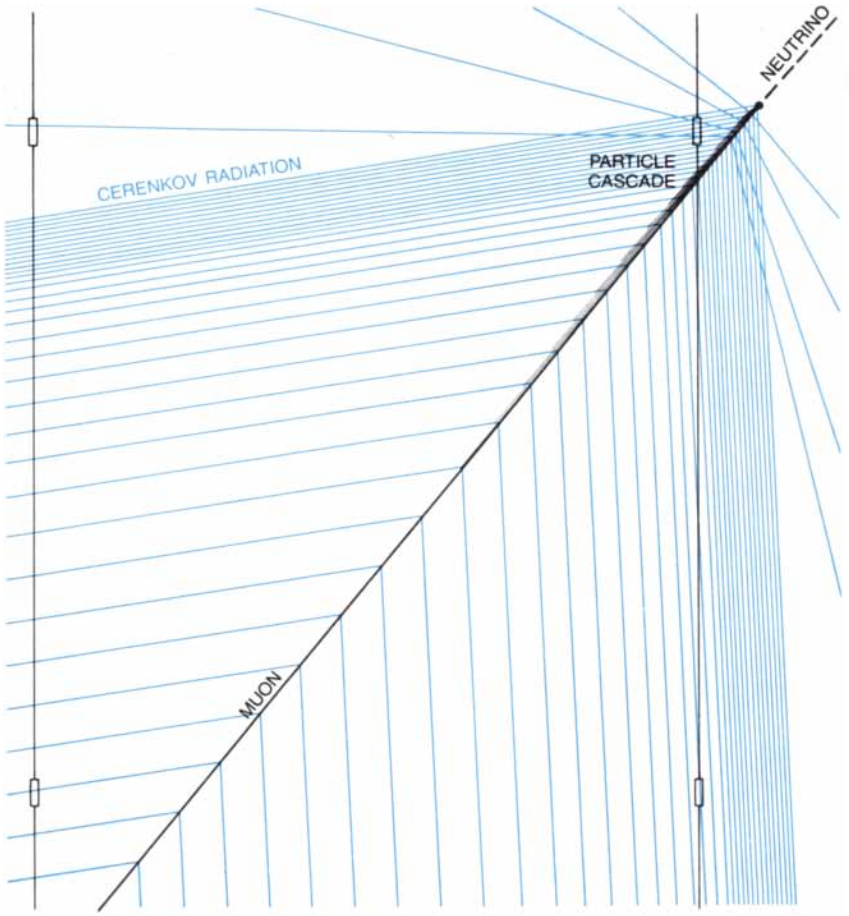
High-energy neutrinos created in interstellar cosmic-ray collisions would trigger a few hundred counts in the DUMAND array each year. These neutrinos, however, would come from a large sector of the sky, and it may be difficult to distinguish such a diffuse signal from the background of atmospheric neutrinos. Whether or not DUMAND is able to resolve the signal depends on the precise energy distribution of the cosmic rays in the galaxy. Even the failure to detect the signal, however, would be an important result that would bear on the sources of cosmic rays.

A concentrated neutrino signal could come from collisions closer to a source

of relativistic protons. Here the neutrinos would arrive not from a large sector of the sky but from a point source. As a result they would stand out above the atmospheric background much better than a diffuse signal. Relativistic particles are known to be generated by a wide variety of astrophysical systems, both within the galaxy and outside it: neutron stars, the blast waves of supernovas, the active nuclei of other galaxies and even quasars. The collisions of relativistic protons from any of these objects might give rise to neutrinos that DUMAND could detect.

One simple scenario for the generation of neutrinos has relativistic protons being created near the surface of a massive astrophysical object. (An example on a modest scale is a solar flare, in which magnetic energy suddenly released near the surface of the sun results in the acceleration of protons to extremely high velocities.) If some of the protons then rain down on the surface of the object, the object itself provides the target nucleons. The resulting collisions yield neutrinos, most of which pass through the object and continue on their way to vast distances.

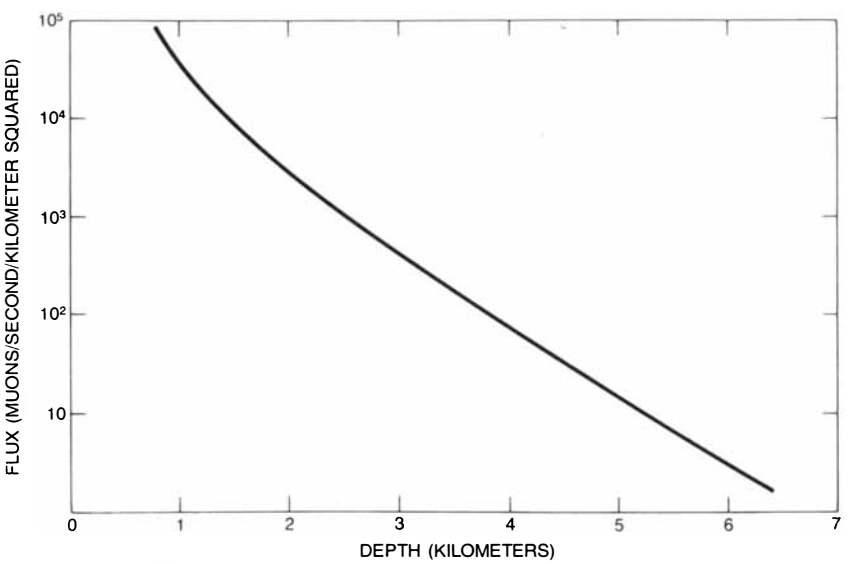
Another scenario has matter accreting, or falling, on a compact object and providing the target for relativistic particles generated by the object. Many galactic X-ray sources are neutron stars to which matter is accreting. The X-ray emission of the source is in fact powered by the falling matter. Quasars and active galactic nuclei may be powered in the same way. According to some theories, quasars and active galactic nuclei generate relativistic particles in their innermost regions; such objects would be candidates for neutrino astronomy.



CASCADE OF PERHAPS A MILLION PARTICLES can be generated when a neutrino collides with a particle in the nucleus of an atom of seawater. These particles in turn can generate billions of Cerenkov-radiation photons. The emitted light will travel at least 25 meters before it is strongly attenuated, which is why the DUMAND sensors will be placed at intervals of 50 meters. A muon emerging from such a collision proceeds nearly in the direction of the neutrino's trajectory. The muon also emits the blue light characteristic of Cerenkov radiation.

If the accreting matter is thick enough, it will obscure the object from view. In that case the emitted neutrinos would be the only direct clue to high-energy processes taking place in the object. The greater the rate of accreting matter, the more powerful the object. Two years ago a remarkable system was discovered that is obscured by accreting matter. Known as SS 433, it seems to consist of a compact object that is expelling two jets of matter in opposite directions at extraordinarily high velocities [see "The Bizarre Spectrum of SS 433," by Bruce Margon; SCIENTIFIC AMERICAN, October, 1980]. Some astronomers estimate that SS 433 is 1,000 times more powerful (that is, it puts out 1,000 times more energy per second) than the brightest stellar object known in the galaxy.

Why should such a powerful object have been discovered only recently? The answer is that SS 433 is a relatively faint source of photons. Although it may seem contradictory that an object with such power should be so faint, the two properties actually go together. The accreting matter that gives SS 433 its



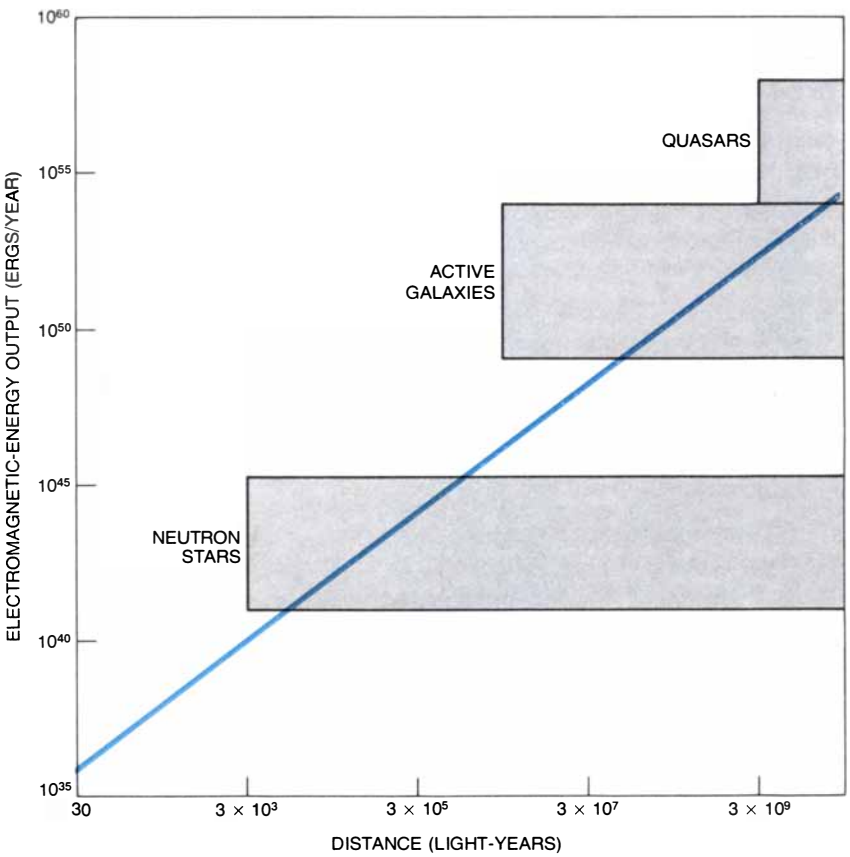
FLUX OF MUONS near the surface of the earth indicates how muons created by cosmic-ray collisions in the earth's atmosphere might swamp a neutrino detector. Even under five kilometers of seawater the DUMAND array will have to process 10 muons per second. The muons generated by cosmic-ray collisions in the earth's atmosphere come from the vertical direction or close to it; the muons generated by neutrino-nucleon collisions come from all directions.

tremendous power also acts to screen its bright central region from view. Any relativistic protons that are created near the compact object would undoubtedly collide with other nucleons, and the resulting neutrinos could escape. SS 433 may be so powerful that only one part in a million of its energy budget need go into the production of high-energy neutrinos for them to be detected by DUMAND. It is not yet known exactly what SS 433 is or whether high-energy protons are actually generated in the accreting matter. Nevertheless, the discovery of SS 433 supports the view that exotic astrophysical systems exist hidden by the accreting matter that powers them. Neutrino astronomy offers the only hope of directly detecting such objects.

Many stellar objects are binary, or double, systems. One member of the system can therefore provide target nucleons for relativistic particles generated by the other. If a young, rapidly rotating neutron star belongs to a binary system, its companion could play the target role. When the companion eclipsed the neutron star, relativistic protons from the neutron star impinging on the nucleons of the companion would generate neutrinos that would proceed through the companion along the line of sight.

Theoretical considerations suggest that at any one time there could be a few young neutron-star binary systems in our galaxy. One such system may have been observed: the binary X-ray source Cygnus X-3. The neutron star in Cygnus X-3 emits gamma rays, which implies it also generates relativistic particles. The details of the X-ray emission indicate that the entire system is shrouded by a cloud of gas that seems to have evaporated from the surface of the companion star when it was heated by radiation from the neutron star. The companion periodically eclipses the neutron star, at which time X rays are no longer detected. From this observation it can be inferred that the companion star is then between the solar system and the relativistic particles associated with the neutron star. The geometry is ideal for the emission of high-energy neutrinos in our direction.

Another scenario for neutrino production involves the ejection of matter from a compact object. For example, neutron stars are apparently born in the explosions of supernovas. When a star explodes as a supernova, it blows off its outer shell. The expanding shell can



OUTPUT OF ELECTROMAGNETIC ENERGY of various astrophysical systems and their distance from the solar system are presented on a double logarithmic plot. The colored line corresponds to the minimum high-energy-neutrino flux the DUMAND array could detect. To be detected by the DUMAND array the objects that are well above the colored line need only generate neutrinos whose energy flux is a small fraction of the electromagnetic-energy flux. Electromagnetic-energy output of a new neutron star may reach 10^{52} ergs per year.

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then provide a screen of target nucleons for relativistic protons from the neutron star. In fact, for the first six months the shell would be opaque to photons and all other relativistic particles, and so the neutron star could not be observed with conventional telescopes. In this period of infancy the neutron star would, it is thought, have more power than it would have at any other time. Indeed, the DUMAND array might detect neutrinos from an infant neutron star shrouded by a supernova shell even if it were not in our own galaxy but in a nearby one. Supernovas are thought to explode at the rate of roughly one per galaxy every 20 years. In a few years of operation the DUMAND array might pick up high-energy neutrinos from a supernova in one of several nearby galaxies.

In principle the supernova shell could act as a source of neutrinos for much longer than six months. If the shell had a significant magnetic field, it could store relativistic protons. Then the shell could continue to emit neutrinos as long as its ever decreasing density allowed relativistic protons to collide frequently. We estimate that the shell would be dense enough to yield neutrinos for perhaps 50 years. Our own galaxy may include two or three such neutrino sources that the DUMAND project could detect.

These are some of the most plausible astrophysical scenarios for the production of high-energy neutrinos. There are many other possible scenarios involving the same concept: relativistic protons colliding with a target, with neutrinos emerging from the collisions.

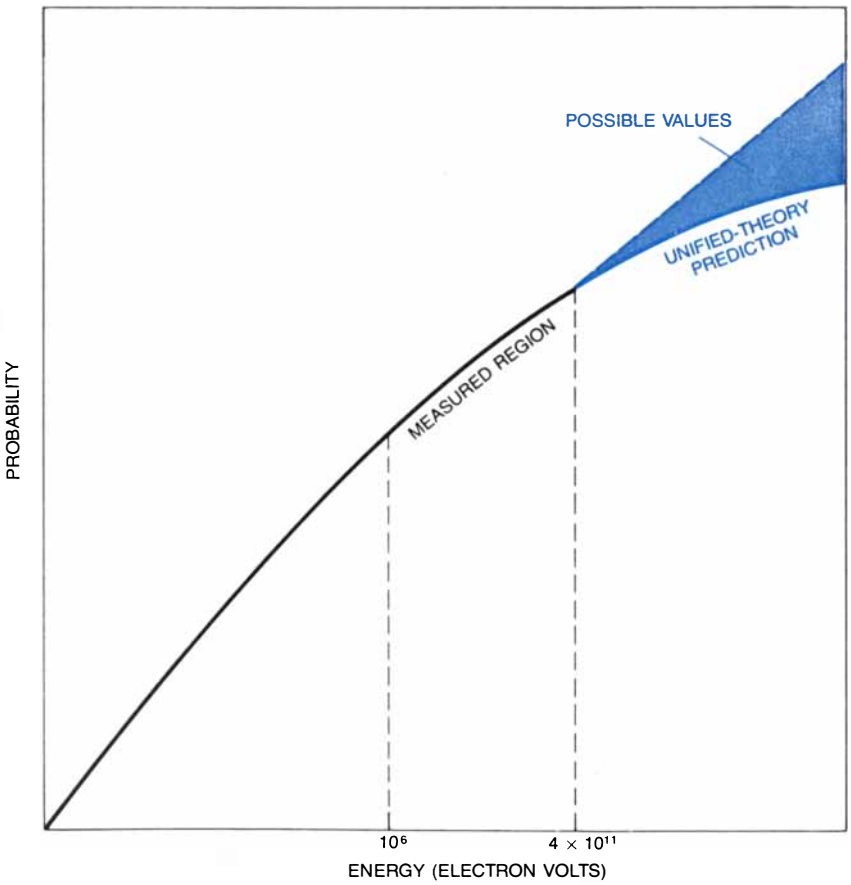
Would the DUMAND array be sufficiently sensitive to detect the neutrinos created by these various objects? Since the neutrinos cannot be detected at present, we cannot give a definite answer. The energy output of many kinds of celestial object is nonetheless compatible with the hypothesis that the DUMAND project will be able to detect neutrinos. From such objects the earth is exposed to a considerable flux of electromagnetic energy, and if it is exposed to a flux of neutrino energy that is only a small fraction of the electromagnetic-energy flux, then the DUMAND array will be able to detect the neutrinos.

For example, the energy flux of photons from neutron stars in our galaxy, quasars and active galactic nuclei is on the order of a few thousand electron volts per centimeter squared per second. Since the threshold neutrino flux for DUMAND is between 10 and 100 electron volts per centimeter squared per second for neutrinos with energies of between 10^{12} and 10^{14} electron volts, nearby neutron stars, quasars and active galactic nuclei need spend only 1 percent of their energy budget on the very-high-energy neutrinos that would be detected by the DUMAND array. Even so, the production of relativistic particles in such objects needs to be quite efficient. There is remarkable evidence, however, that this high-efficiency requirement is frequently met.

