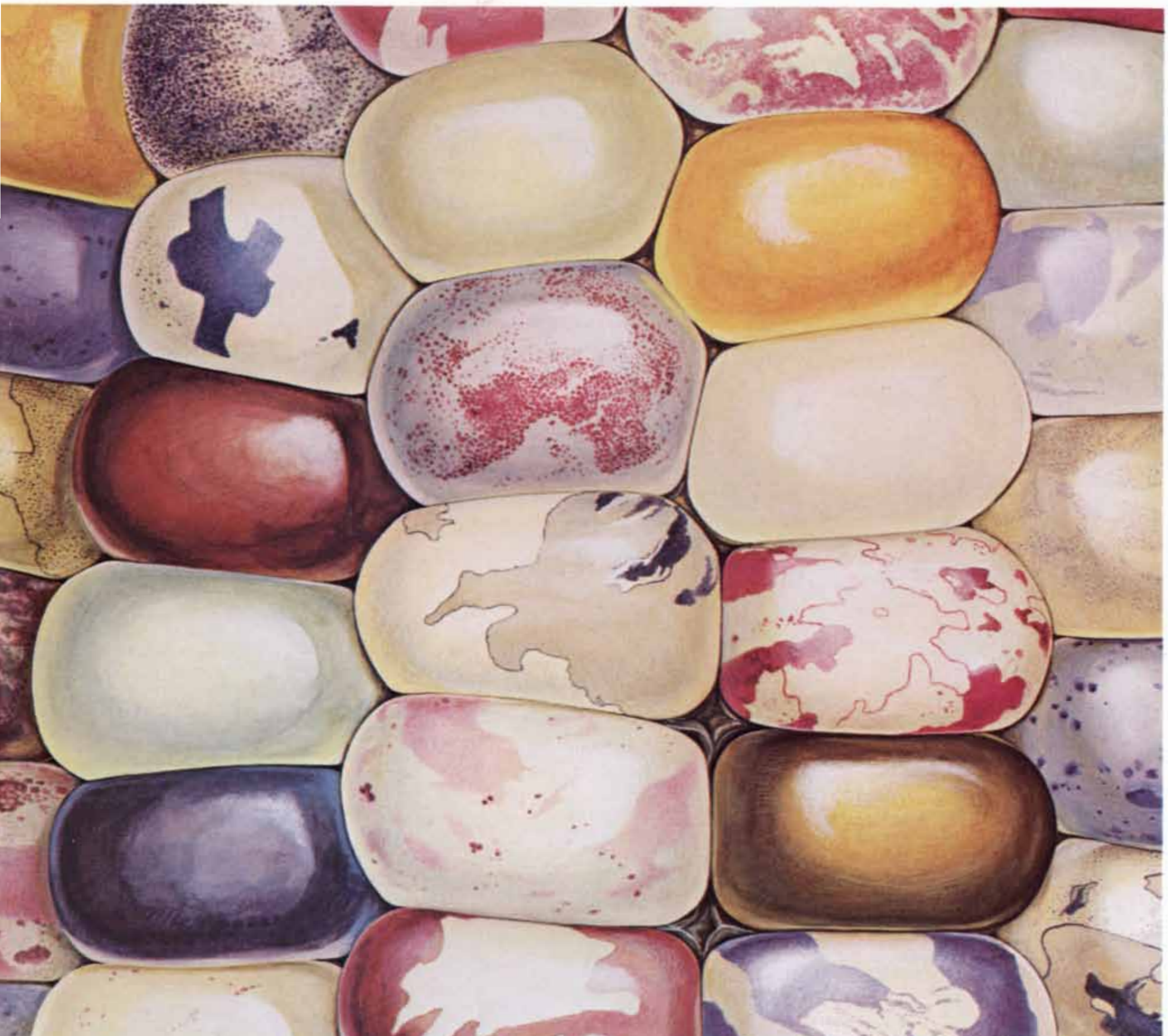
SCIENTIFIC AMERICAN



TRANSPOSABLE GENETIC ELEMENTS IN MAIZE

$2.50

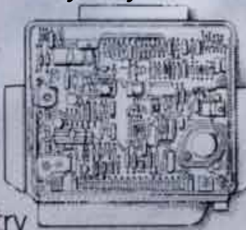
June 1984

INTRODUCING THE ONLY SPORTS SEDAN MORALLY ENTITLED TO BORROW THESE INNOVATIONS FROM BMW.

Each BMW is a repository of innovations derived from its predecessors as well as from present members of the line.

325e

As such, each has inspired imitators seeking to persuade you that 'BMW-like' is synonymous with BMW.



BMW's Digital Motor Electronics senses driving and engine conditions and adjusts in milliseconds.

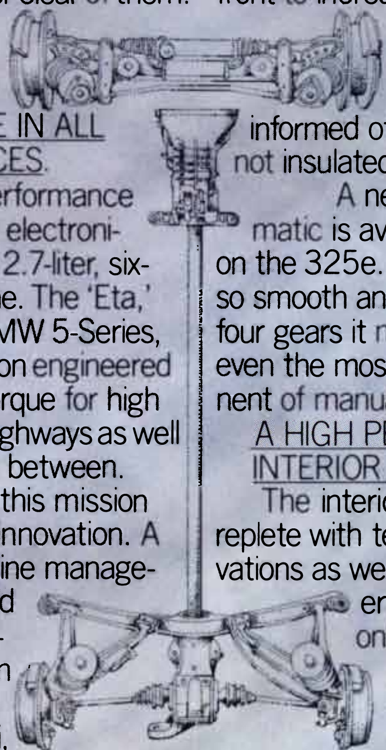
Now there is a new BMW sports sedan destined to motivate the industry to further facsimiles. But more importantly, it's designed to offer you an excellent opportunity to steer clear of them.

It's called the BMW 325e.

HIGH PERFORMANCE IN ALL ITS NUANCES.

The 325e's performance is powered by the electronically fuel-injected, 2.7-liter, six-cylinder 'Eta' engine. The 'Eta,' unveiled on the BMW 5-Series, is a BMW innovation engineered to turn out high torque for high performance on highways as well as on the roads in between.

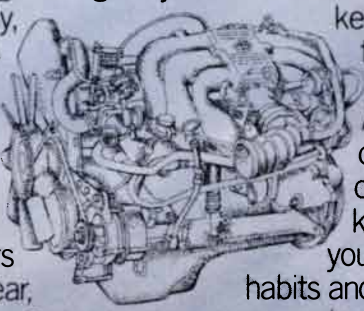
It's assisted in this mission by another BMW innovation. A computerized engine management system called Digital Motor Electronics. This system not only debuted on the BMW 733i, it also manages the BMW engine that powers the current Grand Prix Formula One Championship car.



The 325e's fully independent suspension delivers a comfortable ride while keeping you fully cognizant of the road conditions below.

In tandem on the 325e, the 'Eta' engine and DME deliver a 0-to-60 time of 9.4 seconds, along with a remarkable EPA-estimated [23] mpg, 36 highway.*

Not surprisingly, the 'Eta' system is supported by an innovatively engineered sport suspension. It's fully independent and utilizes anti-roll bars at the front and rear, similar to the ones on the BMW 633CSi, for flatter, more precise road holding and handling.



The ingenious 'Eta' engine provides exuberant responses in all driving situations.

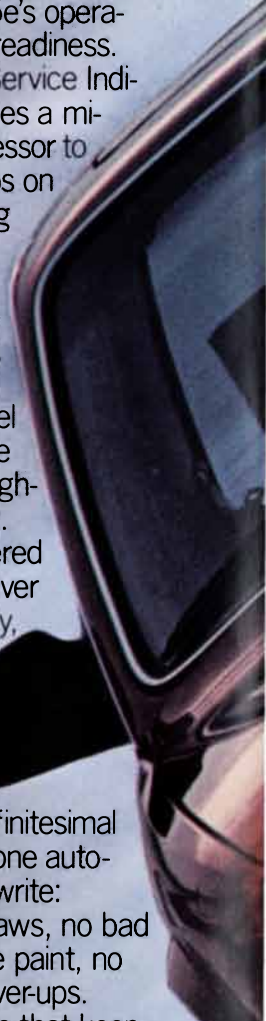
Disc brakes are present on all four wheels. They're vented in front to increase fade resistance. And variable-assist power steering keeps you informed of road conditions, not insulated from them.

A new four-speed automatic is available as an option on the 325e. Its performance is so smooth and responsive in all four gears it may well convert even the most stubborn exponent of manual shifting.

A HIGH PERFORMANCE INTERIOR IS STANDARD.

The interior of the 325e is replete with technological innovations as well. The second generation of BMW's onboard computer provides a host of calculations, including your cumulative fuel economy, average trip speed and cruising range on fuel remaining. It also warns you when the exterior temperature nears freezing and can even be programmed for anti-theft protection.

BMW's early warning system called the Active Check Control keeps you apprised of the 325e's operational readiness. And a Service Indicator uses a microprocessor to keep tabs on your driving habits and computes when routine maintenance is called for.



A leather-bound sports steering wheel and gearshift provide the proper feel for high-performance driving. While newly engineered sports seats grip driver and passenger firmly, yet comfortably.

And like every BMW, the 325e is built with the same infinite attention to infinitesimal details that inspired one automotive journalist to write:

"There are no flaws, no bad joints, no runs in the paint, no stick-ons and no cover-ups. These are the details that keep coming back to reinforce the car's value every time you open the door, drive down the freeway, or just sit and look at it."

You may do all of the above when you arrange a thorough test drive of the new BMW 325e at your nearby BMW dealer.

THE ULTIMATE DRIVING MACHINE.

*Fuel efficiency figures are for comparison only. Your actual mileage may vary, depending on speed, weather and trip length. Actual highway mileage will most likely be lower. ©1984 BMW of North America, Inc. The BMW trademark and logo are registered. European Delivery can be arranged through your authorized U.S. BMW dealer.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Established 1845 **SCIENTIFIC AMERICAN** June 1984 Volume 250 Number 6

ARTICLES

DEPARTMENTS

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SCIENTIFIC AMERICAN

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THE COVER

The painting on the cover shows the remarkable variegation in kernel pigmentation that can be generated in maize by transposable genetic elements, the mobile bits of DNA that were discovered by Barbara McClintock in the late 1940's. Transposable elements have since been found to be present also in bacteria and animals as well as in other plants. Several of the maize elements have now been isolated and characterized at the molecular level (see "Transposable Genetic Elements in Maize," by Nina V. Fedoroff, page 84). As these elements move from one site to another in the genome of a corn plant they can cause mutations and rearrange chromosomes, thus affecting the expression of genes. For example, the insertion of an element into a gene involved in pigment synthesis can inactivate the gene, making a kernel colorless; the subsequent movement of the element away from the gene restores gene function and so generates pigmented spots on the kernel. The kernels depicted in the painting were selected from a number of maize ears having different genetic constitutions.

THE ILLUSTRATIONS

Cover painting by Enid Kotschnig

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60–61	Heather Lechtman, Massachusetts Institute of Technology
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97–98	Bunji Tagawa
101–111	Walken Graphics
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114–121	Tom Prentiss
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131	John Moss, Black Star
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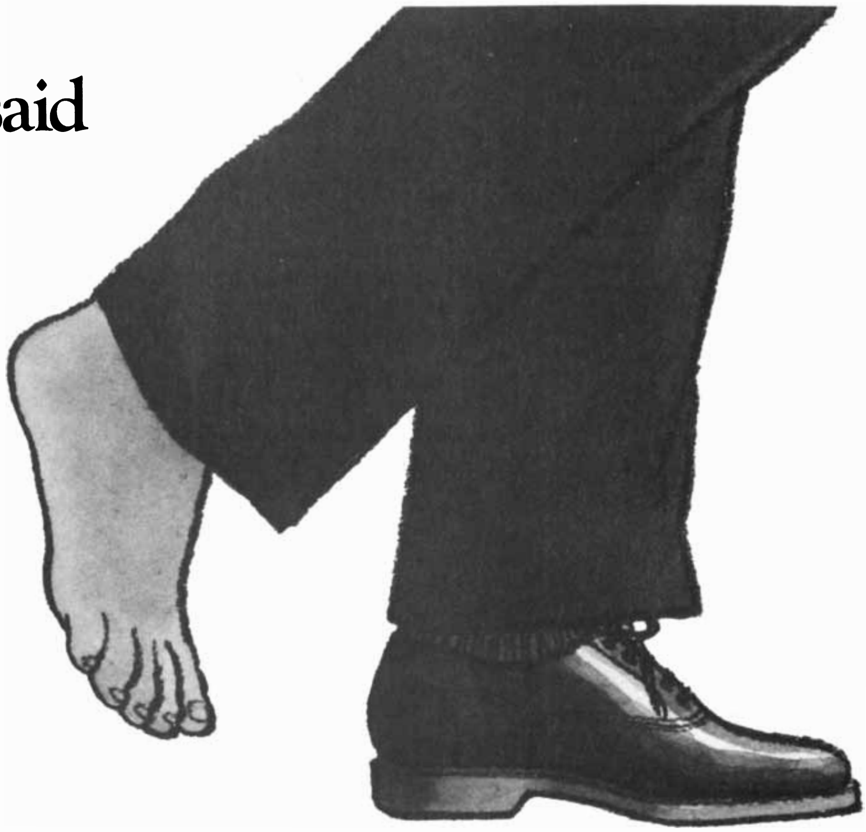
144	National Machinery Co.
150–152	Michael Goodman

When all is said and done, a shoe is meant for walking. Lands' End never forgets it.



In our approach to the shoe market, Lands' End concluded that you are already well served by the "high tech" footwear available to people who walk, jog, or run for their health.

Where we can—and *do*—make a typical Lands' End contribution is in providing exceptional values in shoes that are comfortable, look good and wear well.

Even if you're not athletic, you spend 6,202 hours a year in your shoes, and half of that time you're walking. So there are three things your shoes should do for you, and Lands' End concentrates on them.

Our watchwords: comfort, fit, durability.

To make sure your shoes wear well, Lands' End uses *Vibram,* not leather, in the soles. Vibram is a synthetic composite developed by an Italian mountaineer, who selected it because it provides extremely good traction, along with light weight and durability. Vibram soles outlast leather, and do not soften or rot in wet weather.

The leathers selected for the uppers of Lands' End shoes are light in weight, yet durable too, and should reduce complaints of tiring that come from wearing too heavy a shoe. They are handsewn, not machine stitched, and feature a leather sockliner.

Finally—and perhaps most important—Lands' End shoes fit. We make sure of that because—while we offer no less than 12 different styles, all are shaped on a common last. *(A last being the form around which a shoemaker builds a shoe.)* This commitment to a common last means that whatever Lands' End style you order, a size 10 is a size 10 is a size 10. This is by no means always true elsewhere.

The Lands' End difference.

Our approach to the shoe market is typical of the Lands' End approach to everything we sell—from shoes to shirts to sweaters to soft luggage and beyond.

We don't ask, "What can we do to make it cheaper?" We say, "What can we do to make it better?" A direct question—the kind we believe in getting answers to at Lands' End, Direct Merchants. Our unconditional guarantee is direct, too. In two words it says:

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LETTERS

Sirs:

Jearl Walker's recent column on fish optics and how fishes see objects above the surface of the water [SCIENTIFIC AMERICAN, March] might have mentioned the shooting accuracy of the archerfish. The genus *Toxotes* is a brackish-water fish found in the Indo-Australian archipelago. It is commonly kept in home aquariums and is famed for its ability to shoot down objects with a squirt of water. Anecdotes abound as to how this fish can be trained to shoot food off the side of a tank. Accurate shots of up to two meters have been measured. The sharpshooting of the archerfish has been observed often enough in nature for the Malayans to have given it the name *ikan sumpit,* or blowpipe fish.

The mouth of *Toxotes* is grooved on the roof. When the fish flattens its tongue against this groove, a tube is formed. The fish then suddenly retracts its gill covers, which forces a drop of water out of its mouth at high speed. The ability of the fish to hit targets as much as two meters above the surface suggests it can compensate quite well for refraction. It must be able somehow to calculate angles of refraction and the force at which the water drop is to be fired so as not to overshoot or undershoot.

D. C. SPEIRS

Calgary, Alberta

Sirs:

Readers of "The Earth's Orbit and the Ice Ages," by Curt Covey [SCIENTIFIC AMERICAN, February], might be interested to know that the theory he describes is older than he suggests. The linkage between climate and the earth's orbital parameters was first proposed by J. Adhémar in 1842. James Croll reworked the "astronomical theory" of the ice ages in his 1875 monograph *Climate and Time.* In 1891 Sir Robert Ball, then Royal Astronomer of Ireland, presented a surprisingly modern treatment in *The Cause of an Ice Age.*

Like Covey, Ball suggests that ice ages result from variations in (1) the angle of tilt of the earth's axis with respect to the plane of its orbit, (2) the eccentricity of the ellipse that describes the earth's path around the sun and (3) the precession of the poles with respect to the fixed stars. The values of these orbital parameters given by Ball are nearly identical with those given by Covey.

There are, of course, differences between Covey's position and the 19th-century theories. One of the strongest arguments against earlier versions of the astronomical theory was that they erroneously predicted that glaciation should alternate between the Northern and Southern hemispheres. The modern version accounts for the absence of Southern Hemisphere ice ages by taking into consideration the distribution of landmasses in the two hemispheres. Nevertheless, the similarities are more striking than the differences.

Although Adhémar, Croll and Ball are apparently forgotten, Milutin Milankovitch, who came much later, now has his name associated with the theory that variations in the earth's orbit are responsible for the Pleistocene ice ages. As is sometimes the case with theories that are slow to gain acceptance, credit comes to the originator only after his death. Adhémar's case has much in common with that of Alfred Wegener, also a pioneer in the study of long-term changes in the earth's climate. Wegener laid down the foundations of a theory of plate tectonics long before his ideas were generally accepted. The difference is that Wegener has been rediscovered, whereas Adhémar, Croll and Ball apparently have not.

HUGH P. WHITT

Department of Sociology
University of Nebraska–Lincoln
Lincoln, Neb.

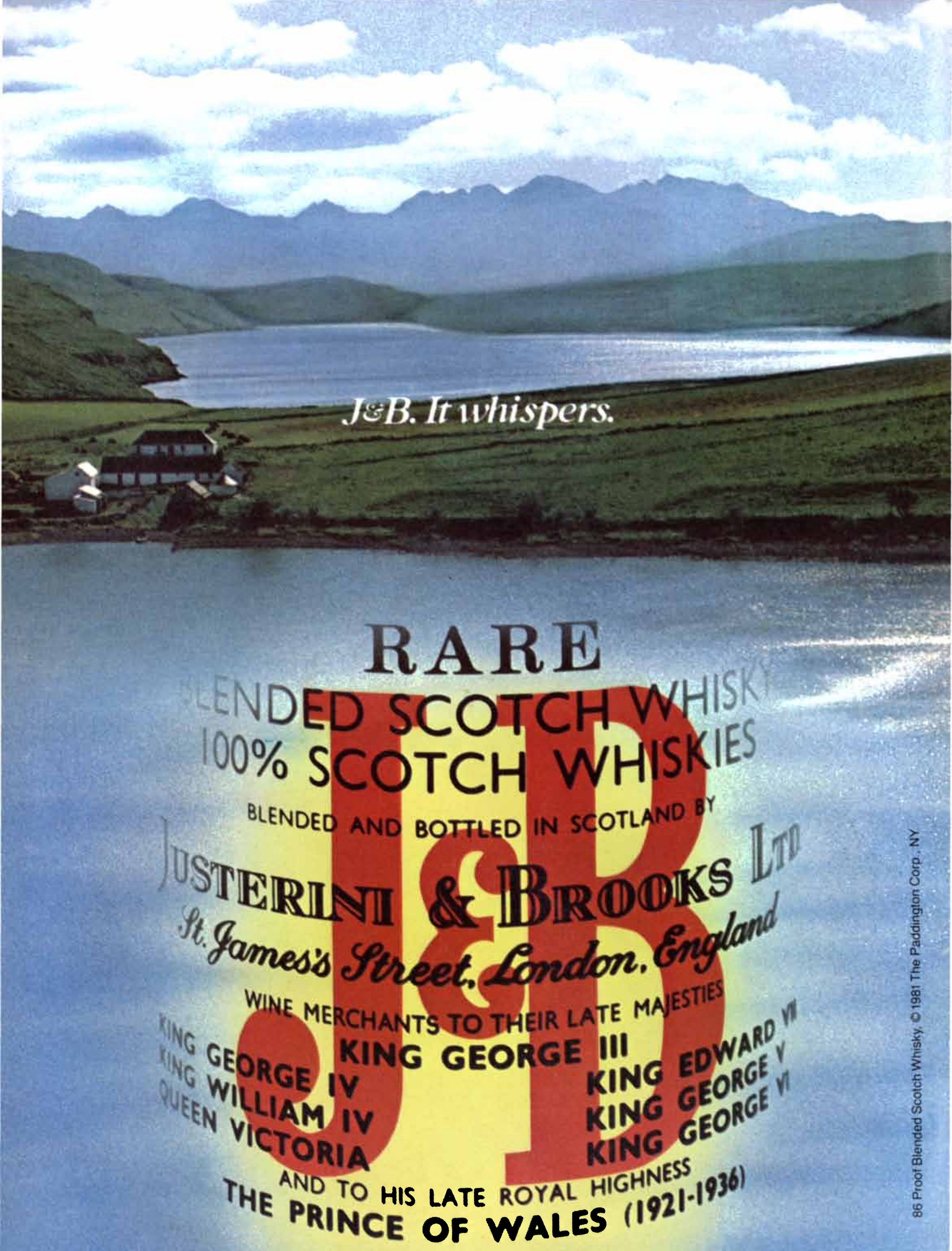
Sirs:

The early orbital theories are indeed fascinating. Interested readers should consult *Ice Ages: Solving the Mystery,* by John Imbrie and Katherine Palmer Imbrie, which I listed in the bibliography for my article. I regret that space considerations prevented me from fully exploring historical matters. Nevertheless, it is my opinion that Milankovitch deserves the credit he gets. He was the first both to rigorously calculate the orbital variations (a stupendous undertaking in the precomputer age) and to suggest a reasonable physical mechanism by which the tiny changes in received sunlight could lead to the large observed changes in climate. The latter contribution was, as Dr. Whitt points out, a key difference between Milankovitch and the earlier theorists.