The Crab Nebula is the best-known system in which particles with energies greater than 10^{13} electron volts are produced with high efficiency. The nebula generates X rays by the synchrotron mechanism, in which high-energy electrons radiate away energy when they are deflected by the nebula's magnetic field. The estimated strength of the field implies that the electrons each have an energy of about 10^{13} electron volts.

Such energetic electrons should radiate away their energy in a year or so, yet their population in the Crab Nebula does not seem to be decreasing. Astronomers have therefore concluded that the electrons are somehow being continuously supplied or reenergized by the rapidly rotating neutron star at the center of the nebula. The neutron star, whose rate of rotation is slowly decreasing, emits a pulse of radiation once per revolution: it is a pulsar. In the gradual decrease of the pulse rate astronomers have a measure of the rate at which the star is spinning down. The spin-down rate in turn yields the approximate rate at which the star is losing rotational energy. The rate of energy loss is comparable to the power needed to sustain the synchrotron emission of the electrons in the Crab Nebula. This numerical agreement suggests that the neutron star is somehow converting a large fraction of its rotational energy into relativistic particles.

Another example of the efficient production of relativistic particles is an entirely different kind of system: the bright quasar 3C 273. Recent measurements by satellite instruments reveal that the quasar emits almost as much energy in gamma rays as it does in any other region of the electromagnetic spectrum. The energy of each gamma ray is more than 10^8 electron volts, which means that the gamma rays could only have been generated by relativistic particles (although precisely how relativistic is not yet known). The quasar is apparently spending a very large fraction of its energy budget on relativistic particles. Energy considerations suggest that neutrinos from this source could register about 100 counts per year in the DUMAND apparatus. Even though the quasar 3C 273 is exceptionally bright, it is not unrepresentative of



PROBABILITY OF A NEUTRINO-PROTON INTERACTION depends on the energy of the impinging neutrino. The electroweak theory, which is a unified theory of the weak interaction and the electromagnetic interaction, predicts that for neutrinos above a certain energy the probability of interaction depends very little on the energy. By counting the number of interactions above the critical energy the DUMAND project will be able to test this prediction.

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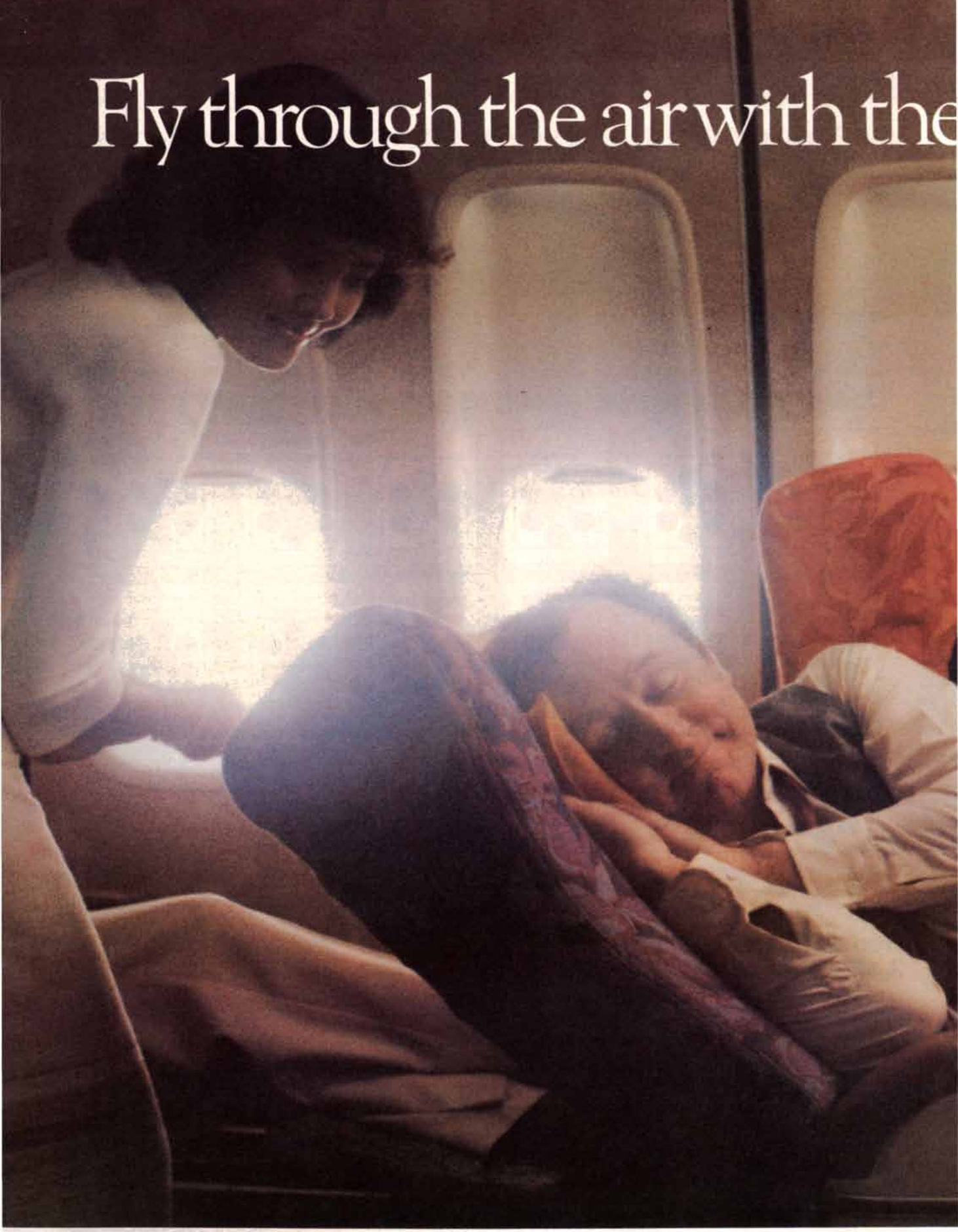

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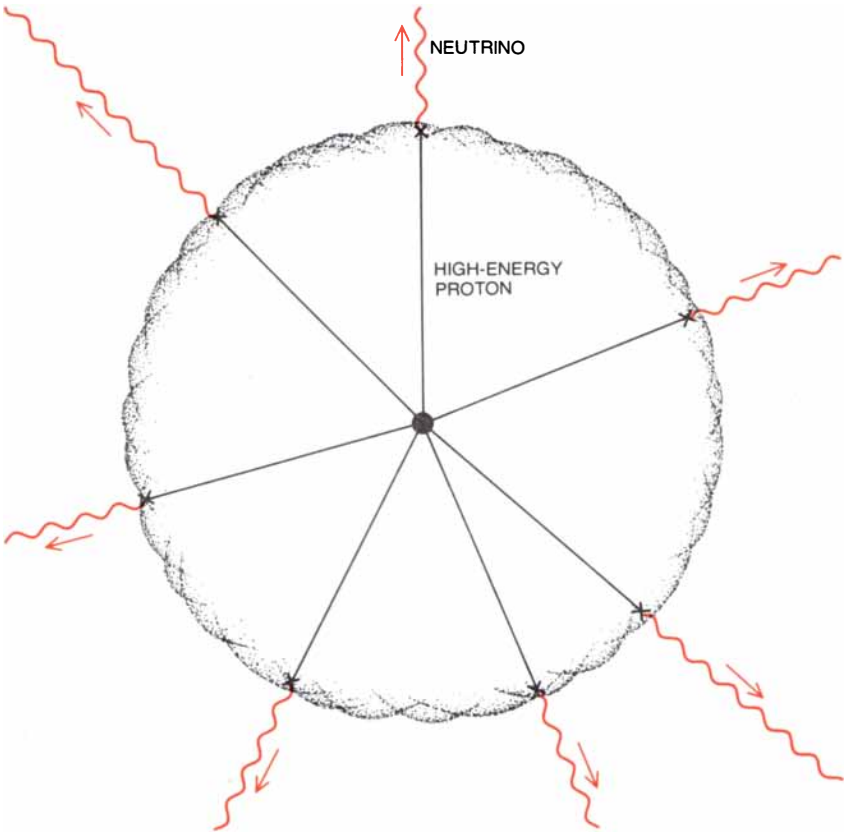
a large class of quasars and active galaxies that are also believed to efficiently produce relativistic particles. Other sites where high-energy particles are generated with unexpected efficiency include blast waves from supernovas and, on a more modest scale, shock waves coming from a variety of sources in our own solar system.

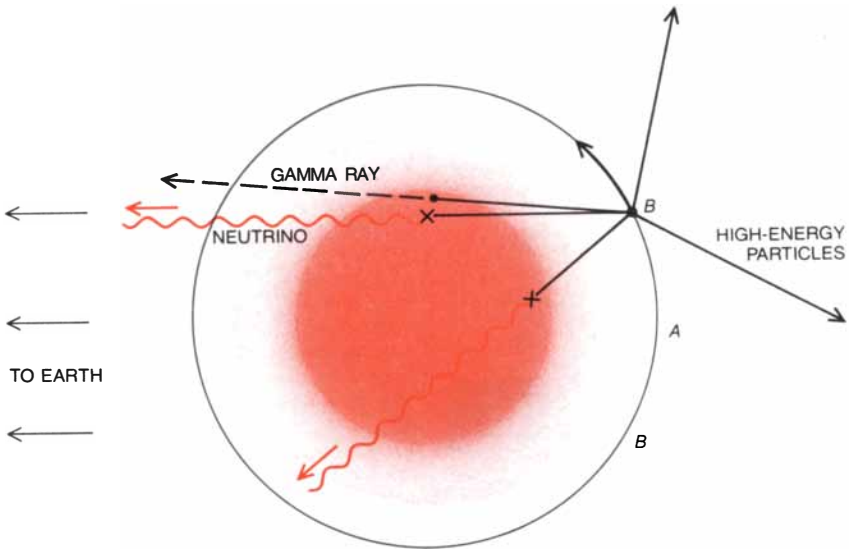
Since astrophysical systems that give rise to high-energy neutrinos also give rise to gamma rays of comparable energy, a measurement of the gamma-ray flux from a system might provide an indication of the expected neutrino flux. There is not, however, a one-to-one correspondence between detected gamma rays and expected neutrinos. Although high-energy gamma rays are always produced where high-energy neutrinos are, high-energy neutrinos are not always produced where high-energy gamma rays are. In other words, the measured gamma-ray flux may result in part from non-neutrino sources. Alternatively, the measured gamma-ray flux can understate the case for neutrinos if some of the gamma rays produced by neutrino sources never reach the earth. Indeed, the same screen of target material that gives rise to the neutrinos can absorb the gamma rays. Moreover, when the highest-energy gamma rays traverse astronomical distances, many of them are stopped by collisions with other photons. Nevertheless, if these caveats are kept in mind, gamma-ray astronomy helps in estimating the flux of neutrinos in the vicinity of the earth.

The gamma rays of interest have the same energy (more than 10^{12} electron volts) as the neutrinos to which the DUMAND array will be the most sensitive. Designated VHEGR, for very-high-energy gamma rays, they have more than 1,000 times the energy of the gamma rays that are routinely observed by satellites. Very-high-energy gamma rays are detected by large reflecting dishes that collect the feeble flash of light produced by the shower of particles marking the entry of such a gamma ray into the earth's atmosphere. VHEGR astronomy, which has been attempted for two decades, has begun to yield positive results in the past few years.

Although a screen of matter that is thick enough to stop most of the relativistic particles striking it will also be thick enough to block gamma rays, the neutrino-production scenarios do not demand that most of the protons be halted. Neutrinos could be efficiently produced if only half of the protons were stopped. It is possible to have a screen that is thick enough to halt a significant fraction of the impinging protons but thin enough to allow much of the gamma radiation to pass through. A case in point is the young neutron star in the binary system Cygnus X-3. Since the



YOUNG SUPERNOVA SYSTEM could give rise to neutrinos when energetic protons emitted by the neutron star at the center of the system collide with matter in the expanding shell of the system. The shell, which for the first six months could screen out photons and other relativistic particles emanating from the star, would be transparent to the neutrinos. The neutrinos might be the only clue to the high-energy processes taking place behind the screen.



BINARY STAR SYSTEM could also generate neutrinos. The radiation from a neutron star could vaporize matter at the surface of a companion star. Both the vaporized matter and the companion could then provide a screen of target nucleons for high-energy particles emanating from the neutron star. At position *A* the neutron star is eclipsed by its companion, and the neutrinos generated in collisions between the high-energy particles emitted by the neutron star and the nucleons of the companion star would pass through the companion star on the line of sight to the earth. Gamma rays, which are always generated along with neutrinos, would be stopped by the companion star. As the neutron star goes into or out of eclipse (*B*) it is observed from the earth through the mist of vaporized matter. The vapor could be thick enough to halt many of the impinging high-energy particles but thin enough to allow most of the incident gamma radiation to pass. Cygnus X-3 is an example of a binary star system that may fit this scenario.

neutron star apparently vaporizes matter from the surface of its companion, it is observed through a mist of matter as it goes into and out of eclipse. At some point as the neutron star is moving away from its eclipsed position the mist must have the optimum thickness for gamma-ray emission.

This conclusion has now been borne out by observation. Over the past decade a group of investigators led by A. A. Stepanian of the Crimean Astrophysical Observatory in the U.S.S.R. has observed very-high-energy gamma rays emitted by Cygnus X-3. The observation has recently been confirmed by the same group and by a group in the U.S. The gamma rays are seen to be emitted only periodically, with the most radiation apparently being produced just as the neutron star emerges from behind its companion. The gamma rays were observed over only 5 percent of the neutron star's orbital period. To account for the observed gamma-ray flux the neutron star in Cygnus X-3, like the one in the Crab Nebula, must efficiently produce particles with an energy of 10^{13} electron volts. If the gamma rays are the product of pion decay, neutrinos are produced along with them. We estimate that these neutrinos would register about 50 counts per year in the DUMAND array.

In 1975 very-high-energy gamma rays were discovered emanating from the radio galaxy NGC 5128. If these gamma rays come from pion decay, the accompanying neutrinos would register at least a few counts per year in the DUMAND array. The significance of the discovery for DUMAND is that active galaxies are capable of efficiently generating relativistic particles with enough energy to create neutrinos the DUMAND array could detect.

Neutrino astronomy may also provide answers to basic questions about the overall structure and history of the universe. One question is whether all galaxies are made of ordinary matter or roughly half of them are made of antimatter. The conventional view is that all galaxies consist of ordinary matter [see "The Cosmic Asymmetry between Matter and Antimatter," by Frank Wilczek; SCIENTIFIC AMERICAN, December, 1980]. Some investigators nonetheless think there is an overall symmetry to the universe requiring that half of it be antimatter. Photon astronomy cannot directly resolve the issue because the photon is its own antiparticle and hence carries no information about whether its source is matter or antimatter. Neutrinos are different from antineutrinos and can be distinguished by the DUMAND array according to the details of the interaction. Galaxies made of matter emit many more neutrinos than antineutrinos, so that a sufficiently strong neutrino signal from a galaxy should reveal whether it consists of matter or of antimatter.

With the DUMAND array it should be possible to examine not only astrophysical phenomena but also fundamental concepts in particle physics such as the electroweak theory: the unified theory of the weak interaction and the electromagnetic interaction. These interactions are two of the three fundamental forces of nuclear physics; the third is the strong force, which binds nucleons together. Neutrinos are subject only to the weak interaction; they do not "feel" the other nuclear forces. According to the electroweak theory, the weak and the electromagnetic interactions have about the same strength within some small distance (less than 10^{-16} centimeter) of a quark in a particle that is subject to both forces. At short range, then, the weak force is not weak.

A neutrino traversing a proton has a probability of less than one in a million of coming close enough to a quark and feeling the weak force. Nevertheless, as the energy of the neutrino increases, the weak force plays more of a role, and the neutrino is more likely to interact with the proton. The electroweak theory predicts that above a certain critical energy the probability of a neutrino-proton interaction is no longer dependent on the energy. Neutrinos whose energies exceed the critical value are regularly created in the earth's atmosphere at a known rate. From this rate and the number of neutrino-nucleon interactions detected by the DUMAND array the probability of the interaction could be calculated, and the measured probability could then be compared with the predicted one. The theory also makes predictions about the distribution of energy among the various charged particles created in a neutrino-proton interaction. The DUMAND array will be able to test those predictions.

The DUMAND organization has recently investigated the possibility of putting another kind of detector at the surface of the sea or on the shore to measure the energy of the cosmic rays that would generate muons that would be detected by the DUMAND array. Information about the energy and the distribution of the muons could reveal much about the nature of high-energy interactions and high-energy cosmic rays.

The strongest motivation for the DUMAND project is that it will exploit a source of information about the universe that has not so far been exploited. The extension of astronomy from visible light first to radio waves and then to X rays and gamma rays never failed to lead to the discovery of unusual objects such as radio galaxies, quasars and pulsars. All these objects came as a surprise. It is likely that neutrino astronomy will bring its own share of surprises.

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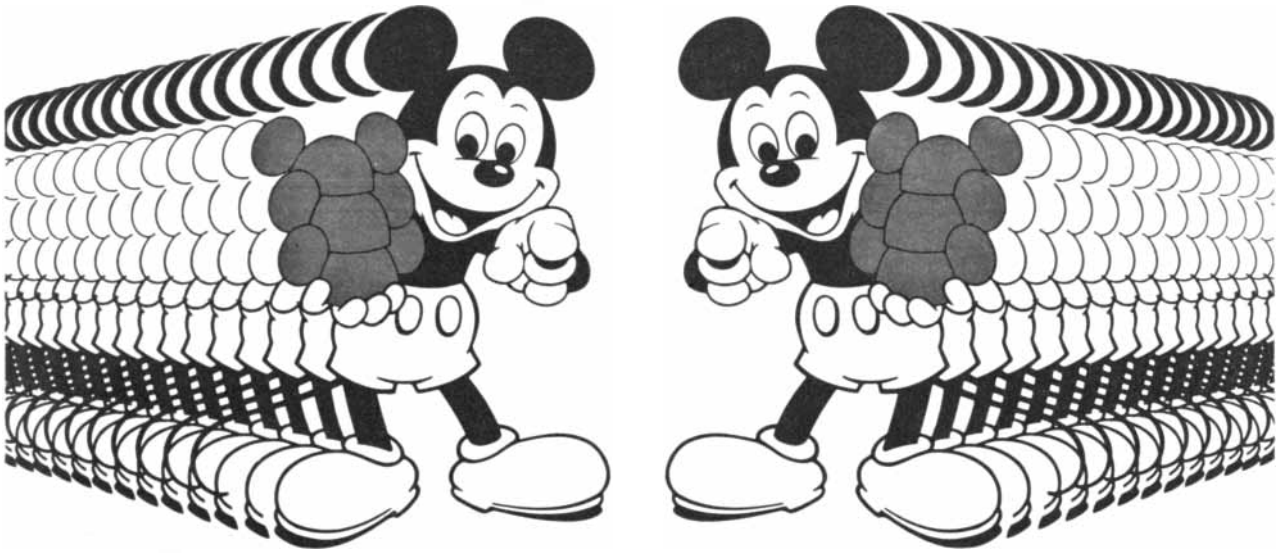

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The Nok Sculptures of Nigeria

These unique terra-cotta figures date back 2,500 years. Associated with both stone tools and early iron-smelting furnaces, they raise questions about the function of art and the definition of a culture

by Thurstan Shaw

Nigeria is the most populous country in Africa, with twice the area of California and more than three times as many inhabitants. It also has the oldest artistic heritage anywhere on the continent south of the Sahara. The sculpture from Benin first amazed the world less than a century ago. Since then scores of other works, for example those from Ife and Igbo-Ukwu, have multiplied that initial astonishment and admiration.

For some time archaeologists have been trying to reconstruct the economic, social and political circumstances that gave rise to these artistic flowerings in Nigeria. It is a slow business, and much of the information needed for such reconstruction has still to be acquired. One fact, however, has been firmly established: the oldest manifestations of Nigerian artistic excellence are to be seen in a remarkable corpus of terra-cotta sculptures discovered in central Nigeria over the past half century. These ancient pottery figures have come to light almost entirely as the result of tin mining. To understand this curious association of works of art with mineral deposits one must know something about the physiography of Nigeria.

Nigeria has almost no mountains or highlands except for the mountains on its eastern border and the Jos Plateau. The latter feature, a granitic intrusion measuring 100 kilometers from north to south, is 1,200 meters above sea level on the average and reaches an altitude of 1,800 meters east of the town of Jos. Oxides of tin and other minerals were crystallized in the cooling magma of the intrusion but are so widely diffused that they are difficult and uneconomic to extract from the granite matrix. Millions of years of erosion, however, have carried the heavy tin grains downhill and have concentrated them in alluvial deposits on the surrounding lowlands.

In the course of working one of these alluvial sources of tin in 1928, Colonel Dent Young, the co-owner of a mining partnership near the little village of Nok, recovered a well-fired terra-cotta sculpture 10 centimeters high as it was washed out of the tin-bearing gravels. Young presented his find to the embryonic museum of the Department of Mines in Jos. The sculpture probably portrays a human head, although partly because other examples of Nok portraiture were then unknown, it was originally thought to represent a monkey.

Fifteen years later a larger terra-cotta sculpture, a human head 22 centimeters high, was recovered from a second tin working near Jemaa some 65 kilometers east of Nok. The head had been buried eight meters deep in the gravels. The clerk in charge of the mine took it home to use as a scarecrow in his yam plot. There it was noticed and acquired by the mine manager, who brought it to Jos.

The Jemaa find came to the attention of Bernard E. B. Fagg, a young administrative officer who had studied archaeology at the University of Cambridge and was then on leave excavating a rock shelter on the Jos Plateau for evidence of early human occupation. Fagg recognized the points of similarity between the new head and the one from Nok already in the museum at Jos. He subsequently visited Young, who showed him a recently unearthed terra-cotta figurine of a seated monkey nearly 24 centimeters high. On a later visit to Nok, Fagg was shown still another terra-cotta sculpture: a human head 19 centimeters high. Fagg inspected the tin workings; the sluice boxes and the spoil heaps proved to contain fragments of terra-cotta, quantities of potsherds and stone axes that had been shaped by grinding.

By now it had become clear that tin mining in the Nok and Jemaa areas was both revealing and destroying archaeological material of the greatest importance. At the same time Fagg was appointed to the newly formed Nigeria Antiquities Service, established to preserve the country's archaeological heritage. He promptly organized a watch over the tin mines, securing the miners' cooperation in rescuing as much as possible of the material that was being uncovered. He also arranged for scholarly publication of the finds that had been made up to that time. Since the first of the discoveries had been made at Nok, he assigned the sculptures to the "Nok culture," in accord with the archaeological practice of the time.

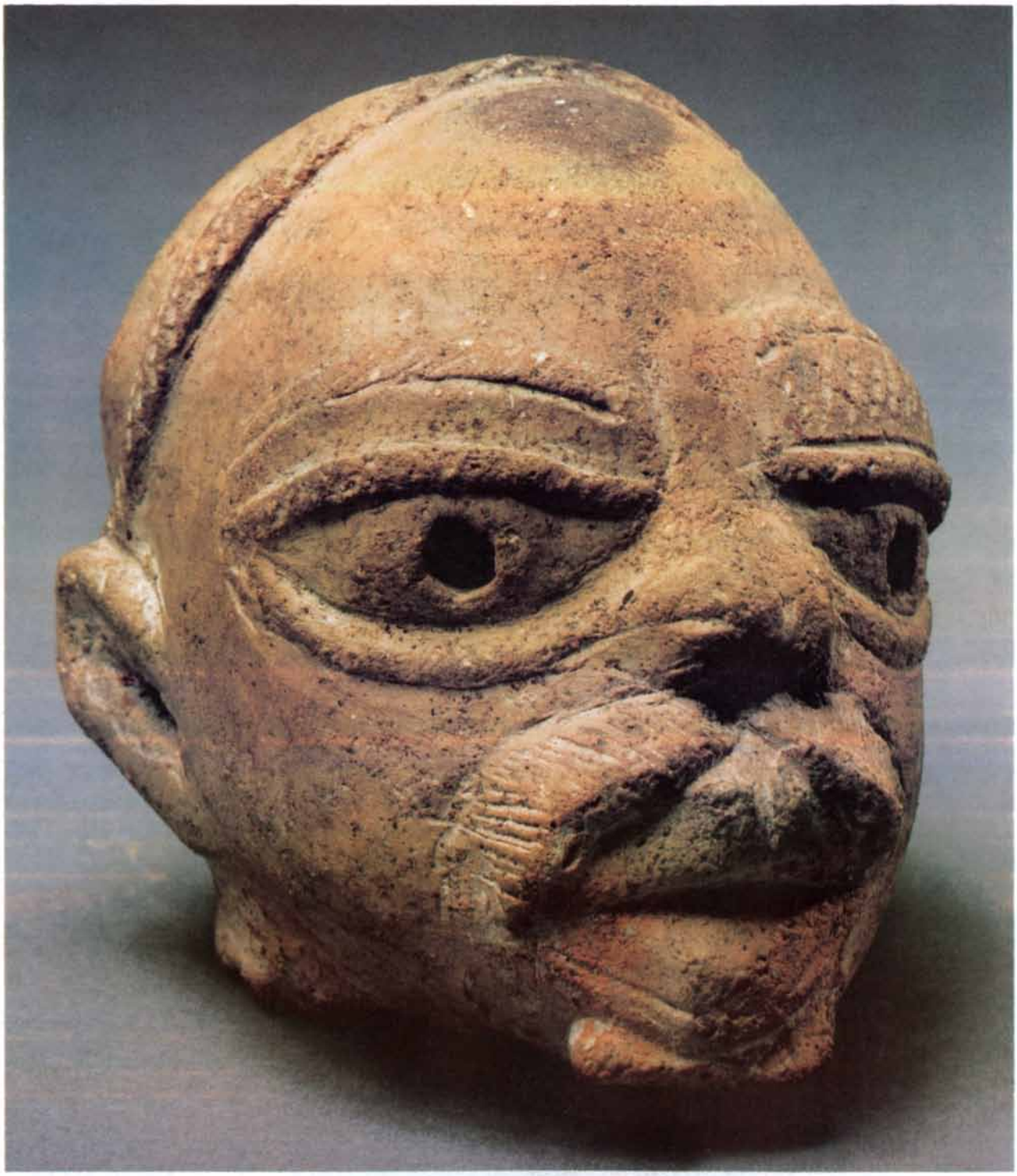
Since those early days, 35 years ago, many more terra-cotta sculptures have been uncovered, and an entire room in the museum at Jos is devoted to them. The interest of the Antiquities Service in rewarding the finders of the sculptures soon became known, and terra-cottas from contexts other than the tin-mining deposits began to appear. Some came from roadside gravel quarries; one was uncovered during leveling for a school playing field. A few have even been found in local shrines; the supposition is that after they had been accidentally unearthed they were judged worthy of veneration. Similar incidents occur today at Ife, where terra-cotta sculptures discovered by chance find their way into shrines or are even reburied in sacred groves.

The area of central Nigeria where Nok-style sculptures have been found now extends from Kagara eastward to the Jos Plateau and from Kachia in the north to Katsina Ala in the south. The greatest concentration of finds continues to be around Nok and Jemaa; between them the two areas account for three-fourths of the terra-cottas so far uncovered. One might think this distribution reflects not so much the location of the area where the sculptures were originally made as the location of the tin-mining activity that has revealed so many of them. Such is not the case; there has now been a great deal of tin mining on the Jos Plateau itself, and the diggings have been consistently monitored for archaeological finds. Yet so far only one find has been made in any of these mines, and it is not in the typical Nok style.

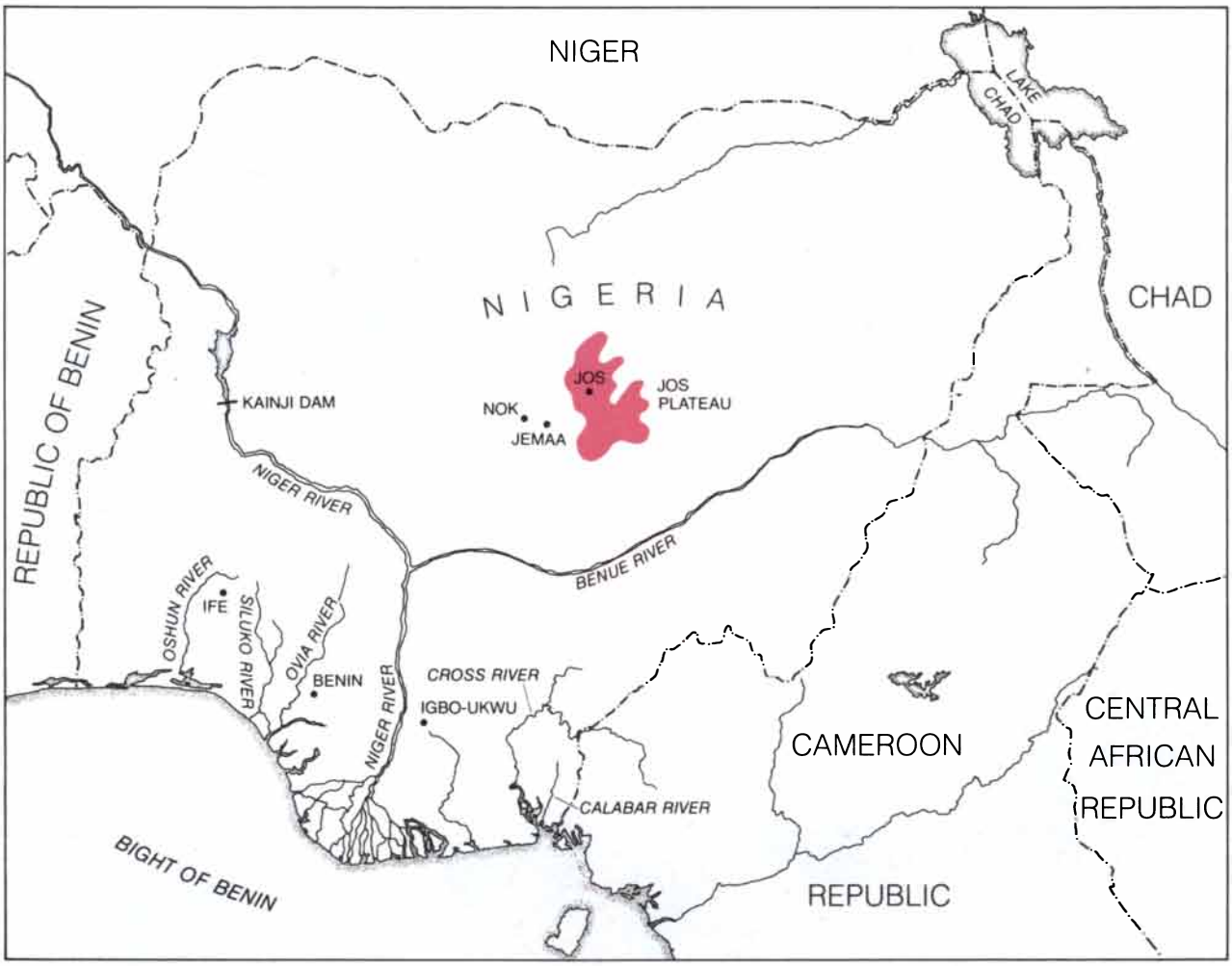
Hence it seems fairly certain that the makers of the Nok-style terra-cottas were predominantly settled not on the Jos Plateau but below it. At the same time the finds around the perimeter of the distribution map are all chance discoveries in nonmining contexts; this

could indicate that much is yet to be found in the area between the present perimeter and the Nok-Jemaa mining region. Some limits, however, are already evident. For example, rescue archaeology in the valley of the Niger River before completion of the Kainji Dam produced terra-cotta sculptures that are apparently contemporaneous with the Nok figures. Their style is not Nok.

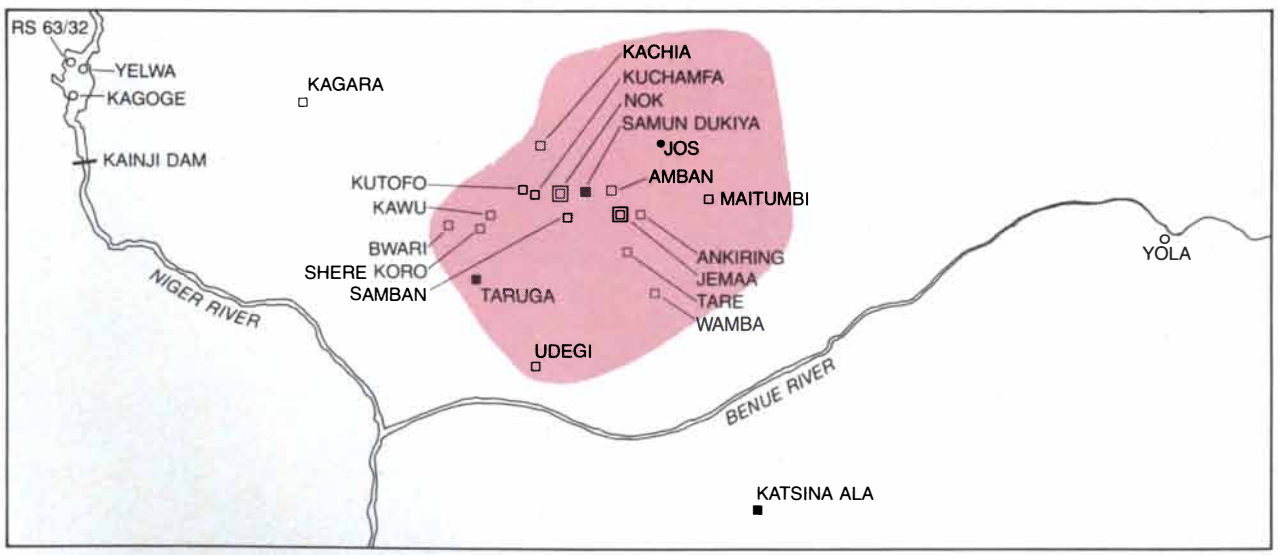
How may the Nok style be defined? To begin, consider the physical variety represented among the 200-odd Nok sculptures now known. About 10 percent of the total are small, solid clay figures that were, or still are, attached to pottery vessels. Most of these portray human beings, but at least one portrays an animal. By far the greater number of Nok sculptures, however, are freestanding figures in a wide range of sizes. A few are still whole; one of them, a kneeling human figure 10 centimeters (four inches) high, is at one end of the size



TERRA-COTTA HEAD 10.5 centimeters high was found in the tin-bearing alluvial deposits at Jemaa, west of the Jos Plateau in central Nigeria. It was buried some four meters below the surface. The spherical head shows the characteristic Nok-style hairline, running over the top of the scalp from ear to ear. The hairs of the mustache are suggested by incisions and part of the beard has been broken away.