CURT COVEY

Division of Meteorology
and Physical Oceanography
Dorothy H. and Lewis Rosenstiel
School of Marine
and Atmospheric Science
University of Miami
Miami, Fla.


Get it together–Buckle up.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THE PRINCE OF WALES (1921-1936)
86 Proof Blended Scotch Whisky, © 1981 The Paddington Corp., NY

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

JUNE, 1934: "Some 30 years ago, in 1903, the inorganic-nitrogen production of the world was 349,000 metric tons, 63 per cent of which was supplied by Chile. In 1933 the inorganic-nitrogen production of the world was nearly five times as much, or 1,700,000 metric tons, less than 10 per cent of which was supplied by Chile. Not until 1913, when the Germans began nitrogen fixation by the Haber-Bosch ammonia synthesis, did there appear to be a real threat to Chilean supremacy. The major consequences of this development have been: first, the destruction of the Chilean monopoly in nitrogen and the decline of the Chilean industry; second, the world-wide sufficiency of cheap nitrogen for agriculture; third, national independence of practically every important world power as to nitrogen supply for war munitions; and fourth, the application of the new high-pressure catalytic technique to the synthesis of methanol and the hydrogenation of numerous substances, particularly of coal and oil for the manufacture of synthetic motor fuel."

"Recent improvements in the construction of radio receivers have opened a new avenue to the listener-in. The sets that make possible long-distance reception on short waves are generally known as all-wave receivers. The design of such a receiver is an engineering problem of no mean proportions. To cover a wide band of wavelengths it is necessary to provide a series of separate tuning circuits, in order to avoid unbalancing and other undesirable factors that necessarily are introduced when a wide tuning range is obtained with a single circuit. In the all-wave receivers the separate coils and condensers are progressively connected in the circuit by means of a selector switch that determines the wavelength band that can be covered by the dial. On the face of the dial are several different scales, one for each wavelength range. This combination of mechanical parts and electrical circuits provides simplicity of operation and convenience and rapidity of switching from one range to another."

"Walter S. Adams and Theodore J. Dunham, Jr., have found that Venus shows no trace of the familiar bands of oxygen or water vapor. But there are three beautiful bands in the deep red and infra-red that have been definitely traced to the carbon dioxide. Such an atmosphere would exert a powerful 'greenhouse' effect, letting the short waves of sunlight in and retarding the escape of the long waves from the warm surface. Rupert Wildt, one of the best men working on the subject, concludes that the temperature at the planet's surface may be as high as the boiling point of water. Life could hardly maintain itself under these conditions, and in its absence the carbon dioxide would remain in the atmosphere. Mars shows no trace of oxygen, water or carbon dioxide. It would seem, then, that Mars may represent a later stage in the history of a planet than the earth, whereas Venus somewhat resembles the earth before life developed upon it. We find ourselves 'wandering between two worlds, one dead, the other powerless to be born.'"

SCIENTIFIC AMERICAN

JUNE, 1884: "From recent statistics it appears that there are 20,000 producing oil wells in Pennsylvania, yielding at present 60,000 barrels of oil a day. The industry requires 5,000 miles of pipe line and 1,600 iron tanks, of an average capacity of 25,000 barrels each, to transport and store the oil and surplus stocks. The speculative transactions in petroleum represent more than $400,000,000 annually. The lowest price crude petroleum ever brought was 10 cents a barrel in 1861. In 1859, when there was only one well in existence, Colonel Edwin L. Drake's 'Pioneer' at Titusville, the price was $24 a barrel. Besides the 5,000 miles of pipe line in use in the oil regions, there are 1,200 miles of trunk pipe lines connecting the region with Cleveland, Pittsburg, Buffalo and New York, and lines building to Philadelphia and Baltimore. These lines are all the property of the Standard Oil Company, except one between Bradford and Williamsport, Pa. Standard employs 100,000 men. The product of its refineries requires the making of 25,000 oak barrels of 40 gallons each, and 100,000 tin cans holding five gallons each, every day."

"One of the most striking of recent scientific explorations is that undertaken by the *Travailleur* and the *Talisman* conducted by M. Milne-Edwards and other *savants* chosen by the government and Academy of France. The fact that attracts attention on reading the narrative of these interesting dredgings is that the ocean appears to have two superimposed faunas. At the surface we encounter all the species we know at present, but at 2,500 to 3,000 meters they become increasingly rare. Farther down we find an abyssal fauna composed of singular creatures that never rise. The ocean thus seems to contain two regions, one over the other, both characterized by a peculiar fauna."

"Of late years Mr. David Gill, F.R.S., H.M. Astronomer at the Cape, and a young American astronomer, Dr. William L. Elkin, have been measuring the distances of some fixed stars in the Southern Hemisphere by means of a telescope with a divided object glass, with the following results expressed in the number of years in which light travels from those stars to the earth: Alpha Centauri, 4.36 years; Sirius, 8.6 years; Lacaille (9352), 11.6 years, and Epsilon Indi, 15.0 years. So far as observations have yet gone Alpha Centauri is the nearest of the fixed stars, and eye observations as to the relative brilliancy of stars are no guide to their relative true distances. Mr. Gill believes that the future of astronomy depends much upon photography, particularly since the recent feat of photographing the nebula of Orion has been so exquisitely accomplished."

"The attendance at some of the leading colleges for the current year is as follows: the University of Michigan stands at the head with 1,554 students; Harvard has 1,522, Columbia 1,520, the University of Pennsylvania 1,044, the Massachusetts Institute of Technology 561 and Princeton 527. As regards the number of professors in each, however, the order is somewhat changed. The University of Michigan is omitted, owing to lack of data. Harvard has 32 professors and a total of 55 instructors. Princeton comes next with 28 professors and a total of 34, including tutors, etc. Yale has 20 professors and a total of 30 instructors. Columbia has 12 professors and a total of 29 instructors."

"The remarkable communications that M. Pasteur has recently made to the Academy of Sciences upon the subject of his new study of rabies have again attracted the attention of scientists and the public. The laboratory of the Normal School, wherein so many great labors have already been performed, is at present being conducted in a very uncommon manner, and M. Pasteur, thanks to the liberality of the Municipal Council of Paris, has been enabled to construct kennels for mad dogs, coops for poultry afflicted with cholera, pens for measly swine, and stables and sheep folds for animals suffering from the disease known as *charbon*. 'Never,' said M. Pasteur in one of his recent lectures, when he had just killed a bird in air deprived of oxygen, 'should I have the courage to kill a bird by shooting it; but, when it concerns experiments, I am deterred by no scruples. Science has the right to invoke the sovereignty of the end in view.'"

Cracking

Summary:

Microelectronics is a major force behind the information age. It permits faster information processing through packing more and more components on a chip. GTE scientists have developed methods of producing advanced VLSI chips with 1.2μm feature size. The next stage is 0.8μm, and further reductions are on the way.

The ability of today's microelectronics to process information lags behind industry's need to transmit it.

GTE is working on this problem both by increasing data-handling capability, and by reducing data-processing time.

This is being achieved with VLSI (Very Large-Scale Integration) system densities approaching a million components per quarter-inch square, with reaction times in subnanoseconds, and with computer-aided design.

GTE scientists are developing advanced compiling systems for the full hierarchical design of more and more complex integrated circuits. They have also developed gate-level and functional-level circuit simulators that were five to ten times faster than previous systems.

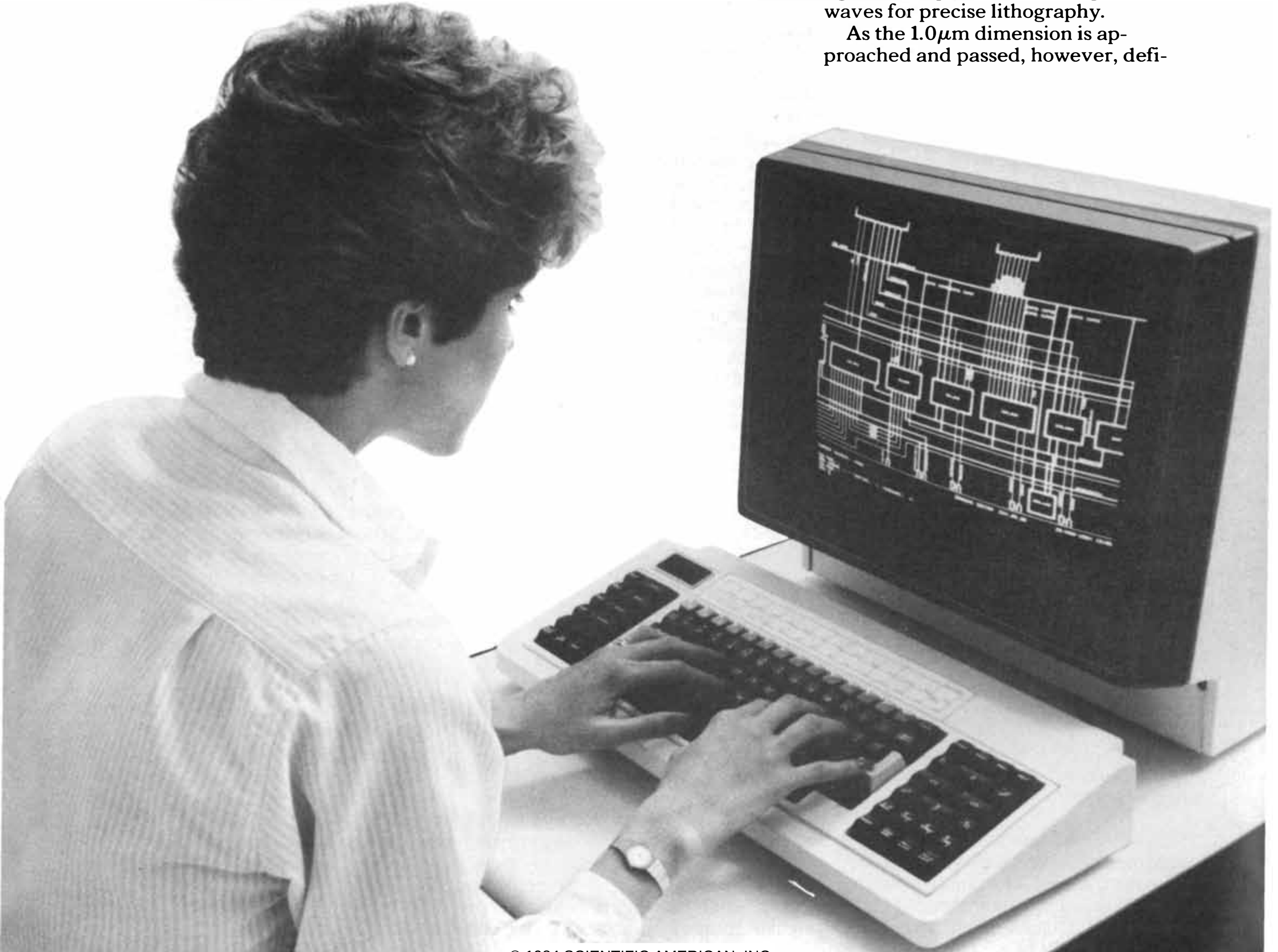
Making the chip.