NIGERIAN SCULPTURE, unknown outside Africa a century ago, gained fame after European contacts in southern Nigeria, first at Benin and later at Ife and Igbo-Ukwu. Now it is known that the oldest terra-cotta sculptures are found close to the Jos Plateau (*color*).



DISCOVERY SITES of Nok-style terra-cottas appear on this map. The double squares at Nok and Jemaa indicate that large numbers of the sculptures have been found in tin deposits in both areas. An open square indicates the discovery of one or more of the sculptures elsewhere in central Nigeria. Three sites (*black squares*) have been excavated. One, Katsina Ala, marks the southernmost discovery of Nok-style terra-cottas to date. Kachia is the northernmost occurrence and Kagara the westernmost. The tin-mining region is indicated in color. Three Niger River sites to the west and one site, Yola, to the east (*open circles*) have yielded early terra-cottas but not of the Nok style.

range. At the other end the size of some heads (the part of the figure that has most commonly survived) and of some leg fragments suggests that the largest complete figures cannot have been less than 120 centimeters (four feet) high.

Nearly all the freestanding figures are hollow; only a few of the smallest are solid. The walls of most of the hollow figures are less than a centimeter thick; the fabric consists of a matrix of clay containing grains of quartz, mica, granite or other suitable "tempering" materials. This is true of much modern Nigerian pottery that is not made on the potter's wheel. The advantage of such a fabric is that it can be fired in as little as two hours in an open bonfire no hotter than 800 degrees Celsius, provided it is first preheated to drive out the last of the moisture in the clay. This is how much pottery is fired in Nigeria today, and doubtless the Nok craftsmen employed the same method.

Breaks in the terra-cottas reveal that the cylindrical parts of some of the sculptures were formed by coiling rope-like lengths of clay; a vessel wall formed by coiling is later consolidated by applying pressure to the soft clay simultaneously inside and out. Other breaks indicate that certain surface features of the sculptures, for example tresses and such ornaments as beads, bracelets and necklaces, were sometimes modeled separately and then joined to the body. Parts of the body too, such as the head, the torso or the limbs, were sometimes shaped separately and then joined.

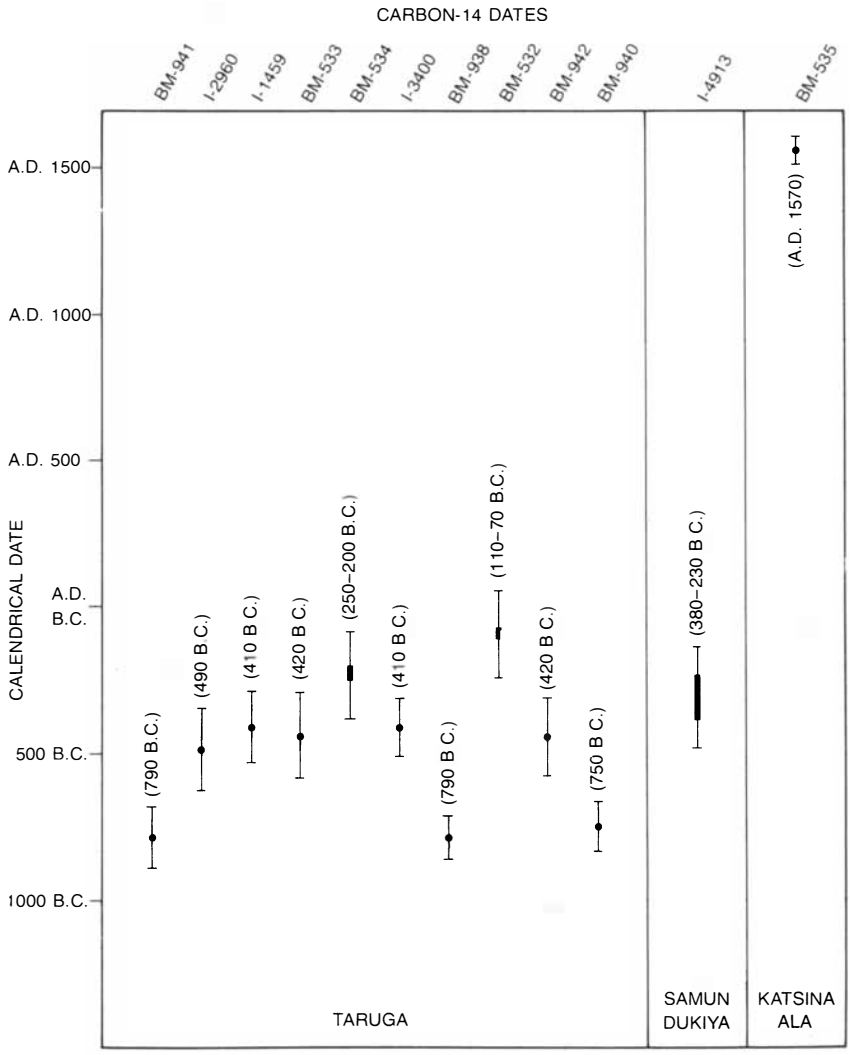
The Nok sculptors commonly followed the African tradition of modeling the human figure with the head enlarged out of normal proportion; the ratio of head size to body size is one to three or four, rather than one to seven or eight as it is in life. It also appears that form and features were not always exclusively the result of modeling. The clay, perhaps after partial drying, was occasionally whittled away to produce the desired result. Indeed, some of the terra-cottas bring to mind the technique of the woodcarver, who first blocks out certain prominent features and subsequently refines them.

Art is always symbolic to a greater or lesser degree, and African art is highly so; naturalism is seldom appropriate to its purpose. It is therefore not surprising to find that the Nok sculptures show a number of conventions. I have already mentioned the unnatural ratio of head size to body size. Another example is found in the representation of the eye. It is usually triangular in shape or forms a segment of a circle, with the upper eyelid horizontal and the lower one a downward curve. Less commonly it is the upper eyelid that is slightly curved. The pupil is indicated by a circular perforation that extends to the interior of the hollow head, and arching eyebrows balance the curve of the lower eyelid. Sometimes the eyebrows are applied strips of clay that were later pinched into ridges. These conventions are almost universal in the Nok terra-cottas; they are followed even in sculptures of animals, for example the head of an elephant.

Other conventions include a high forehead, the result of commonly positioning the hairline along a vertical arc over the top of the head running from one ear to the other. The hair is indicated in a number of ways; among the many different styles are the topknot and buns not unlike those still worn in parts of Nigeria until recently. Beards are often represented by ridged projections around the jaw. Mustaches also appear, and one head bears a plaited goatee.

Noses are modeled wide and flat. Large nostrils, like the pupil of the eye, are indicated by circular perforations. Perforations also commonly indicate ears, which are occasionally exaggerated. Mouths are usually shown closed, with clearly modeled lips that are wide and prominent.

The human heads are spherical, conical or cylindrical. In some instances the basic form of the head and the trunk is that of one cylinder placed obliquely on top of another. This is a convention known in other traditions of West African art. A few "Janus figures" have been



AGE OF NOK TERRA-COTTAS is indirectly indicated by carbon-14 determinations of the age of charcoal or carbonized-wood samples from sites where Nok figurines have been found. Twelve selected carbon-14 dates appear here; the length of the black line shows the standard error of each determination. The 10 dates from the Taruga site are from charcoal samples associated with iron slag or smelters; the prefix "BM" identifies measurements by the British Museum and the prefix "I" ones by Isotopes Inc. The readings range from about 790 to about 100 B.C. One Taruga British Museum reading has been omitted for reasons of scale; it is No. 939—A.D. 1640. The Samun Dukiya reading is from a wood sample unearthed in the lower part of the occupation horizon. The very late date from Katsina Ala, like No. 939 from Taruga, suggests that the sample, from a mass of charcoal in the occupation layer, was contaminated.

THREE-ACRE TERRACE in the Taruga Valley was investigated by Bernard E. B. Fagg when prospectors uncovered two Nok-style terra-cottas. After a magnetometer survey showed many anomalies excavation over four seasons revealed iron slag and other evidence of iron smelting.

found, heads with two faces back to back. Details of dress and other accoutrements are carefully executed; they include male and female waistbands and pubic aprons. The overall impression conveyed by most of the terra-cottas is one of great confidence on the part of the makers in the tradition they were perpetuating. In spite of a variety of substyles there is an almost universal assurance of line and cleanness of surface.

Having established the fact that most Nok-style terra-cottas were being found in alluvial tin deposits at depths as much as 13 meters below the surface the staff of what was by now titled the Department of Antiquities embarked on a three-part program. First, they undertook the collection of the nonsculpture artifacts, chiefly potsherds and stone tools, unearthed in the same alluvial gravels. Second, studies were made of the stratigraphy and geomorphology of the tin deposits. Third, and most important, efforts were made to determine the age of the deposits and of the artifacts found in them.

Among the artifacts were not only potsherds and stone axes but also other pieces of baked clay. These were recognized as probably being parts of the furnace walls and the tuyères, or draft pipes, of iron smelters. In addition there were axes and other objects made of iron, tin beads, bits of quartz and tapered cylinders, ground from quartz crystals, that had probably served as lip, ear or nose plugs. This assortment led to the cautious suggestion that the various artifacts, the sculptures included, belonged to a time of transition when stone implements were giving way to iron ones but when both materials were still being used. The caution was required by the fact that objects of very different ages can be mixed together by flowing water and end up in the same alluvial deposit.

OVAL SMELTING FURNACE, 45 centimeters wide and 60 centimeters long, is one of 13 excavated at Taruga. The Taruga site may be the earliest iron-smelting site in West Africa.

It was assumed that the deposits had been emplaced in a period when the rainfall was greater than normal, and so they were assigned to the final wet phase of a system of "pluvials" and "interpluvials." In the 1940's these periods were believed, on the basis of evidence from East Africa, to hold throughout the continent and to have corresponded in some way to the glacial and interglacial periods of the Pleistocene epoch in northern latitudes. On this basis the Nok deposits were assigned to sometime in the last half millennium B.C.

As a result of more detailed geomorphological work in many different parts of Africa, and of a better understanding of climatic changes in the past, it has now become clear that the pluvial-interpluvial scheme was too simple. It was therefore amusing to find, after carbon-14 dating emerged in the 1950's, that the carbon-14 determinations suggest the same last half millennium B.C. as the period when most of the Nok sculptures were made. The geomorphological evidence had given the right answer for the wrong reasons.

Some have now suggested that the deep burial of the artifacts was not so much the result of an abnormally wet climate as it was of the activities of the pre-Christian-Era inhabitants themselves. This hypothesis suggests that the makers of the Nok sculptures were fully iron-using and that the ground-clearing activities and general deforestation associated both with farming and with the making of charcoal for the iron smelters resulted in widespread sheet erosion. Hence it may be that human factors combined with climatic ones to give rise to the conditions that buried the Nok terra-cottas.

The suspicion that material of different ages had been mixed together in the alluvium was solidly confirmed when the first carbon-14 dates of carbonized wood from Nok were secured in 1957. Three specimens were taken from a single alluvial deposit. The first one came from the tin-bearing gravel at the main level where terra-cottas had been found. The second came from a mixture of sand and gravel overlying

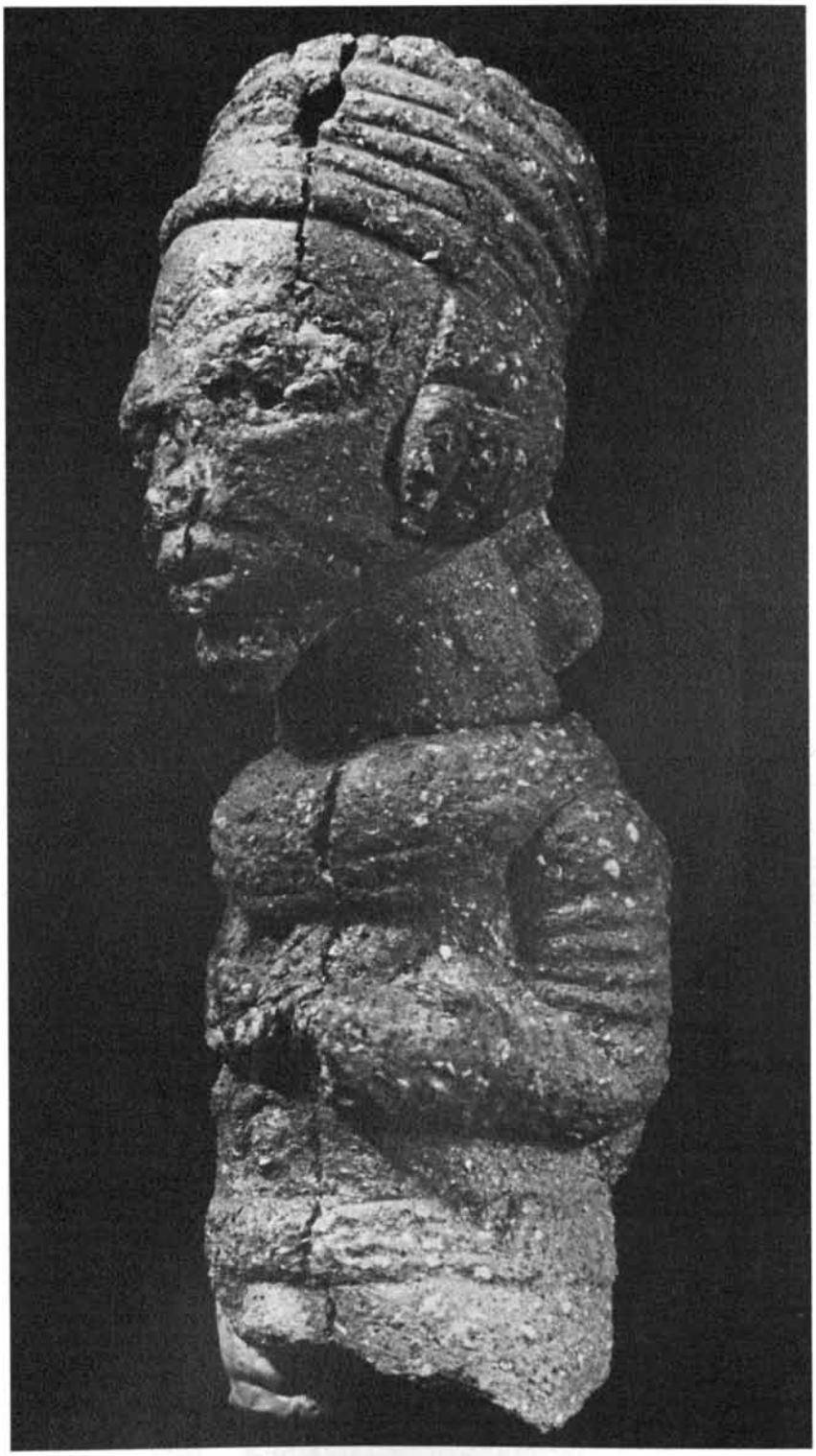
that level, and the third came from the overlying sand. Their calibrated dates were respectively 4450–4400 B.C., 2800–2690 B.C. and 1100 B.C. A fourth specimen, wood with bark adhering to it found in a level of black clay above all the sands and gravels, was dated to A.D. 210. The findings led only to a limited conclusion: the terra-cottas from this particular horizon were likely to have been made earlier than the third century A.D., but how much earlier was entirely uncertain.

In the years since these first analyses additional dates obtained by the carbon-14 method for samples from nonalluvial contexts have helped to give more precision to the age of the Nok material. For example, of the charcoal samples associated with iron smelters in the Taruga Valley three fall in the eighth century B.C. and five fall in the fifth century B.C.

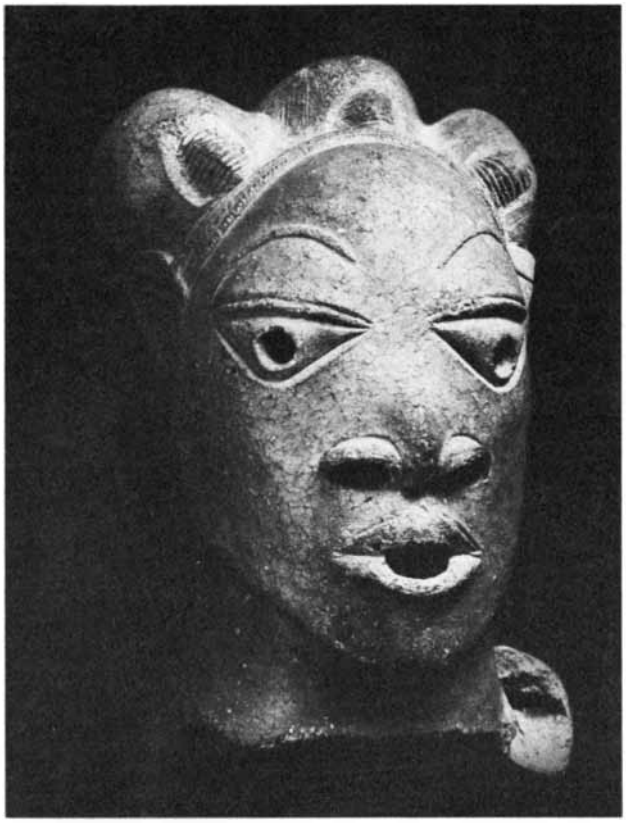
What was needed to confirm the association between the Nok sculptures and all the other artifacts found in the potentially scrambled alluvial deposits was the controlled excavation of Nok material from a nonalluvial site. The first opportunity came when a school playing field was being enlarged at Katsina Ala, south of the Benue River well outside the tin-mining area. One terra-cotta head and fragments of three large figures, all seated on stools, were uncovered. When a trench for a pipe was dug in the same area three years later, four more terra-cotta heads turned up. When formal excavations were eventually undertaken by the Department of Antiquities in 1963, a sixth head was unearthed. Although one carbon-14 date has been announced, details of these excavations have not yet been published. The dated sample was from a mass of charcoal said to have been "in the Nok culture occupation layer." The date fell in the middle of the 16th century A.D., suggesting either that the charcoal had been contaminated or that the stratigraphy had been disturbed.

The only known ancient habitation site within the Nok valley was discovered by Fagg's daughter, Angela, herself a trained archaeologist, at Samun Dukiya in 1969. Here some rocks rise up from the level ground. It appears that, as is the common practice today, the prehistoric inhabitants had built their huts on top of the rocks. Debris of occupation accumulated on the ground around the rocks as various articles fell or were thrown down from above. Angela Fagg excavated the deposit for the Department of Antiquities. In addition to fragments of terra-cotta figurines she found quantities of potsherds, grinding stones and pounding stones, stone beads, lip plugs and many iron fragments: hooks, bracelets, pieces of knives, arrowheads and spearheads, and a strip of iron twisted into a cylindrical shape. In one densely packed deposit of potsherds she found a stone axe together with a large stone marked with shallow grooves. The grooves could have been formed by the process of grinding and sharpening stone axes. She concluded that although the inhabitants of the site possessed iron, they still made and used stone axes. A sample of charcoal from the lower part of the accumulated debris yielded a calibrated carbon-14 date of 380–230 B.C.

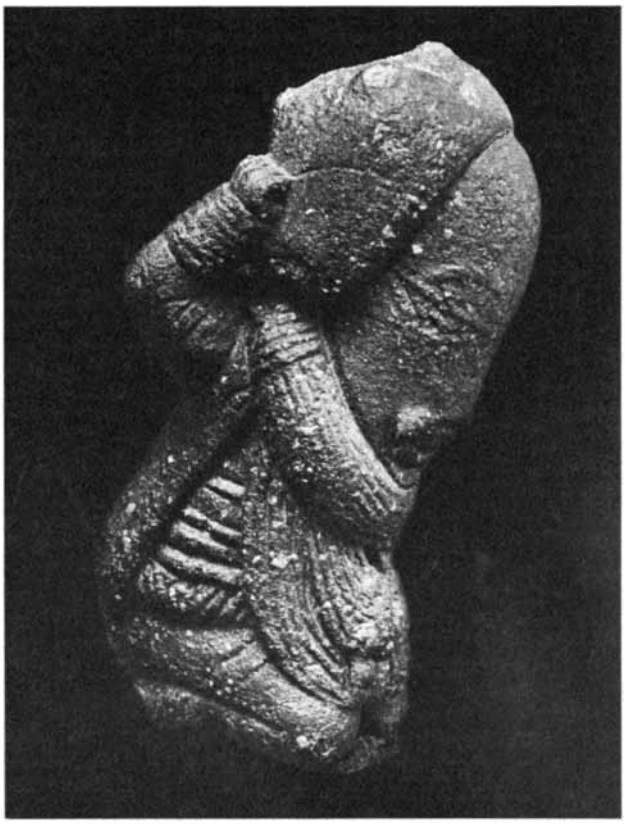
Another opportunity to examine a Nok site arose when prospectors examining the remote Taruga Valley, some



COARSE TEXTURE of some Nok terra-cotta is evident in this broken but nearly complete figure, portrayed with a cap, a waistband and perhaps armbands. The figure, 16.5 centimeters high, is one of several found during mining at Nok and later photographed by Bernard Fagg.

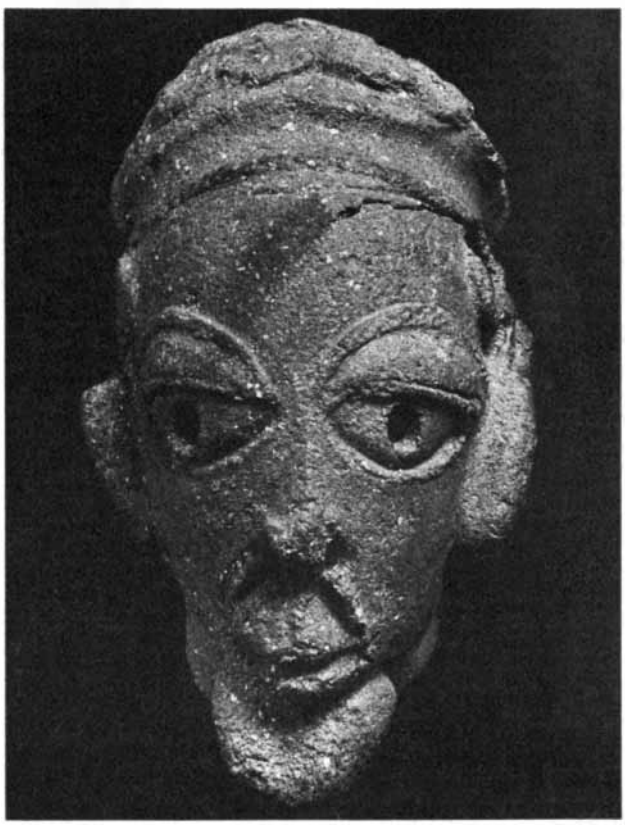


LIFE-SIZE HEAD, 35 centimeters high, was found at Nok in 1954. Three strings of beads or of plaited fibers accent the high hairline.



KNEELING FIGURE, 10.5 centimeters high, is made of solid terra-cotta. Found near Bwari, it could have been a pendant or an amulet.

SEATED FIGURE, 26.5 centimeters high, is of hollow construction. Arms and legs appear only in slight relief. Figure was found at Jemaa.



HEAD OF A MAN, 21 centimeters high, is shown with mustache, beard and tresses down each cheek. The sculpture was found at Nok.

100 kilometers southwest of Nok, uncovered two terra-cotta figures, each showing a woman seated on a stool and holding her breasts. Inspecting the place of discovery, Bernard Fagg was convinced that the terra-cottas had been lying in undisturbed soil. He decided to conduct excavations and ran trial trenches that revealed not only evidence of habitation but also iron slag and furnace tuyères, suggesting that the valley had been a site of smelting activity.

The site was a three-acre flat terrace between two streams tributary to the Takushara River. As a preliminary to full-scale excavation the area was surveyed by proton magnetometer in search of anomalies that might indicate deposits of metal. Some 60 anomalies were indeed located, and in the course of four seasons' digging between 1960 and 1969 all were investigated. Of the 60 anomalies 20 were found to result from concentrations of iron slag. Many of these concentrations held the remains of smelting furnaces, and 13 were excavated. All were low shaft furnaces made by digging a pit to a depth of about 30 centimeters. Some remains of the furnace walls rose 20 centimeters above the ancient ground level; when the furnaces were intact, they were probably a meter or more high. The smallest smelter was 36 centimeters in diameter at ground level and the largest was 105 centimeters. Tuyères for the furnaces were also uncovered, but none of them was in position; presumably they had been in parts of the wall that had collapsed.

In addition to the remains of the smelting furnaces the Taruga excavations yielded a few terra-cottas. One is a small solid Janus figure. Another is a fragmentary hollow piece, the right arm and torso of a figure that was probably seated and may have been 30 centimeters high. A third is still another fragment: a nearly cylindrical head set obliquely in typical Nok style on a broken cylindrical torso.

It seems most likely that the iron smelters associated with the Nok-style terra-cottas at Taruga were in action mainly from the fifth to the third centuries B.C. This is the earliest known evidence of iron smelting in West Africa. If iron metallurgy was not invented independently south of the Sahara, the technology must have been introduced. But from where? There are huge piles of iron slag at Meroe in the Republic of Sudan, and it was once a popular hypothesis that iron technology entered the region from there. Intensive research in recent years, however, has shown that the large-scale iron industry at Meroe dates back only to the early centuries of the Christian Era and was based on Roman-style furnaces from which slag could be tapped. Not only are the Taruga furnaces older but also slag could not be tapped from them. It therefore seems

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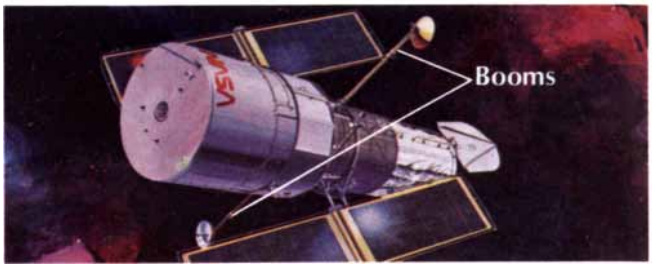


Graphite/Aluminum booms. They have extraordinary strength-to-weight ratios.

This wonder of advanced technology will be made, in part, of a remarkable new material based on aluminum metal matrix composite technology. Two slender, rectangular, hollow structures—13 feet by 3.4 inches by 1.7 inches—will do double-duty as structural booms and antenna waveguides.

Made of 60% aluminum and 40% graphite fibers, they will be as stiff as any known structural material—30% stiffer than steel but 13% lighter than conventional aluminum. Weighing only 8 pounds apiece, they will have one of the highest stiffness-to-weight ratios of any structure ever built.

This use of graphite/aluminum in space points the way to Earth applications where great stiffness and extremely light weight are needed.

to an old metal.

Powdered aluminum would be used in 40% of this advanced jetliner in the 1990's.

"Fill 'er up...with 37 lbs. of aluminum."

The electric car has long been a dream, but approaches with traditional lead acid or nickel iron batteries present a problem. They must be recharged every 80 to 100 miles.

Lockheed, however, is working on a possible solution: an aluminum-air battery that provides much greater range.

Basically, the battery uses 37 pounds of aluminum plates and 6½ gallons of tap water, with caustic soda as an active, circulating electrolyte that reacts with air. It would power a small car about 250 miles. Then the driver would make a 9-minute stop at a service station, adding 6½ gallons of water and removing 107 pounds of residue—aluminum hydroxide that can be recycled back into aluminum.

Every 900 miles, the driver would spend 15 minutes at the service station to "recharge" with 60 aluminum plates weighing 37 pounds.

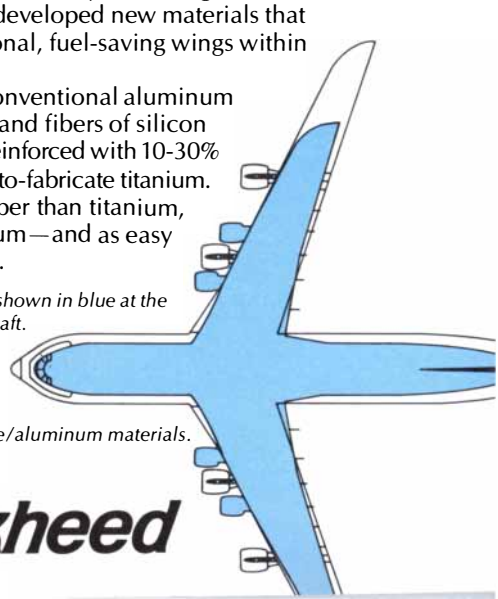
A fanciful vision? Not when the industry on which the battery is based—aluminum—is already in place.

Bewhiskered aluminum.

To save fuel, the ideal wing of a large aircraft would be long or narrow—or both. The wider the wing relative to its length, the more fuel the aircraft burns. However, long aluminum wings tend to flutter and vibrate due to their lack of stiffness. Solving those problems thus far has required extra structural weight that largely reduces the fuel savings.

The solution: new structural materials stiffer and lighter than conventional aluminum alloys. Working in that direction, Lockheed has developed new materials that could be used in operational, fuel-saving wings within 10 years.

Lockheed reinforces conventional aluminum alloys with tiny whiskers and fibers of silicon carbide. One such alloy reinforced with 10-30% whiskers is as stiff as hard-to-fabricate titanium. It also is lighter and cheaper than titanium, lighter even than aluminum—and as easy to fabricate as aluminum.



Today the Lockheed-built C-5 (shown in blue at the right) is the world's largest aircraft. The drawing shows an even larger, more economical transport that would be possible through extensive use of these new silicon carbide/aluminum materials.

Lockheed

JETTA. 4 IN THE FRONT. 8 IN THE BACK.

Compare the relative merits of today's family cars, and you'll find that a trip to your relatives would be a lot nicer in a Volkswagen Jetta.

In the front, for example, there's room enough for a family of 4 to actually stretch out and enjoy the ride.

In back, there's a trunk big enough to handle 8 suitcases. (Something you don't even get with a Rolls-Royce.)

And under the hood, there's a CIS fuel-injected engine powerful enough to take you from 0 to 50 in just 9.2 seconds. As well as around any trucks, onto any highways and up any mountains you meet along the way.

What's more, even though Road & Track has said it "will embarrass a lot of cars costing a lot more" with its performance and handling, Jetta will never embarrass you at the gas pump.

It gets an EPA estimated 25 mpg, 40 mpg highway estimate. (Use "estimated mpg" for comparisons. Your mileage may vary with weather, speed and trip length. Actual highway mileage will probably be less.)

And it gives you front-wheel drive, rack-and-pinion steering, all-independent suspension and classic European styling.

Impressed with Jetta's relative merits?

Your relatives will be, too.

VOLKSWAGEN DOES IT AGAIN

more likely that the Taruga technique was derived ultimately from Carthaginian North Africa.