The computer is also put to work in the chip manufacturing process. It directs the lithography, level by level, as well as other processes such as selective etching of deposited materials by ionized gases.

Currently, we are completing pilot-plant studies of a 1.2μm process and will transfer it to production facilities.

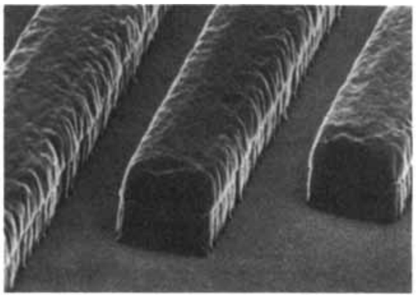
But feature dimensions continue to shrink. When they were comfortably above the wave length of visible light, it was possible to use light waves for precise lithography.

As the 1.0μm dimension is approached and passed, however, defi-

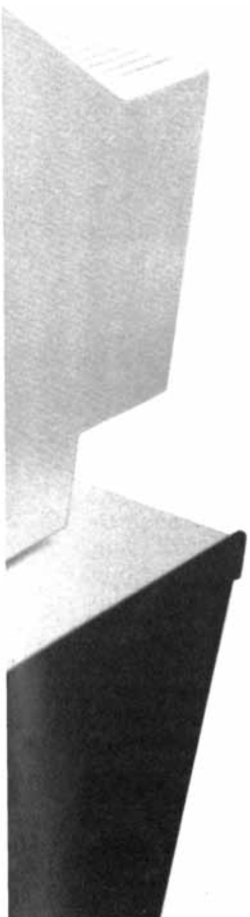


the 1 μm barrier.

nition begins to blur, and other techniques are needed. Among these is electron-beam lithography, with sub-micron resolution.



We are now working in the 0.8μm dimension. And we have identified experimental devices of 0.5μm and below as our next targets. (This dimension range begins to approach the distance an electron travels in solids before it scatters. By the time it has a collision, it has performed its work. Imagine the speed and precision this signifies.)

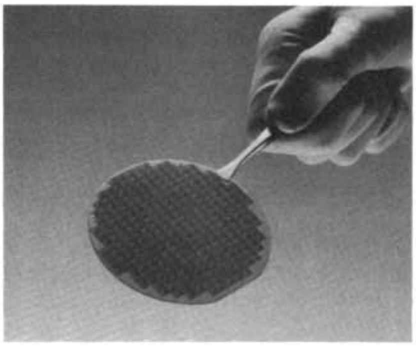


VLSI tomorrow.

Shrinking feature size to sub-micron dimensions is only part of the story. Other ongoing work in our laboratories includes replacing silicon as the chip matrix with faster-acting gallium arsenide, and building up the chip with epitaxial-film deposition, layer by layer.

Such VLSI research is helping accelerate the evolution of more sophisticated microprocessors, "burst" switching, PABX-on-a-chip, high-speed digital technology, and more.

In the box at the right is a partial list of pertinent papers by GTE people on VLSI and related subjects. For any of these, you are invited to write GTE Marketing Services Center, Department TPIA, 70 Empire Drive, West Seneca, NY 14224.



Pertinent Papers.

End Point Detection for Reactive Ion Etching of Aluminum, J. Electrochem. Soc., 1984.

Highly Selective Dry Etching of Polysilicon Using Chlorinated Gas Mixtures for VLSI Applications, Electrochemical Society Meeting, May 6-11, 1984.

Negative Resistance Switching in Near-Perfect Crystalline Silicon Film Resistors, 30th American Vacuum Society Symposium, November, 1983.

Vertical, Dual-Gate CMOS NAND in Two Laser-Recrystallized Silicon Layers over Oxidized Silicon Substrate, Materials Research Society Spring Meeting, February, 1984.

Reactive Sputter Etching of Single Crystalline Silicon, Proceedings of 3rd Annual Symposium on Plasma Processing and Extended Abstracts 83-1, 163 Electrochemical Society Meeting, May, 1983.

Reactive-Ion Etching of Single Crystalline Silicon with $Cl_2 + SiCl_4$, Proceedings of Fourth Conference on Plasma Processing, Electrochemical Society Meeting, May, 1983.

GTE

THE AUTHORS

RICHARD L. GARWIN, KURT GOTTFRIED and DONALD L. HAFNER ("Antisatellite Weapons") are respectively IBM Fellow at the Thomas J. Watson Research Center of the International Business Machines Corporation, professor of physics at Cornell University and associate professor of political science at Boston College. Garwin's B.S. was awarded by the Case Institute of Technology and his Ph.D. in physics by the University of Chicago. After getting his doctorate he spent three years on the Chicago faculty before moving to IBM; there he has held several jobs, including that of director of the Watson laboratory. He is also Andrew D. White Professor-at-Large at Cornell and adjunct professor of physics at Columbia University. Gottfried, a native of Austria, emigrated to Canada in 1939. He was graduated from McGill University and went on to earn his doctorate from the Massachusetts Institute of Technology. After serving on the faculty of Harvard University from 1960 to 1964 he moved to Cornell, where he has remained. Hafner received a B.A. at Kalamazoo College in Michigan in 1966; he got his Ph.D. in political science in 1972 from the University of Chicago. In 1977 and 1978 he took time off from teaching at Boston College to join the staff of the U.S. Arms Control and Disarmament Agency; thereafter he returned to the Boston College faculty.

HEATHER LECHTMAN ("Pre-Columbian Surface Metallurgy") is professor of archaeology and ancient technology at the Massachusetts Institute of Technology. She holds a joint appointment in the anthropology and archaeology program of the Department of Humanities and in the Department of Materials Science and Engineering. After getting her bachelor's degree at Vassar College she took a job as an assistant physicist in the department of physics and biophysics at the Sloan-Kettering Institute for Cancer Research. After four years she moved to the American Institute of Physics, where she served as assistant to the director. She then entered New York University to continue her studies, obtaining her master's degree in fine arts and a diploma in the conservation of art and archaeological materials. After receiving her master's degree she joined the faculty at M.I.T. Lechtman is director of the interinstitutional Center for Materials Research in Archaeology and Ethnology.

STEVEN M. STANLEY ("Mass Extinctions in the Ocean") writes: "I am professor of paleobiology in the department of earth and planetary sciences at Johns Hopkins University. I received my undergraduate degree at Princeton University and my doctorate from Yale University. I am interested in the area of overlap between geology and biology and my previous work has concerned the functional morphology and evolution of marine organisms and the nature of large-scale evolution. I have recently been studying molluscan faunas of Florida that suffered extinction at the beginning of the most recent ice age."

NINA V. FEDOROFF ("Transposable Genetic Elements in Maize") is a member of the staff in the Department of Embryology of the Carnegie Institution of Washington and associate professor of biology at Johns Hopkins University. She writes: "I started out to be a musician and left Syracuse University, where I was an undergraduate, to study music with William Kincaid in Philadelphia. After a couple of years I decided on a career in science and returned to Syracuse. I got my graduate degree at Rockefeller University. My involvement with the transposable genetic elements in maize dates from an encounter with Barbara McClintock during a visit to Cold Spring Harbor in about 1977 that prompted me to read all her early work. Just as I was thinking it a glorious and unrealistic notion to undertake the isolation of the maize elements I was offered a staff position at the Carnegie Institution. Carnegie's policy of undivided attention to research and support of long-range goals made it possible for me to tackle the molecular biology of maize, which had not then got off the ground."

MARIE-ANNE BOUCHIAT and LIONEL POTTIER ("An Atomic Preference between Left and Right") are members of the staff of the French National Center for Scientific Research (CNRS) who have collaborated in work on the subject of their article since 1974. Bouchiat works in the physics laboratory of the École Normale Supérieure in Paris (ENS). After her graduation from the École Normale Supérieure de Sèvres she came to the U.S., where she spent two years as a visiting fellow at Princeton University. At the end of that period she returned to the ENS to continue her studies; her doctorate was awarded in 1964. Pottier did his first experimental work in Bouchiat's laboratory as an undergraduate at the ENS. After getting his bachelor's degree he continued his studies at the same institution, earning his doctorate in 1972.

LEE C. RYKER ("Acoustic and Chemical Signals in the Life Cycle of a Beetle") is a research associate in forest entomology at Simon Fraser University in British Columbia. He also teaches life science at Hedrick Junior High School in Medford, Ore. He was graduated in 1963 from Franklin College of Indiana with a B.A. and went on to obtain an M.S. in biology at the University of Michigan. In 1965 he moved to Oregon to take up a job as a high school teacher. After several years of teaching he entered the University of Oregon to continue his postgraduate education; he earned his second M.S. in biology in 1971 and his Ph.D. in entomology in 1975. After getting his doctorate he joined Julius A. Rudinsky at the Forest Insect Laboratory at Oregon State University in studying the Douglas-fir beetle and other economically costly bark beetles. He continued the work, which was funded by the National Science Foundation, for two years after Rudinsky's death in 1980.

J. MAYO GREENBERG ("The Structure and Evolution of Interstellar Grains") is professor of laboratory astrophysics at the University of Leiden. Born in Baltimore, he went to Johns Hopkins University as an undergraduate. During World War II he did work on theoretical hydrodynamics for the National Advisory Committee for Aeronautics. After the war he returned to Johns Hopkins, which awarded him his Ph.D. in physics in 1948. In 1952 he joined the faculty of the Rensselaer Polytechnic Institute, becoming professor of physics in 1957. In the late 1950's his scientific interests shifted from physics to astronomy. In 1968 and 1969 he was invited by Leiden to initiate the new chair in laboratory astrophysics there. He returned to the U.S. to become professor of astronomy at the State University of New York at Albany. In 1975 Greenberg took a permanent job at Leiden, where he set up a laboratory for studying the effects of ultraviolet radiation on the interstellar grains.

FREDERICK E. GRAVES ("Nuts and Bolts") is an engineer who works as a consultant to manufacturers of fastening devices. After being graduated from Pennsylvania State University with a B.S. in 1940, he went to work for Battelle Memorial Institute as a research engineer. He spent three years with Battelle before leaving to join private industry. He worked for nine years with the Surface Combustion Corporation and with W. S. Rockwell. In 1956 he joined the staff of the Russell, Burdsall and Ward Corporation, a major manufacturer of industrial fasteners. In 1959 he became technical director of the company, a job he held for a decade. Graves left Russell, Burdsall and Ward in 1969 to start his own consulting firm.

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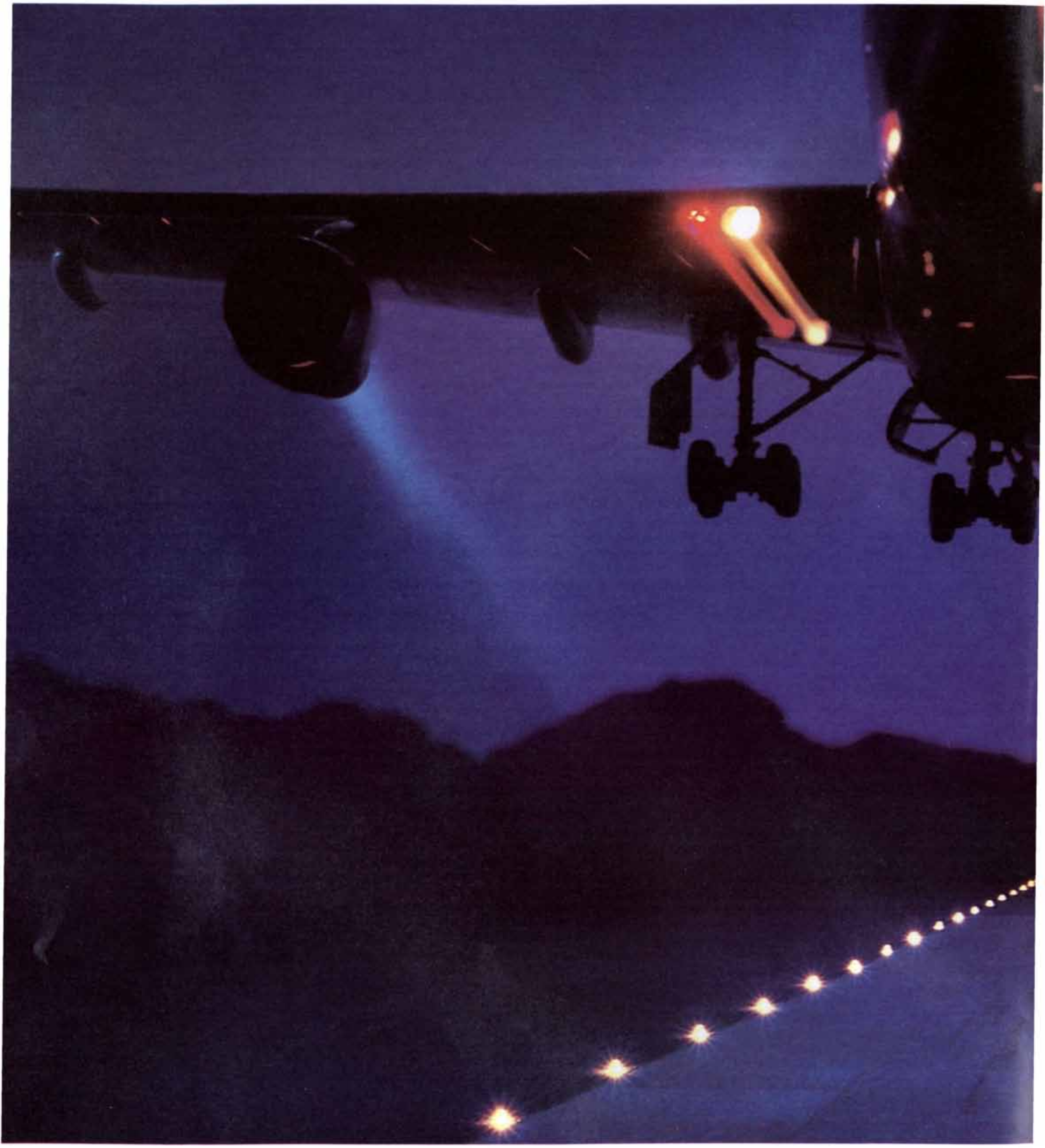

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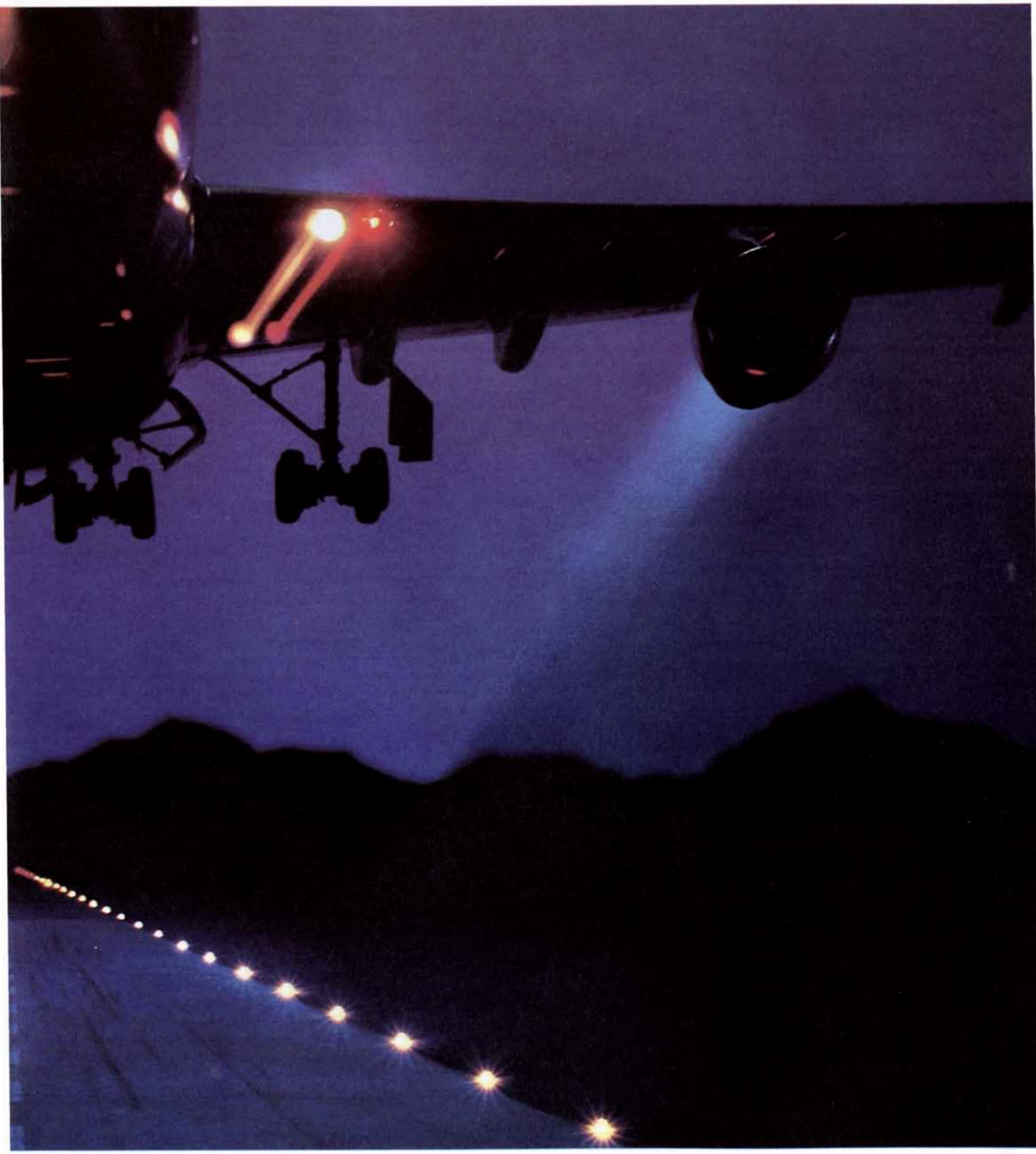

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COMPUTER RECREATIONS

On the spaghetti computer and other analog gadgets for problem solving

by A. K. Dewdney

Mention computers these days and one thinks invariably of digital machines. All but forgotten are their analog cousins, the electromechanical devices that once ruled the computational scene. Before World War II major laboratories employed elaborate analog computers with names such as the continuous integraph and the differential analyzer. The machines exploited electrical or mechanical analogies to mathematical equations; a variable in an equation would be represented by some physical quantity, such as a voltage or the rotation of a shaft. Analog computers could be applied to equations that arise in many fields: ballistics, aerodynamics, the analysis of power networks and so on.

The analog machines could not compete with the digital computers developed during World War II and immediately after. Analog computers seemed to be capable of solving only certain kinds of problems, chiefly those defined by differential equations, and even then with less than perfect accuracy. In contrast, it quickly became apparent that digital computers could be programmed to solve an infinite variety of problems with very high accuracy. Slowly the analog machines faded into the background until by the mid-1960's they were barely mentioned in books on computing.

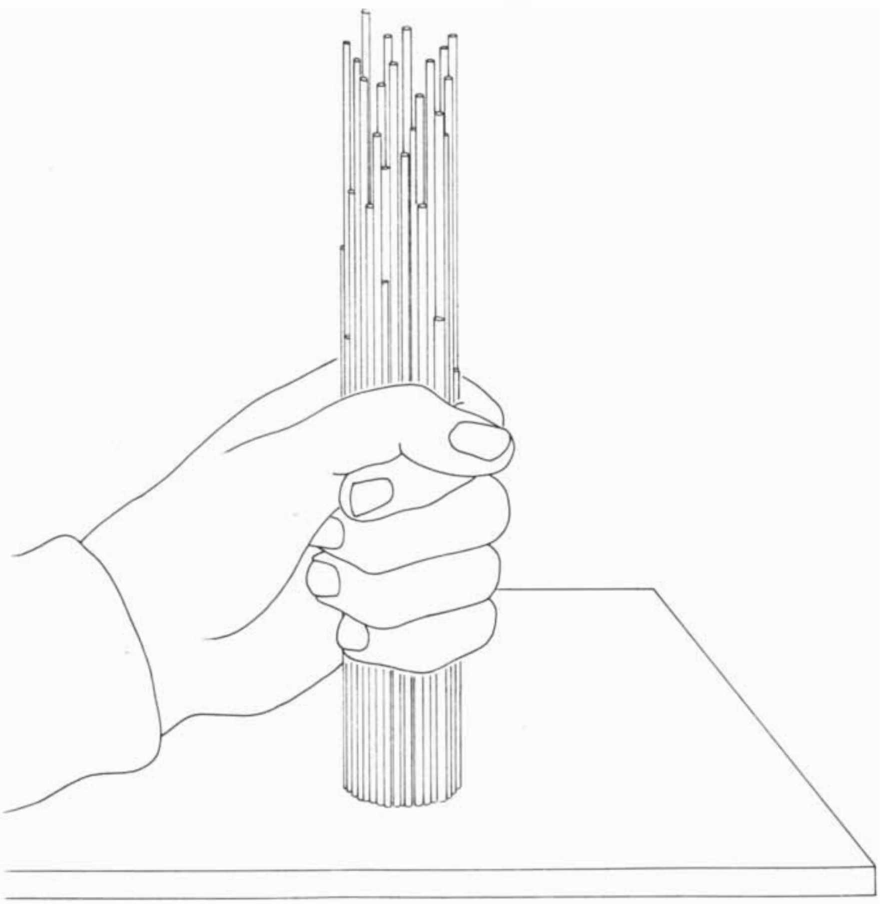
Although the successors of the great analog machines of the 1920's and 1930's are still in use (and under continuing development) in a few laboratories, no one seriously expects analog computers to spring to the forefront again. The digital revolution cannot be turned back. It is also true, however, that a revolution sometimes blinds us to the charms of an earlier milieu.