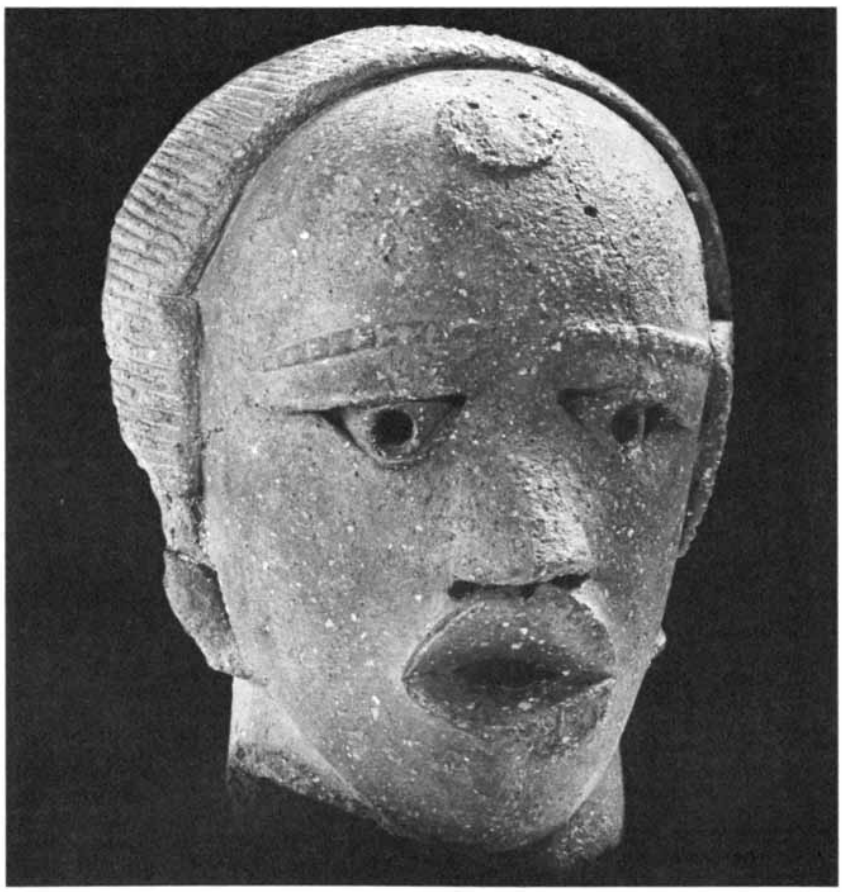
What function did the Nok terra-cottas serve? The modern viewer may value these remarkable figures on aesthetic grounds, but it is most unlikely that their makers had any aesthetic aim in mind or that they judged their work by any standard familiar to us. As I have mentioned, African art is strongly symbolic. What, then, did the Nok figures symbolize? In 1977 the National Museum at Lagos published a volume by Bernard Fagg that contains both color and black-and-white photographs of the 150 most important Nok figures then known. (Indeed, Fagg kindly provided many of the illustrations in this article.) A study of this important work is a necessary prelude to answering any question about function. Yet if one is to weigh objectively all the data that are potentially available, it will be necessary to obtain detailed reports of the excavations, including descriptions of the sites where the figures were found and the analyses conducted by various specialists. All of this is promised in a second volume.

Meanwhile all the facts we have as a basis for estimating the possible function of the figures are as follows. First, the majority of the figures must originally have been in places where they could readily become incorporated in the alluvial tin-mining deposits. Second, some were associated with a residence (Samun Dukiya). Third, others were intimately associated with iron-smelting furnaces (Taruga). Finally, the circumstances surrounding the discovery of the six Nok heads and other fragments at Katsina Ala suggest, although no positive evidence exists for it, that they may have occupied a shrine in a sacred grove.

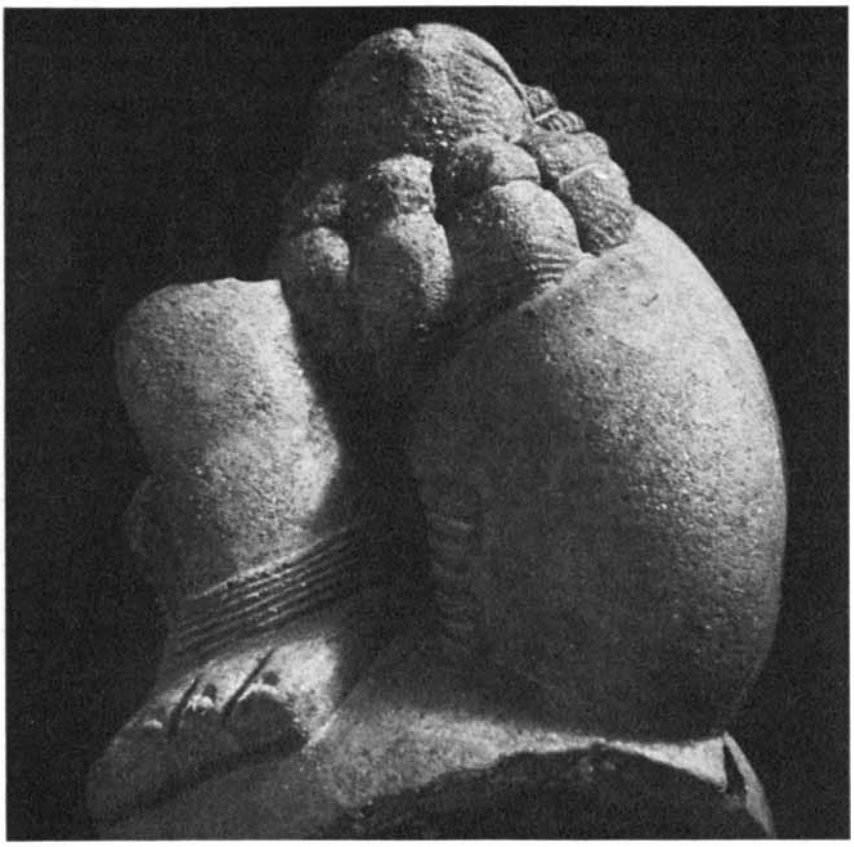
The internal evidence of the terra-cottas themselves, correctly interpreted, may also help to suggest what function they served. Included in this category of information are the character and degree of the stylization of the figures, the posture of the figures, the proportion of human subjects to animal ones and, among the human subjects, the proportion of males to females. The question of size also enters in. For example, some figures are quite small and have holes in them suggesting that they could have been worn as pendants or amulets. The association of still others with the domestic site at Samun Dukiya lends support to the suggestion that figures with a circular base like an inverted pot could have been the finial on the thatched roof of a round hut. Pots are still used in this manner in the Gwari country of Nigeria.

It seems likely that many of the figures symbolized supernatural forces their makers wanted to manipulate, such as those connected with the maintenance of the food supply. For example, shrines

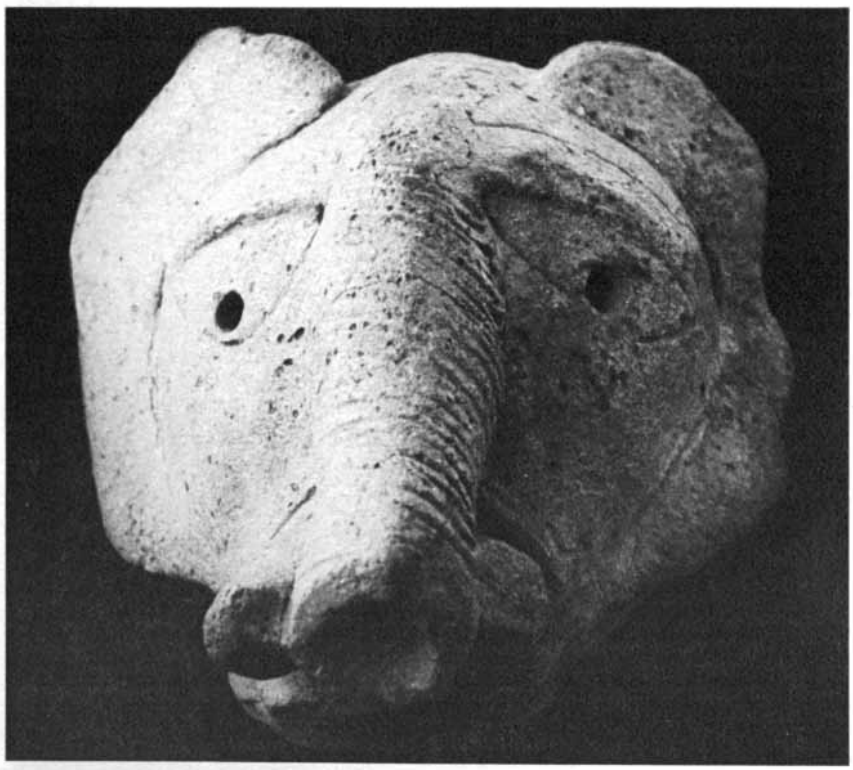
FIRST DISCOVERY, this terra-cotta head 10 centimeters high, was found at a tin mine in 1928. It was donated to the Department of Mines museum at Jos. First thought to portray a monkey, it is probably a human representation. Because the mine was near the village of Nok the head and the 200-odd terra-cottas similar in style found since 1928 are all designated Nok.



HEAD WITH AN OPEN MOUTH, 22 centimeters high, was found at a tin mine near Jemaa in 1943 and was also donated to the Jos Museum. Bernard Fagg, recognizing the similarities between this and the first Nok discovery, then began research that has since defined Nok style.



BROKEN SCULPTURE shows the lower part of a figure resting on the left knee and the right foot. Anklets adorn the right leg and between the legs is a beaded pubic apron. The fragment is 18.5 centimeters high. The seated figure on page 160 shows no such careful limb modeling.



ELEPHANT HEAD, with tusks and trunk broken short, shows use of the same convention in representing the eyes of an animal as is employed in representing the human eye, even to the extent of giving the elephant eyebrows. Head, 14.3 centimeters high, was found at Udegi.

might have been placed on or near cultivated fields. In a system of shifting cultivation each time a new area was cleared for cultivation the establishment of a new shrine could call for the commissioning of new figures. The old shrines might be left to decay, and when seasonal floods inundated the valleys, their contents would be swept away and incorporated in the alluvium downstream.

Similarly, magico-religious rituals almost certainly accompanied the technical procedures of iron smelting; perhaps that is why terra-cottas are associated with the Taruga furnaces. One can multiply hypotheses of this kind. Were the heads that appear to portray diseased individuals associated with rituals designed to ward off sickness? Were the snake figurines associated with snake cults, which have been widespread in West Africa? Were monkey and elephant figures associated with hunting rituals? At the moment we do not know, and in the absence of written testimony it will always be difficult to be sure. Nevertheless, further archaeological work designed to test such hypotheses should in the future make more probable those that survive testing.

Finally, can we speak of a "Nok culture" in V. Gordon Childe's sense of an assemblage of artifacts recurring repeatedly together that may be assumed to be concrete expressions of common social traditions? Bernard Fagg, the pioneer in these investigations, holds that the artistic similarity of the terra-cottas is reason for considering the entire collection as being the product of a single culture. Is the Nok style alone sufficient to identify "a culture" in Childe's sense? A number of archaeologists are more cautious and think not. Leaving aside the theoretical doubts now held by many prehistorians about the entire concept of "a culture" and whether "cultures" are identifiable through artifacts, their point is that although evidence may emerge that will demonstrate the existence of a Nok culture, the current evidence is insufficient to do so.

Fifty years ago European prehistorians spoke of a "megalithic civilization" and supposed all the different groups of ancient stone monuments in Europe were ultimately derived from a common source in the eastern Mediterranean. It is now realized that several different European groups independently developed an architecture that made use of large stones. "Megalithic civilization" was a unity only in the minds of prehistorians. The Nok situation is not precisely analogous, but perhaps the history of the megalithic concept can sound a cautionary note. It seems unwise to turn a common artistic tradition into a culture until (to use Childe's phrase) far more concrete expressions of common social traditions have come to light.

SCIENCE/SCOPE

Data rates of 4 billion bits per second -- a speed at which the Encyclopaedia Britannica could be transmitted in just two seconds -- have been demonstrated by an experimental modulator. The modulator, an important step toward ultra high-speed satellite communications, is a quadriphase shift-keyed arrangement of two field-effect transistor biphase modulators. Use of microwave FETs in the modulator driver circuit resulted in the very low power consumption of tens to hundreds of milliwatts of direct current. In addition to the modulator, Hughes engineers have built a demodulator that functions at 2 gigabits per second.

Nearly 25 orbit-years of flawless service have been accumulated by radiative coolers built for weather satellites in synchronous orbit. These devices are used to passively cool infrared detector arrays to less than 75K. They are far more reliable than mechanical refrigerators because they have no moving parts. They also require no power for operation. Radiative coolers built by the Santa Barbara Research Center, a Hughes subsidiary, have suffered no degradation in performance due to contamination. Since pioneering development of staged radiative coolers in 1966, SBRC has won six separate contracts to provide these devices. Designs qualified for space flight include a unit for an interplanetary mission to Jupiter and another for an earth resources satellite.

Field-effect transistors are emerging as strong contenders for microwave switch applications in communications satellites. Gallium-arsenide FETs are likely to replace PIN diodes in satellites due to advantages like higher speeds and lower power consumption. Using arrays of FETs, Hughes researchers built an 8x8 switch matrix for time-division multiple-access applications at 4 GHz. The device achieved a 1-nanosecond transition time at 10 milliwatts drive control power.

An ultramodern facility spanning 1.75 million square feet will be the showcase where outstanding Hughes engineering will combine with advanced manufacturing techniques and production processes. Our complex is nearly completed, so we're looking for experienced and graduating engineers to work on such programs as: infrared thermal imaging systems, laser rangefinders and designators, and missile launching and guidance systems. Send your resume to Dan O'Daly, Hughes Electro-Optical and Data Systems Manufacturing, Professional Employment, P.O. Box 924, Dept. SSA, El Segundo, CA 90245. Equal opportunity employer.

Listeners of National Public Radio can now hear concerts live and in stereo, thanks to Western Union's Westar communications satellites. Before using the satellite network, NPR broadcast programs throughout the continental United States over telephone lines and land-based microwave links. The system was limited only to monaural signals, so programs that depended on good audio fidelity were duplicated on tape and distributed by mail to member stations. With the Hughes-built Westars, however, the radio network can broadcast with better sound quality and also transmit programs to some 220 stations at once.

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THE AMATEUR SCIENTIST

How can the amateur detect metals in air, liquids or solids? Sam Epstein discourses

by Jearl Walker

It is not difficult for an amateur to detect microgram quantities of metals in a variety of samples, as is done in several types of monitoring for pollution. Sam Epstein, a chemist at the Hyperion Treatment Plant in Los Angeles, has described to me a method that he calls chemical-spot testing. Although it requires no elaborate equipment, it can be employed to detect the presence of nearly any metal in samples of alloys, minerals, water and air.

As an example of the method, Epstein described how to detect copper, iron and nickel. The first step is to prepare test solutions of each metal. (Usually, of course, the experimenter does not have the benefit of knowing what is in the test sample.) The copper solution is prepared by dissolving copper sulfate ($CuSO_4 \cdot 5H_2O$) in about 10 milliliters of distilled water containing one drop of concentrated hydrochloric acid. The acid is necessary to prevent the metal from forming insoluble hydroxides that would block its participation in the chemical reactions of the test procedure. The test solutions for iron and nickel are prepared in the same way with nickel sulfate ($NiSO_4 \cdot 6H_2O$) and ferric chloride ($FeCl_3$).

A sample solution can also be prepared by dissolving .1 gram or less of a metal in 10 milliliters of a warm mixture made by adding 2.5 milliliters of hydrochloric acid to 7.5 milliliters of distilled water. (Always slowly add acid to water; never add water to acid. When you work with acids and bases, always wear safety goggles and work either in a well-ventilated area or under a chemical hood. Whenever water is called for in this article, distilled water is meant.) To the iron and copper solutions you should also add a few drops of 3 percent hydrogen peroxide (antiseptic grade). In the copper solution the peroxide reacts with the hydrochloric acid to form chlorine gas, which is necessary to dissolve copper in the acid. In the other solution it converts the iron into the ferric state that is required for the test.

To prepare a nickel solution a nickel-plated object is dipped in the acid long enough to remove the thin nickel coating. A nickel-plated screw would do. One or two drops of peroxide might be necessary here too. A final step is to boil each solution gently to eliminate any remaining peroxide and chlorine.

Another set of solutions must be prepared to serve as the indicators for the metals. The indicator reagent for nickel is dimethylglyoxime (DMG), a solution of which is prepared by adding a gram of solid DMG to about 100 milliliters of warm rubbing alcohol. Shake the reagent well to ensure that the solution is saturated. The indicator for both copper and ferric iron is 1 percent potassium ferrocyanide ($K_4Fe(CN)_6$), which is made by dissolving one gram of the solid in 100 milliliters of water.

To demonstrate the detection of nickel Epstein puts one drop of the nickel solution on a piece of filter paper. Then he holds the paper over the mouth of an open bottle of concentrated ammonium hydroxide for about 15 seconds. This operation is commonly called fuming. Next he puts one drop of the DMG solution at the same place on the filter paper. After a few seconds a bright scarlet spot appears, revealing the presence of nickel on the paper.

The procedure for indicating the presence of copper or iron is similar. The paper is prepared by adding a drop of the copper or iron solution. Then a drop of ferrocyanide is added. The spot turns blue green if ferric iron is present and red brown with copper.

The testing can be done on a "spot plate" instead of paper. The plate is a flat slab of smooth porcelain with small circular depressions, in one of which a drop of the test solution is placed, followed by a drop of the indicator reagent. The colored compounds revealing the presence of the metals appear almost immediately.

If nickel is being tested for, a drop of 50 percent ammonium hydroxide is also added. The mixture is stirred with a rod of glass or plastic. A drop of DMG is added and the mixture is stirred again. If the test solution contains nickel, nickel DMG, which is red, precipitates out, indicating that the test solution has nickel among its contents.