The essential delight of an analog computation lies in the notion that one is getting something for nothing. A problem that would require hours of computation by hand (or even by a digital computer) is solved by merely observing a physical system as it comes rapidly into equilibrium. In the most dramatic cases the process seems wellnigh instantaneous, and we have a gadget that computes.

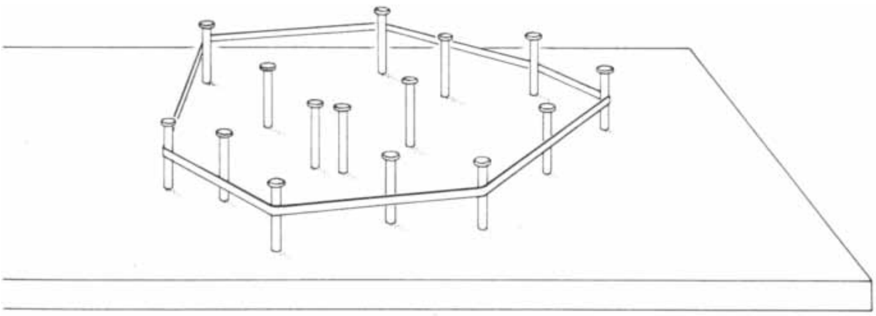
Consider the SAG computer, or Spaghetti Analog Gadget. This device, in the configuration I have tested, is able to sort up to 700 numbers in order of decreasing magnitude. Sorting is a common task in digital computing, and algorithms for doing it have been highly refined, but the time needed to sort a list of numbers still grows somewhat faster than the size of the list. With SAG one must spend a little time setting up the machine for the particular list of numbers and a little more time reading out the results, but the actual sorting appears to take no time at all.

Here is how SAG works. For each number in the sequence to be sorted trim a piece of uncooked spaghetti to a length equal to the number. Naturally, appropriate units of measurement must be adopted. Now take all the pieces of trimmed spaghetti in one hand and, holding the bundle vertically and somewhat loosely, bring it down on a table rather sharply. The momentum of the individual rods ensures that all of them have one end resting on the table. In order to obtain the sorted sequence from the resting bundle, one has only to remove the tallest rod, then the tallest of the remaining rods and so on until the bundle is exhausted. As each rod is removed it is measured and the number is recorded.

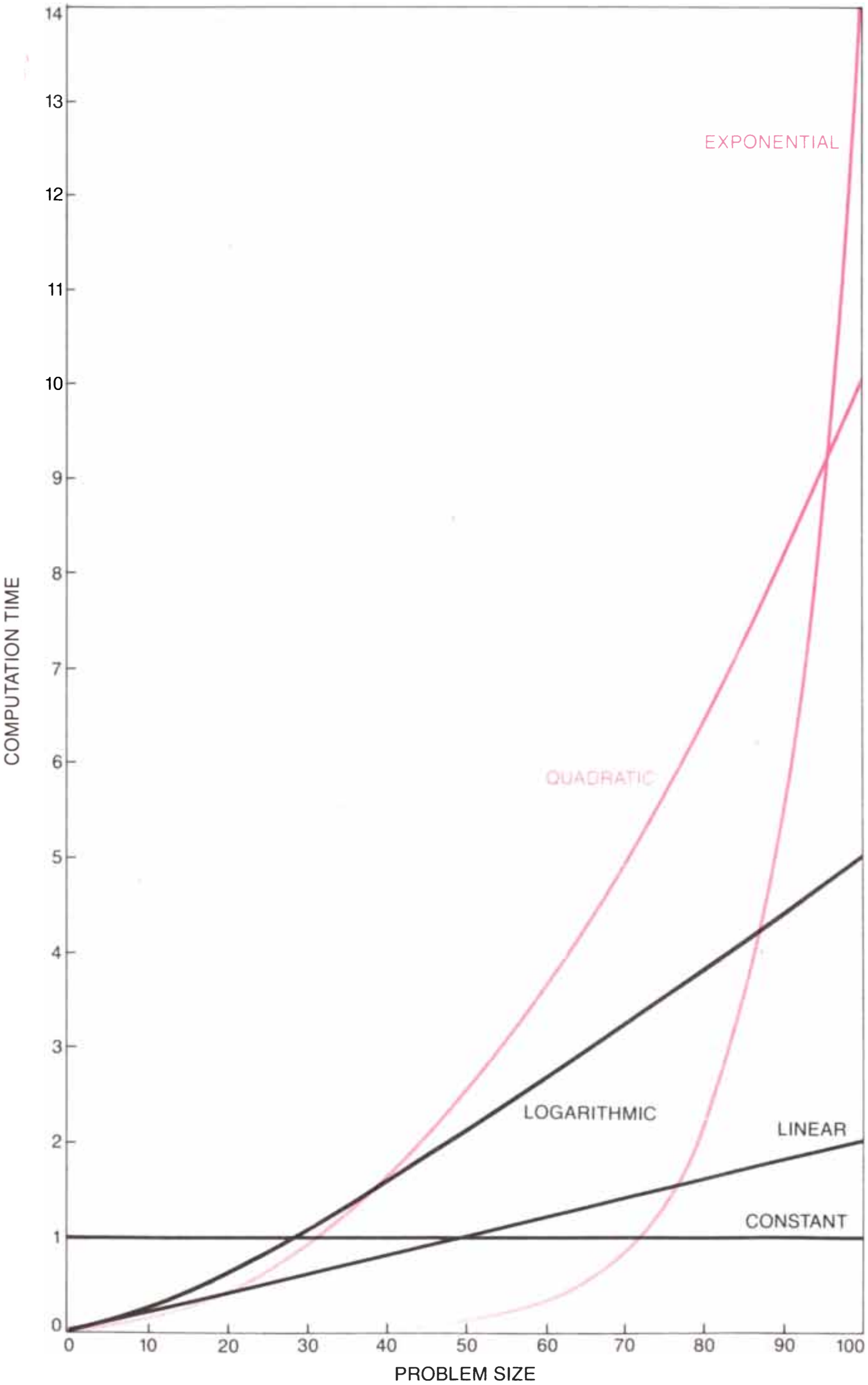
It is important to distinguish three phases of the sorting operation; I call them the preprocessing, the analog and the postprocessing phases. In the preprocessing phase the spaghetti is measured and trimmed; in the analog phase a simple mechanism sorts the rods; in the postprocessing phase the rods are removed one at a time, yielding the sorted sequence. All the gadgets described here require pre- and postprocessing. Indeed, so did the early analog computers, and



The spaghetti computer sorts a bundle of numbers in descending sequence



Finding the convex hull of a set of points in the plane



Several possible functions relating computation time to problem size

much research and development was invested in speeding up these phases.

There will be those who say, "SAG may be able to sort 700 numbers, but what about 7,000 or seven million?" The only reasonable way to deal with questions of this kind is to mention SUPERSAG, a modified fork-lift truck capable of picking up seven million pieces of carefully trimmed (extralong) uncooked spaghetti and slamming them sideways against a brick wall.

There will be others who say, "I can sort 700 numbers faster than SAG can. I'll do it all with pencil and paper and I'll finish before the spaghetti is even trimmed!" Sadly for SAG, this remark is probably true. Suppose it takes one minute to read a number from the unsorted sequence, measure a piece of spaghetti to that length, cut it and insert it into the bundle. Suppose further it takes 10 seconds to remove and measure each piece of spaghetti after the (one-second) slamming operation. It will then take SAG more than 13 hours to sort the 700 numbers, with all but one second of the time being spent in preprocessing and postprocessing. The challenger, on the other hand, sorts the sequence by scanning it, selecting the largest number on each pass, recording it and stroking it off the sequence. It takes him a tenth of a second to scan each number, and thus he needs (700 + 699 + ... + 2 + 1)/10 seconds to sort the sequence. This works out to 175 minutes 15 seconds, a clear victory for the challenger. Will the wonderful, all-at-once quality of the analog phase be completely undone by the lengthy pre- and postprocessing phases? Not quite.

Suppose the human sorter becomes cocky and challenges SUPERSAG to a seven-million-number sorting duel. SUPERSAG would need some 15 years, whereas the challenger would not finish for almost 74,000 years! SUPERSAG's superiority can be explained by examining the way the speed of a computation depends on the size of the problem. The slamming of the spaghetti against the wall is said to be a constant-time operation: it is essentially independent of the size of the bundle. The pre- and postprocessing phases are linear-time operations: they grow longer in simple, linear proportion to the size of the sequence of numbers. The human sorter's task grows much faster. He must inspect each remaining member of the sequence on each pass through it. Even though the sequence gradually shrinks, the total number of inspections goes up as the square of the size of the sequence; the sorting is said to take quadratic time. Sooner or later a linear-time procedure is bound to beat a quadratic-time one.

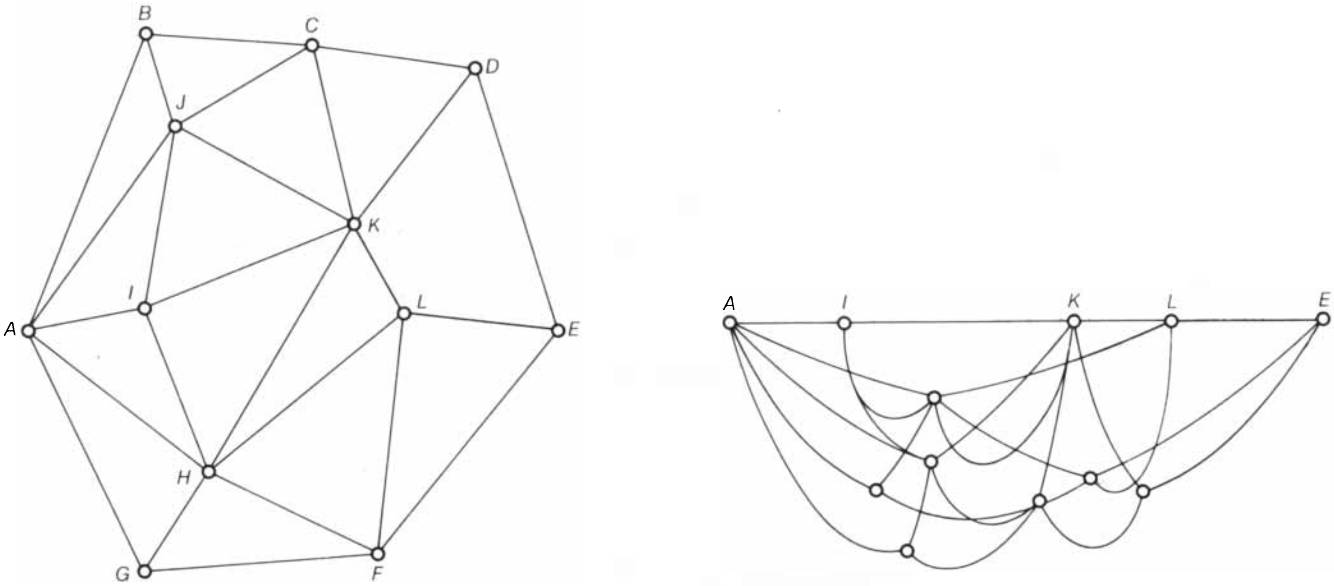
Even with its lengthy pre- and postprocessing phases, a large enough SAG machine could outsort a modern digital

computer employing the fastest sorting algorithms. These require on the order of $n \log n$ steps, where n is the size of the sequence and log represents the logarithm function. Linear time is certainly superior to this in principle, but one shudders to imagine the size of the spaghetti gadget needed to win such a contest. SUPERDUPERSAG would have to be constructed in space and slammed against the moon.

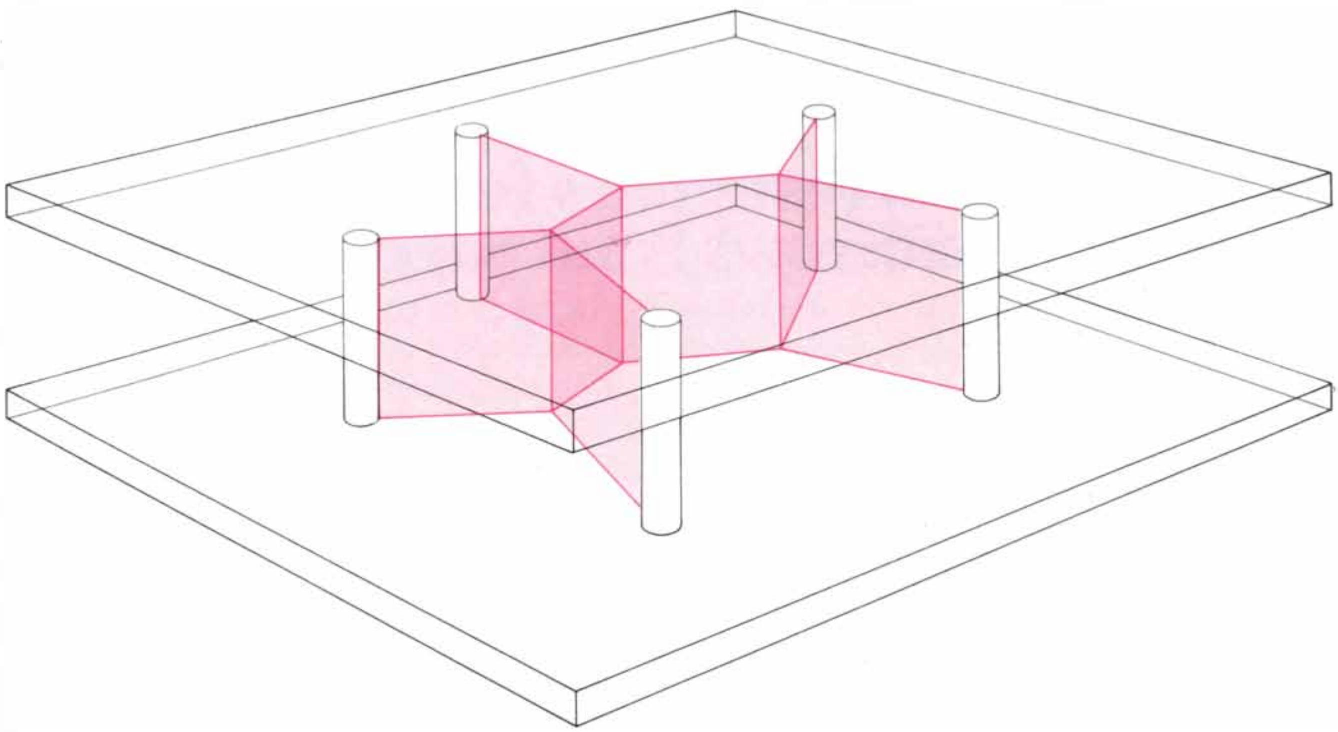
The next gadget in my collection computes the convex hull of n points in the plane. The convex hull is just the smallest convex region containing all n points. It is entirely defined by its boundary, a polygon that has one of the points at each vertex. The gadget that computes the boundary is made from a large board, some nails and a rubber band. I call it RAG, short for Rubber Band, Nails and Board Analog Gadget. It would have been nice to include "nails and board" in the acronym, but one would end up with a grotesque name such as RUNBAG.

To set up RAG simply drive n nails into the board at positions corresponding to the n points in the plane. Then pick up the rubber band, stretch it into a large circle surrounding all the nails and release it. The rubber band will snap into place, precisely defining the polygonal boundary of the convex hull.

Here again a linear amount of work precedes the analog operation of releasing the rubber band. It will take a certain number of seconds to determine the position of each nail and then to drive it into the board. Once the rubber band has been released, noting the ver-



An analog device for finding the shortest path between two vertexes in a graph



A soap-film solution to the minimum Steiner-tree problem for five points in the plane

texes of the convex hull takes somewhat less than linear time. Only the nails touched by the rubber band need to have their position recorded.

The fastest digital algorithm known for finding the convex hull requires on the order of $n \log(\log n)$ steps. This is so close to being linear that perhaps only a RAG machine the size of the solar system would be able to compete with a digital computer running the algorithm.

The function of a third gadget is to find the shortest path joining two vertexes of a graph. In this context a graph is a network of lines, or edges, joining the points called vertexes. In some graphs the edges can have different lengths, and it is this kind of graph that serves as input to STAG, an analog gadget that uses string to represent graphs. Specifically, each vertex is represented by a small brass ring. If two vertexes are joined by an edge in the graph, the corresponding rings are connected by a piece of string cut to the right length and supplied with a hook at each end.

To find the shortest path between the vertexes u and v in a graph, pick up the network by the rings u and v, holding one ring in each hand. Then pull the network taut. Instantly the shortest path stands out as a sequence of taut strings at the top of the network; all the strings representing edges that are not in the shortest path remain more or less slack [*see upper illustration on page 22*]. If the rings are labeled with the names of the vertexes they represent, one can now read off the labels along the shortest path.

If the size of a graph is measured by n, the number of vertexes, both pre- and postprocessing require at most a linear number of steps. The analog phase of the computation is as usual virtually instantaneous. The fastest digital algorithms known for the problem take on the order of n^2 steps.

It has been mildly irritating to include the pre- and postprocessing phases in analyzing the relative speeds of these gadgets, but honesty compels me to include them as part of the overall operation. How else could one specify a problem or interpret the gadget's output?

Some gadgets require no processing at all because they are incorporated into a system that uses the results directly. Two examples that come to mind are the needle-sorter once widely used in libraries and a trick for balancing a plate of food on one finger. In the needle-sorter a set of cards with notches and holes along one edge serves to show which books are due on a given day. The cards are stacked and a long needle is inserted into the hole corresponding to that day. When the needle is lifted, only the cards with holes at that position come with it. The notched cards slip off the needle and remain in the stack.

The balancing trick was shown to me by mathemagician Ronald L. Graham of AT&T Bell Laboratories. Graham begins by holding aloft a plate of food on a thumb and two fingers, widely spaced. As he draws the three digits together the plate's center of gravity remains between them because the digit supporting the least weight slides most easily. The final intrusion of another finger supports the center of gravity well enough to balance the plate. Graham warns beginners to practice the trick carefully before demonstrating it at Thanksgiving dinner.

Up to now I have applied gadgets only to problems that already have a reasonably fast algorithmic solution. Such problems are said to have polynomial-time complexity, because the number of steps needed to solve a size-n instance of a problem can be expressed as (or at least is bounded by) a polynomial function of n. For example, the solution time might be proportional to n itself, to n^2, to $n \log n$ or to n^{27}. There are other problems, including some of practical importance, for which no polynomial-time algorithm is known; the best algorithms seem to require an amount of time that grows exponentially with the problem size. Typically the solution time is proportional to 2^n, a function that increases faster than any polynomial. For a large instance of such a problem, or even for one of moderate size, the time needed is exorbitant. Why not try to solve some of these difficult problems with a gadget?

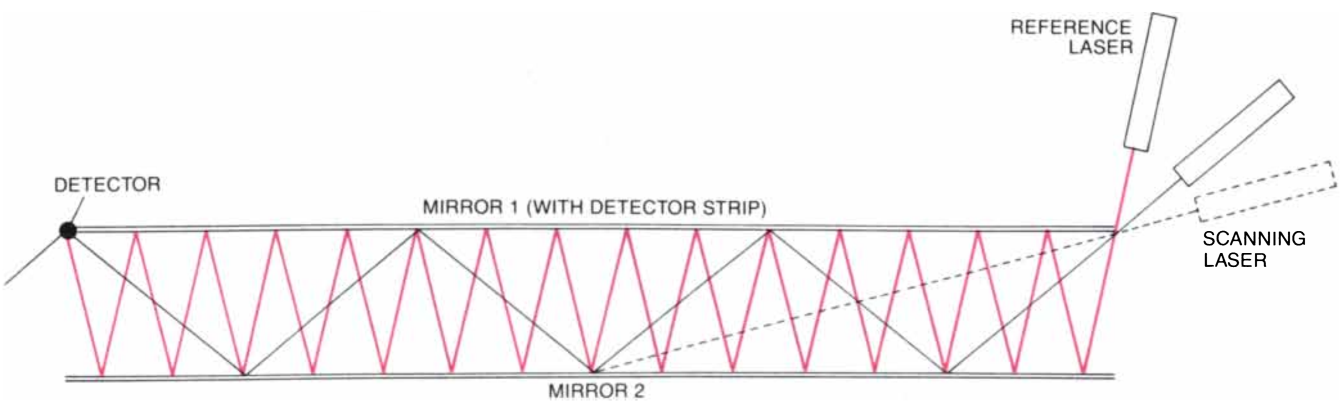
One candidate problem is to find the longest path joining two points in a graph, which turns out to be much harder than finding the shortest path. Indeed, the problem is said to be *NP*-complete, a property that appears to condemn it to eternal algorithmic intractability. (Readers who would like to know more about *NP*-completeness, and who do not mind an occasional bit of mathematical notation, are urged to consult the excellent book *Computers and Intractability: A Guide to the Theory of NP-Completeness*, by Michael R. Garey and David S. Johnson of AT&T Bell Laboratories.)