Epstein demonstrates the sensitivity of the testing procedure by diluting the test solutions repeatedly. Each time he adds five milliliters of water to five milliliters of the test solution. After every third dilution he adds another drop of hydrochloric acid. The telltale colors, he says, are still detectable even after a number of dilutions.

A sample collected from the environment may contain several metals. Sometimes a single test is not conclusive because the indicator reagent might be able to indicate more than one metal. Ferrocyanide, for example, reveals both copper and iron. If both are in the sample, two colored compounds appear in the test, confusing the results.

Several techniques have been developed to overcome interference of this kind. For most metals several color-forming reagents are available. By experimenting you may be able to isolate one reagent that reacts with only one of the metals in the solution. For example, copper can be detected in the presence of ferric iron if one of the indicator reagents for copper other than ferrocyanide is employed.

Another way (known as masking) to eliminate interference is to add to the test solution a chemical that will combine with one of the metals, preventing it from reacting with the indicator reagent. Only the other metal is left to react. With an unknown sample from the environment you would obviously have to experiment to hit on the correct reagent.

Sometimes the *p*H of the drop being tested can be altered to make possible the detection of two metals in a sample. For example, both nickel and palladium react with DMG. The nickel yields a scarlet compound, but only in a basic solution, and the palladium a yellow one, but only in an acid solution. If you think both metals are in the sample, put ammonium hydroxide in the sample to ensure that it is not acidic. When the DMG is added, a scarlet compound indicates the presence of nickel. Now add hydrochloric acid to the test drop. The scarlet color disappears and the palladium combines with the DMG to form a yellow compound.

A different procedure to eliminate the interference of colors makes use of a simple device called a ring oven. The procedure allows the detection of several metals simultaneously and also increases the sensitivity of the test. A flat metal plate with a hole in the center is put on an electric hot plate. Small drops of solution are added to a filter paper placed over the hole. The liquid spreads through the paper to the edge of the hole. There the solvent and other volatile compounds evaporate, leaving the dissolved solids in a thin ring. A wash solvent is added drop by drop to the pa-

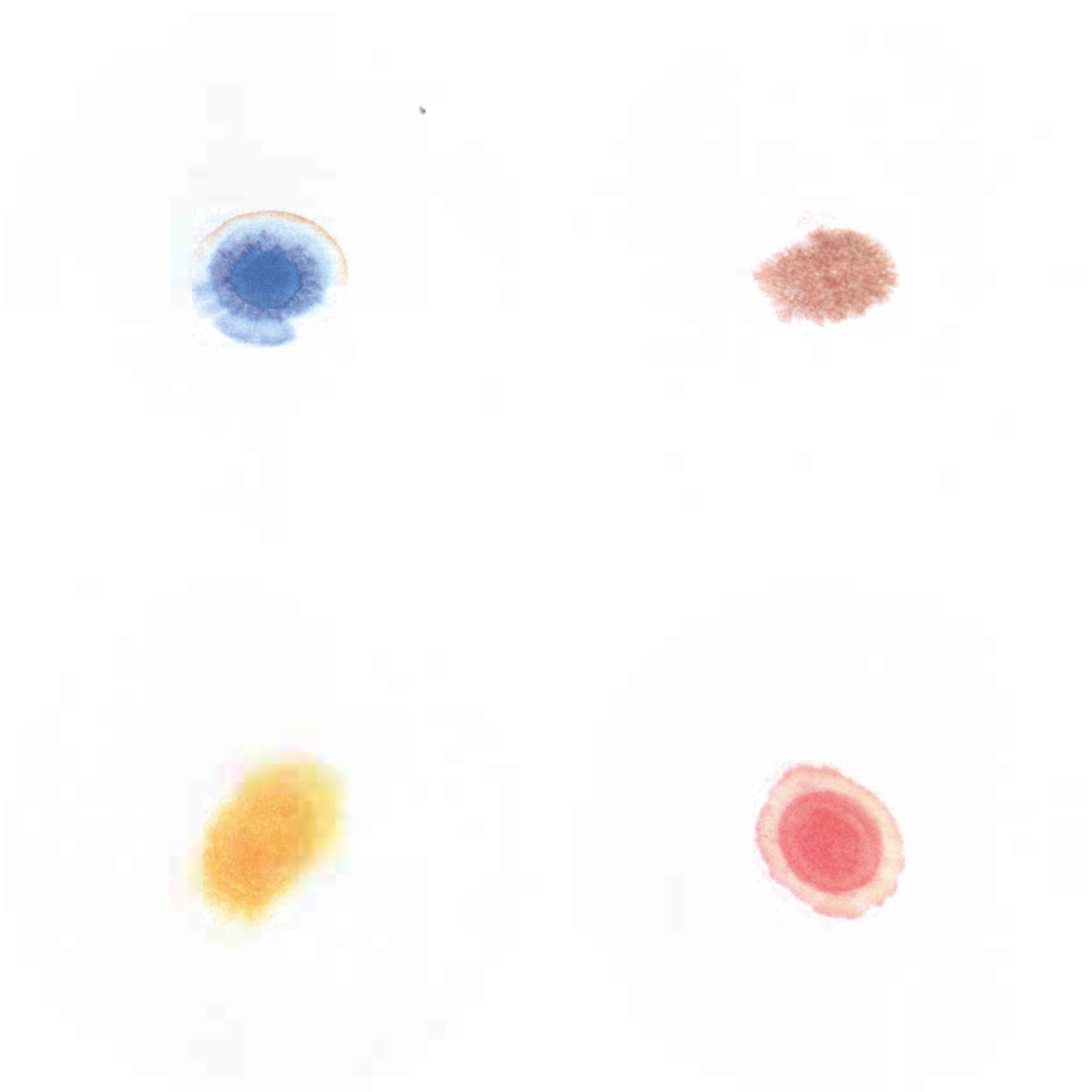
per to wash the test solution completely out to the ring. This detection scheme is more sensitive than the others I have described because all the dissolved materials are concentrated in the thin ring. When the filter paper is dried, it can be cut into pie-shaped segments that can be tested individually for different metals by the filter-paper technique.

Epstein's ring oven consists of three parts: an electric hot plate, an aluminum plate with a hole in it and a dropper guide by which he aligns a medicine dropper to deposit a drop of solution or reagent. The aluminum plate is put on the hot plate and a filter paper is placed over the hole. The aluminum plate has two brass screws by which Epstein positions the dropper guide over the paper. Liquid is deposited on the paper through a medicine dropper inserted in the dropper guide. Since the guide is fixed in position, successive drops land at the same spot on the paper.

The filter paper is five and a half or seven centimeters in diameter and is moderately retentive; the Whatman No. 40 filter is suitable. The hot plate is at a temperature of a few degrees above the boiling point of water. To collect a liquid sample Epstein dips the tip of the dropper into the liquid, allowing capillary action to move a small amount of it into the opening of the tip. Then he puts the dropper in the guide hole, which he has designed to make a snug fit for good alignment. He lowers the dropper until the liquid touches the filter paper; then he raises the dropper.

Although the amount of liquid deposited on the filter paper is small, it is enough. The wet spot on the paper is approximately a quarter inch in diameter. If the liquid spreads beyond the edge of the hole in the aluminum plate, discard the paper and try to make a smaller spot on another paper.

To move all the test solution out to the edge of the hole in the aluminum plate Epstein deposits drops of a weakly acidic or basic solution with another dropper. About 10 drops of this wash solution are needed. Again the liquid should not spread beyond the edge of the hole,



Sam Epstein's chemical-spot tests for **(clockwise from upper left)** *iron, copper, nickel and palladium*

otherwise uneven or multiple rings appear. The wash solution is prepared by adding 10 drops of concentrated acid or ammonium hydroxide to 100 milliliters of water. Epstein points out that you should use several medicine droppers to avoid contaminating the various solutions and reagents with one another.

As an example of how to work with the ring oven Epstein described to me his test for iron in the ferric chloride solution. One drop of the solution is applied to the filter paper. Then 10 drops of weak hydrochloric acid are added, drop by drop, to wash the ferric chloride out to the edge of the hole in the aluminum plate. After the first five drops the ring becomes visible. When the paper is dry, it is removed from the oven assembly. When Epstein puts a drop of ferrocyanide on the ring, the blue green color signifying the presence of ferric iron appears.

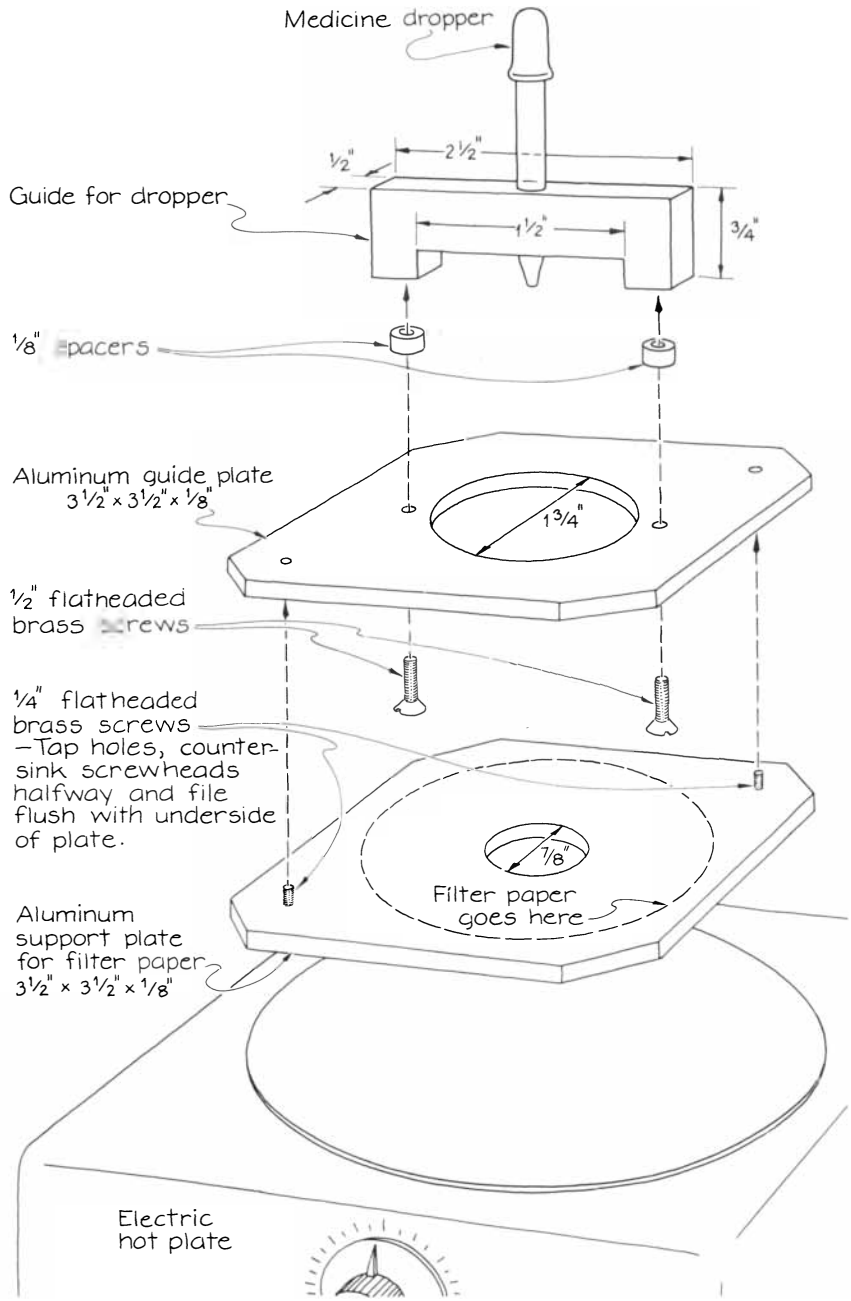
Epstein also explained how to do an analysis for two metals in a solution. He mixes some of the nickel solution with the copper solution and puts a drop of the mixture on a piece of filter paper in the ring oven. Hydrochloric acid is added to facilitate the movement of the material outward to form a ring. After the paper dries he cuts it in half. On one half he puts ferrocyanide to get the red brown color indicative of copper. He fumes the other half over ammonium hydroxide and adds a drop of DMG solution. The scarlet color characteristic of nickel appears.

The ring oven also overcomes the problem of interference when an indicator reacts with more than one metal. Epstein illustrates the possibility by mixing solutions of copper and ferric iron. A drop of the solution to be tested is put on the filter paper and washed outward by a weak acid solution to form a ring. This time, however, a pie-shaped segment is cut from the dried paper and fastened to half of a fresh filter paper. A tiny bit of Duco cement is needed to hold the tip of the wedge on the fresh filter so that enough contact is made to bring about the transfer of liquid between the two.

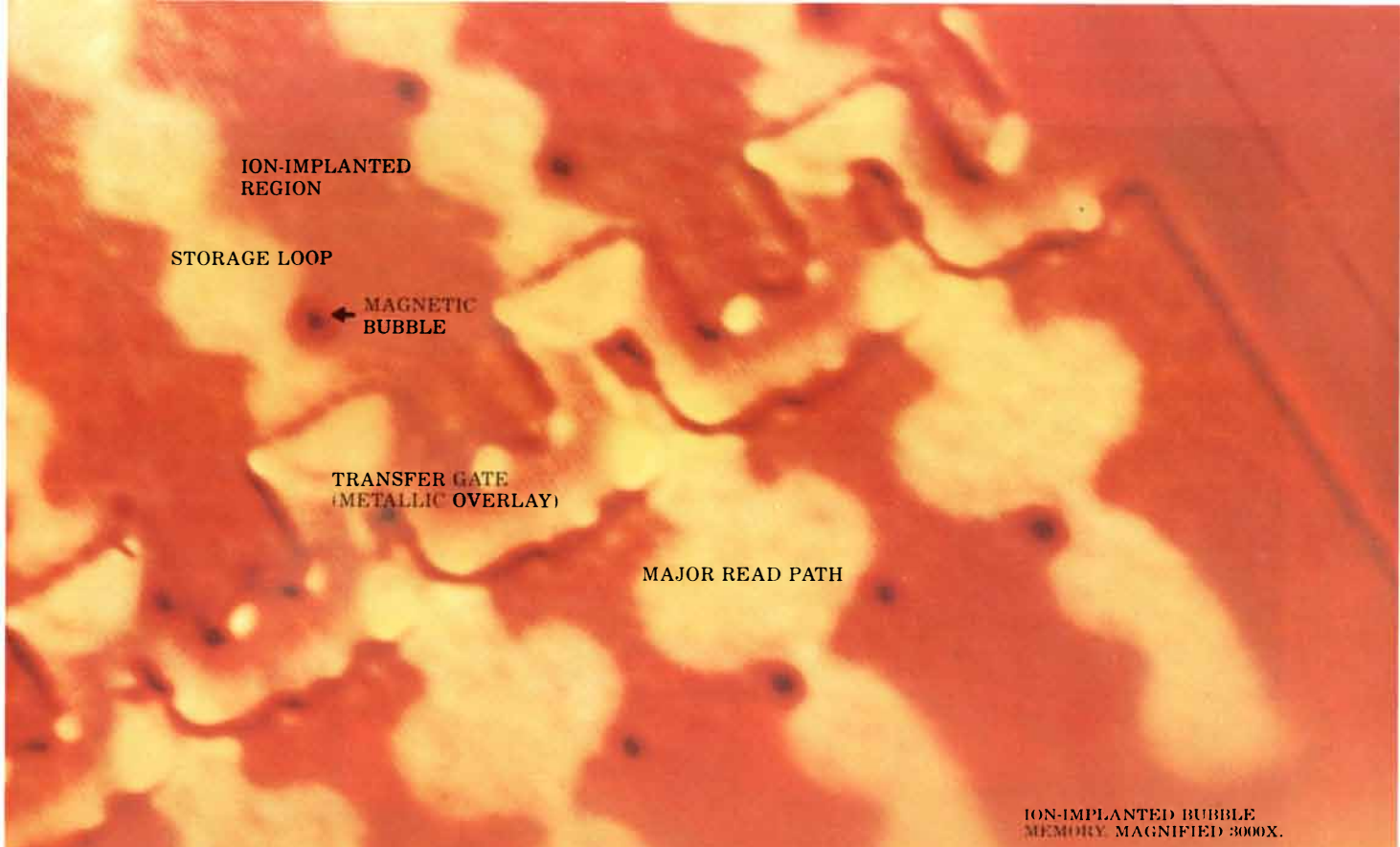
The combined filters are inserted into the ring oven with the contact area centered over the hole in the supporting aluminum plate. Ammonium hydroxide is applied drop by drop to wash the copper out into a new ring. The iron ring remains on the filter wedge because it consists of insoluble ferric hydroxide. Once the wedge dries it is removed from the oven and fumed over concentrated hydrochloric acid. A drop of ferrocyanide solution is deposited on each ring segment. The outer ring turns red brown to reveal the presence of copper and the inner ring turns blue green to reveal ferric iron.

Still another way of overcoming interference is to make one of the metals precipitate in the area where the test drop is placed. Then the other metal can be washed outward to form a ring and be detected. This technique will work for a mixture of copper, nickel and ferric iron. A drop of the mixture is put on the filter paper and ammonium hydroxide is added to wash material out to form a ring. The hydroxide, however, also reacts with the iron to form ferric hydroxide, which remains where the drop was placed. The copper and nickel are washed out to make rings because they are soluble in ammonium hydroxide. Test part of the ring for nickel by adding DMG (and fuming with ammonia if necessary). Test another part of the ring for copper by fuming with hydrochloric acid and then adding ferrocyanide. Finally detect the presence of iron at the center of the paper by fuming that section with the acid and then adding ferrocyanide. If several metals precipitate out in the center of the paper, you can continue the testing by cutting out the center and putting it on fresh filter paper. Add appropriate solvents drop by drop to wash the material out to form a new ring on the fresh filter.

Epstein described how one might analyze the metal in a coin such as a dime or a quarter, each of which is made out of an alloy of nickel and copper. File off a tiny bit of metal from the edge of the coin and dissolve the scrapings in a mixture of hydrochloric acid and hydrogen



Epstein's ring oven for spot testing



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- Method of growing epitaxial garnet films from a supercooled solution
- Basic technology for device manufacture
- Ion implant method of propagating bubbles
- Dual-conductor sheet method of propagating bubbles

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1981
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THE HUGGER.

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peroxide. Pick up a drop of the solution and put it on a filter paper in the ring oven. Follow the procedure I have described to test for copper and nickel in the deposited drop.

If the coin is too valuable to damage, you can employ another method that is essentially the reverse of electroplating. The coin is made to act as the anode in the circuit shown in the top illustration on the next page. The filter paper, spotted with a 10 percent solution of an electrolyte such as sodium nitrate, is put on the aluminum plate. Against the spot of electrolyte place a part of the coin that is free of dirt and grease. Epstein suggests an edge. Touch the wire from the positive terminal of the battery to the coin, allowing current to flow for about 10 seconds.

Practice might be necessary to regulate the time, the current and the pressure on the contact. If the procedure is successful, a small amount of dissolved metal is left in a depression on the paper. Put the paper in the ring oven, apply the appropriate wash solutions and analyze the rings with the proper reagents. The coin is not visibly altered.

To investigate a silver coin, which can be obtained from a coin dealer, file a bit of metal from the edge, add the filings to a few milliliters of 10 percent nitric acid and gently boil the acid to eliminate oxides of nitrogen. When the solution has cooled to room temperature, put a drop of it on a filter paper. Add a drop of 1 percent potassium chromate. The spot will turn red brown to reflect the presence of silver.

You could also use the electric circuit to deposit a small amount of the silver alloy directly on the filter paper. Older American silver coins consist of 90 percent silver and 10 percent copper. Both can be detected if the sample spot is run through the ring oven to create a ring. Use 1 percent nitric acid as the wash solution. Add potassium chromate to part of the ring to signal the presence of silver. Ferrocyanide, however, will fail to reveal the copper. For a more sensitive test Epstein suggests using a saturated solution of rubeanic acid (dithiooxamide) in alcohol and a 20 percent solution of malonic acid. Add the malonic acid and then the rubeanic acid to part of the ring. That part of the ring turns black if copper is present.

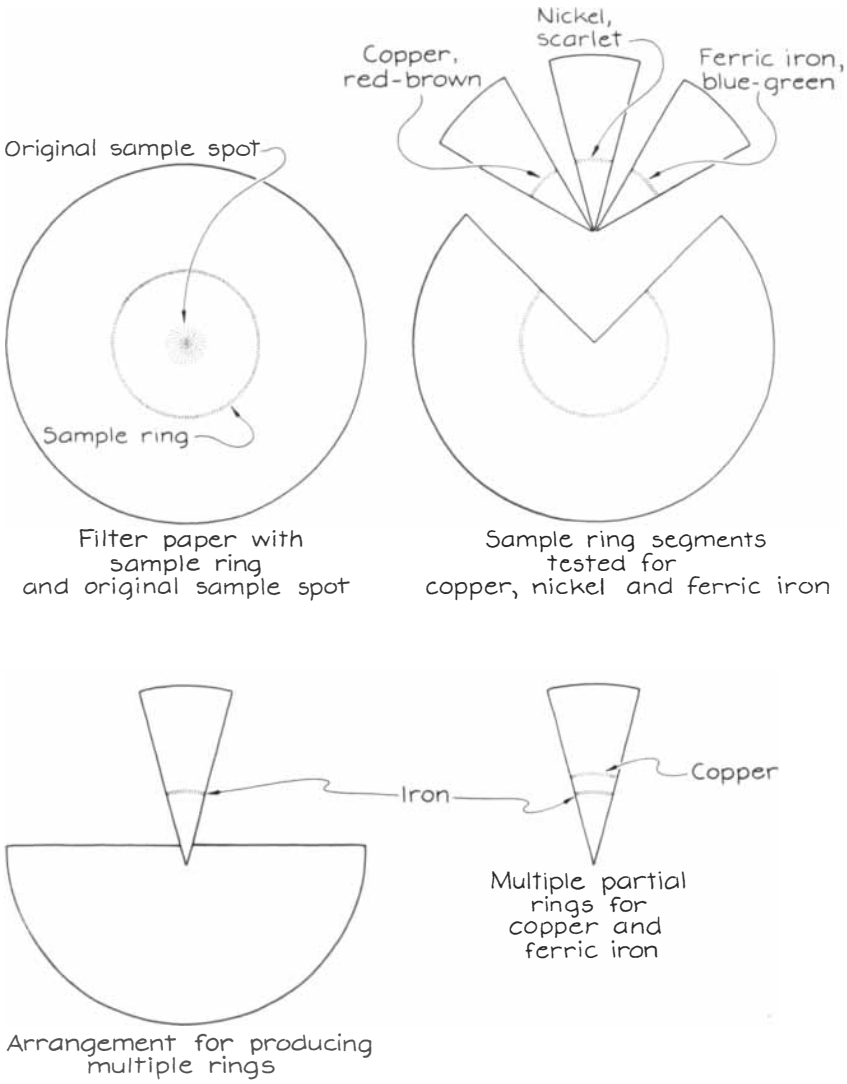
Samples of water can be tested for metals, including iron, copper and zinc. Epstein cautions that if the first trials in a ring oven prove negative, you should concentrate the sample by boiling it in a Pyrex flask. Add a few drops of hydrochloric acid. Then run the tests again, using ferrocyanide for the iron test and malonic and rubeanic acids for the copper test.

Epstein's test for zinc requires two solutions. For one mercuric thiocyanate is prepared by dissolving nine grams of ammonium thiocyanate (NH_4SCN) and eight grams of mercuric chloride ($HgCl_2$) in 100 milliliters of water. (Good ventilation is essential.) The solution must then stand for two or three days. The other necessary mixture is a .02 percent solution of a cobalt salt in 4 percent hydrochloric acid. Epstein says that cobalt chloride ($CoCl_2$), cobalt sulfate ($CoSO_4$) and cobalt nitrate ($Co(NO_3)_2$) are suitable.

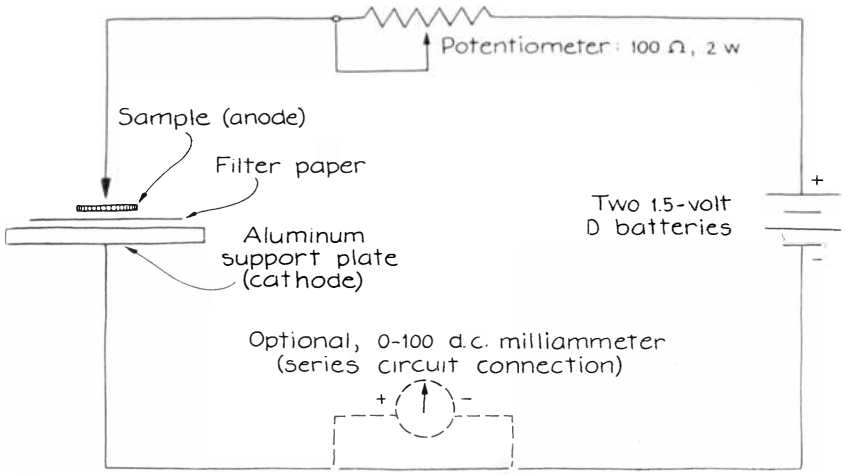
The water sample is applied to a filter paper in a ring oven as usual. When the ring has formed, test a wedge for zinc by spotting it with a drop of cobalt solution and dipping it several times in a small amount of mercuric thiocyanate. If zinc is present, the ring turns blue almost immediately. If zinc is not present, the precipitation is delayed by two or three minutes.

To practice the test you might employ hydrochloric acid to dissolve a small amount of zinc from a piece of galvanized iron or the case of a flashlight battery. Zinc can also be obtained from certain aluminum alloys if a small amount is dissolved in hydrochloric acid. If the treatment results in a gray, insoluble residue, which is silicon, the sample should be filtered before the test is made. Copper alloys may also serve as a source of zinc. A small amount of the metal is dissolved in hydrochloric acid and hydrogen peroxide and then boiled. To remove the copper, which would interfere with the test, add iron filings. When the blue copper color disappears, filter the solution and test it for zinc.

Epstein points out that aluminum bronze, which is an extremely hard copper alloy containing no zinc, can be identified by a negative zinc test followed by a positive aluminum test. In a depression on a spot plate a drop of the solution to be tested is mixed with a drop of 1 percent ammonium acetate solution. Then a drop of .1 percent aluminon solution is added. (Aluminon is the ammonium salt of aurintricarboxylic acid.) The mixture turns red when aluminum is present. The test can also be run on filter paper. You can practice the



Sample rings on filter paper



Reverse-electroplating circuit for testing the content of a coin

test with aluminum foil dissolved in 10 percent hydrochloric acid.

The aluminum compound responsible for the buffering effect of buffered aspirin can be detected with filter paper or a spot plate. Dissolve a tablet of aspirin in warm, dilute hydrochloric acid. You may have to filter the solution to eliminate sediments. Then follow the test procedure for aluminum.

Zinc is a major constituent of manganese bronze, a copper alloy prized for its high tensile strength in such things as ship propellers. Smaller amounts of manganese and aluminum are also present. The alloy can be distinguished from aluminum bronze and ordinary yellow brass (an alloy of copper and zinc) by testing it for zinc, manganese and aluminum. To test for the manganese add a drop of the sample to a filter paper, followed by a drop of concentrated ammonium hydroxide and then a drop of 10 percent silver nitrate. Manganese is revealed by the black color that appears.

Many of the procedures I have described can be reversed to show the presence of what normally serves as the indicator of a metal. For example, a nickel solution can be added to a test sample in order to reveal the presence of DMG. Similarly, manganese will serve to test for silver. A filter paper bearing a sample drop is fumed with hydrochloric acid and treated with one drop each of 1 percent manganese nitrate solution and .5 percent sodium hydroxide. (Household lye can serve as the source of sodium hydroxide.) If silver is present, a black spot appears. Epstein says this test for silver is more conclusive than the one with potassium chromate because metals other than silver can form colored compounds with chromates. One compound is lead chromate, a yellow insoluble substance.

One interesting source of water with which you might work is the discharge from industrial plants. Metalworking plants, electroplating shops, foundries and mining and smelting operations may discharge waste water with relatively large concentrations of toxic metals such as copper, zinc, lead and chromium. Test for chromium by using the ring oven to create a ring. Hydrochloric acid is the wash agent. On a segment of the ring place a drop of concentrated ammonium hydroxide and a drop of hydrogen peroxide. Dry the filter over the hot plate. Add a drop of freshly prepared 1 percent diphenylcarbazide solution in alcohol and a drop of 5 percent sulfuric acid. If chromium is present, the ring segment turns violet. Epstein cautions that a sample of distilled water should be tested as a control because the procedure can give rise to faint color even when no chromium is present.

When the water sample is tested for lead, the solution should be washed into a ring with nitric acid rather than hydrochloric acid, which produces insoluble lead chloride that precipitates out in the center of the paper. Add a drop of freshly prepared .2 percent sodium rhodizonate to the ring. If lead is present, the ring segment turns blue. You can practice this test with a solution of lead nitrate ($Pb(NO_3)_2$) or metallic lead dissolved in 10 percent nitric acid.

Epstein has also described how minerals can be tested for metals. Since a mineral sample will often not dissolve easily in acid, it must be solubilized by bead formation, a standard mineralogical procedure. A platinum-wire loop is heated in a flame and dipped in sodium carbonate. (Ordinary washing soda serves here.) The loop is reheated until the fluxing material clinging to the wire fuses to form a clear bead. You may have to repeat the procedure until a solid bead forms.

While the bead is still hot it is immersed in a powdered test sample and then reheated until a homogeneous colored bead is shaped. This technique may require a rather hot flame, which can be generated with a Meker burner and compressed air or with a mineralogy blowpipe. Epstein also says that in some instances borax might work better than sodium carbonate.

When a bead has formed, it is broken out of the wire loop, pulverized and poured into a test tube. Add a few milliliters of 50 percent nitric acid to the tube, which is then heated carefully until its contents become dry. (Do not overheat the tube.) After the tube cools add three milliliters of hydrochloric acid and boil the mixture for a few seconds. Add five milliliters of water and boil the mixture again briefly. Filter it to remove insoluble silica. Now the solution can be utilized in any of the spot-testing techniques.

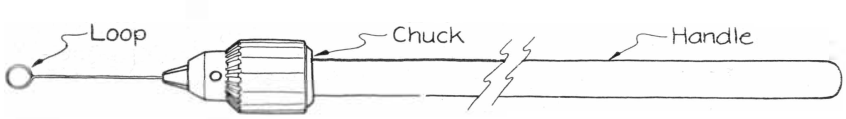
The electrical arrangement set up to analyze coins will also work with other large samples such as a piece of metal or a length of wire. The rig can be employed not only to test pure metals and alloys but also to analyze surface coatings and detect a lack of uniformity such as pinholes in platings.

As an example Epstein described how nickel can be detected in a five-cent coin. A one-liter solution of 50 grams of sodium carbonate and five grams of sodium chloride serves as an electrolyte. Four pieces of filter paper form a pad that is dipped in the solution for a few seconds and sandwiched between two paper towels to remove the excess liquid. This pad is placed on the aluminum cathode plate.

When the circuit is closed, an imprint of one side of the coin is transferred to the paper. The top filter is removed from the pad and fumed with ammonium hydroxide. Two or three drops of DMG are added. Epstein says a good reproduction of either Thomas Jefferson or Monticello appears in bright scarlet.

With a similar method you can produce a gray black print of a silver coin. Make the electrolytic transfer. Remove the top filter and hold it near a light bulb. The silver that was transferred during the flow of current has combined with the chloride in the solution to form silver chloride, which is sensitive to light. In the light from the bulb the filter behaves like a photographic plate exposed to light.

The copper in the coin can be detected



Wire loop for fusing mineralogical samples

by working with the other side of the coin. The filter paper is fumed with ammonium hydroxide to generate the deep blue of the copper-ammonium ion. (After each test the aluminum plate should be washed and dried.) Although these tests for silver and copper in a coin are satisfactory for electrographic analysis, they lack the sensitivity for microspot testing.

The equipment and chemicals required for spot testing can be obtained from many chemical-supply houses. Epstein got his chemicals from Pfaltz & Bauer, Inc. (375 Fairfield Avenue, Stamford, Conn. 06902). Some of the chemicals can be bought at drug and grocery stores. Denatured alcohol is adequate for the alcoholic solutions.

Proper laboratory procedures are crucial when you handle potentially dangerous chemicals. Do not touch the chemicals with your bare hands. If a solution splashes on you or the work area, immediately wash off the splash with plenty of cool water. When you are diluting concentrated acids, particularly sulfuric acid, add the acid to the water by running it slowly down the wall of the container while you stir the mixture. Beware also of the heat that is generated by the process.

Much more can be done with chemical-spot testing. At another time I shall describe Epstein's procedure for detecting air pollution, including acid rain. If you test environmental samples of water or soil, I should like to hear about your results.

Chemical	Weight (grams)
Aluminon	5
Ammonium acetate	100
Ammonium thiocyanate	100
Barium chloride	100
Cobalt chloride	50
Copper sulfate	100
Dimethylglyoxime	25
Diphenylcarbazide	5
Dithiooxamide	10
Ferric chloride	200
Lead nitrate	100
Malonic acid	25
Manganese nitrate	50
Mercuric chloride	10
Nickel sulfate	25
Oxalic acid	100
Potassium chromate	50
Potassium ferrocyanide	50
Silver nitrate	5
Sodium carbonate	100
Sodium hydroxide	100
Sodium nitrate	50
Sodium rhodizonate	1

Chemicals for the experiments

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