On occasion a little force must be brought to bear on a problem. Take the network of strings that was stretched taut to solve the shortest-path problem. When you pull on it even harder, first one of the strings breaks, then another. Eventually, just before the network falls into two pieces, all the strings that remain intact are taut. You have solved the longest-path problem.

Or have you? The method is effective for some networks but not for others. Readers may enjoy discovering examples of both kinds of graph. At each stage in the stretching where more than one string is taut, assume the worst about which one breaks.

Perhaps one should have known better than to attempt a snappy analog solution to an *NP*-complete problem. The theory of computability, however, says only that an *NP*-complete problem is hard for a digital computer to solve; there is nothing to indicate that it should not yield to analog methods. Therefore let us try again.

The minimum Steiner-tree problem asks that n points in the plane be connected by a graph of minimum overall length. The task is virtually the same as



The Laser Analog Gadget demonstrates that 15 is not a prime number

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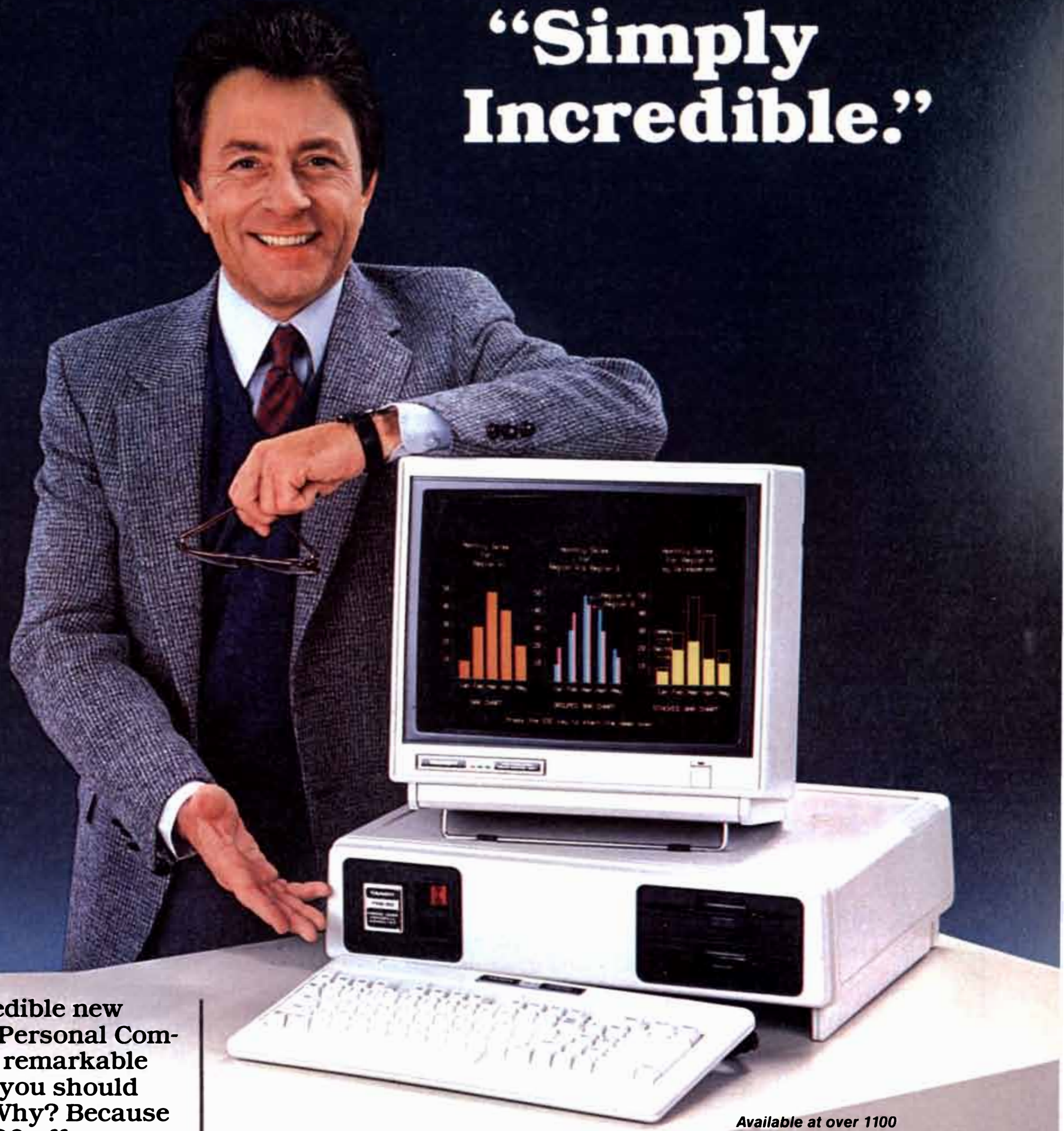

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that of connecting n towns by a system of roads whose total length is a minimum. One is allowed to take as vertexes of the graph not only the n original points but additional ones as well, which represent crossroads in the countryside, so to speak. It is not hard to see that the minimum graph must be a tree: a graph without closed loops. It turns out, moreover, that any additional vertexes in the minimum tree are joined to three other vertexes by edges making angles of 120 degrees with one another [*see lower illustration on page 22*].

The minimum Steiner-tree problem is *NP*-complete, and there is no algorithm known for it that requires fewer than 2^n computational steps (where n is the number of vertexes). Nevertheless, there is a strange device I call the Bubble Analog Gadget that seems to find a soap solution to the problem. Attach two parallel sheets of rigid transparent plastic to a handle and insert pins between the sheets to represent the points to be spanned. Now dip the gadget into a soap solution and withdraw it. There before your eyes is a soap film connecting the n pins in a beautiful Steiner-tree network.

Joy at the appearance of this solution is premature, however. How can one be certain that the tree generated is the one of minimum length? As it happens, the soap film always creates the shortest possible network for a given topology, but there may be another topology in which a still shorter tree could be formed. Depending on the configuration of pins and on the angle at which the gadget is withdrawn from the solution, the length of the film network may or may not be the absolute minimum. Once again an attempt to solve an *NP*-complete problem by analog methods has come to nought.

One of the most famous computational problems is to decide whether a given integer N is composite or prime. (If it has factors other than N and 1, it is composite; otherwise it is prime.) There is a very fast analog solution to this problem based on LAG, the Laser Analog Gadget. Set up two parallel mirrors, *M1* and *M2*, and two lasers so that both lasers bounce light back and forth between *M1* and *M2*, as is shown in the illustration on page 24. The angle of one laser is adjusted so that its light bounces N times from each mirror and finally strikes a detector at the end of *M1*. The second laser is placed in such a way that its beam is initially coincident with that of the first laser, but the second beam is subsequently swept through a range of angles.

As the angle of the second beam changes it periodically strikes the detector at the end of *M1*. The mirror *M1* also has a detection strip running its length, so that whenever two beams strike the same point, the coincidence can be detected. A simple electronic circuit monitors both the detector at the end of the mirror and the detection strip. If they report a simultaneous coincidence, the circuit turns on a light. The signal indicates that the number is not prime but composite. For there to have been a double coincidence the second laser must have bounced its light n times off the mirror *M1*, and n must also divide N evenly.

When speaking of the difficulty of deciding whether a number N is composite or prime, one must be careful about measuring the size of the problem. If the size is defined simply as N, there are digital algorithms that can solve the problem in polynomial time. It is generally considered fairer, however, to state the size as log N, because this is the length of the string of digits needed to represent N. By this measure no one knows whether the composite-prime decision problem is *NP*-complete or not. Based on the success of the LAG computer and the failure of other analog gadgets in solving intractable problems, might one conjecture that the problem is not *NP*-complete?

Throughout the foregoing discussion I have dodged the important issue of the feasibility of constructing gadgets such as SAG, RAG, STAG, BAG and LAG. Although each of the gadgets can be built and persuaded to work, after a fashion, on small problems, it would be silly to suggest that one construct them with serious computations in mind. Yet, considered in the context of an ideal world in which ideal materials are available, each gadget works, by definition, exactly as described. It is a fascinating question to pursue (in this ideal realm) just what analog computations are possible.

I would be interested in hearing from readers with other gadgets to describe. As things stand, I do not know who invented either of the first two gadgets described here; they are part of computer-science folklore. The string gadget seems to have been invented by Marvin L. Minsky and Seymour A. Papert of the Massachusetts Institute of Technology. The bubble gadget I found in Cyril Isenberg's wonderful little book *The Science of Soap Films and Soap Bubbles*. The laser gadget is my own invention.

The laser gadget reminds me of a little problem readers might enjoy pondering. There is a square box in the plane and its interior walls are lined with perfectly reflecting mirrors. In the ideal realm mentioned above it would be possible to remove the point at one of the corners and to shine a one-dimensional beam of laser light into the box through this vanishingly small hole. The resulting gadget computes something quite profound about the angle of the beam. The answer depends on whether the light ever emerges from the box, but what is the question?

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The Council's final report was issued in January. By that date Connecticut had attracted nearly 650 high-tech companies employing more than 148,700 workers. Connecticut ranked among the top three states in America in the percentage of manufacturing jobs in advanced technology, the number of industrial research laboratories per capita, the number of patents granted per capita and the number of engineers per capita. These were some of the strengths on which the Council would build.

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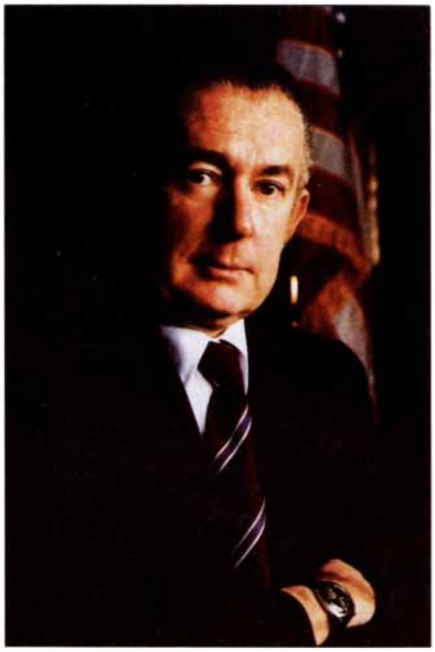


Connecticut Governor William A. O'Neill is the state's top manager —and chief salesman.

technologically creative people seem to need. Shelton is symbolic of what has been happening in Connecticut, although corporate growth in advanced technology is occurring across the state's 5,000 square miles.

"The 'new Connecticut' is a balanced blend of strong, growing industries, aided by the fast-developing communications field and other high-tech areas," says Don Klepper-Smith, corporate economist at Southern New England Telephone Company (SNET). "The communications industry now employs approximately 25,000 in the state, about 1.4 percent of the manufacturing work force." After more than a century of service to Connecticut industry and consumers, SNET entered the newly unregulated marketplace in January, 1983.

At the same time, SNET guided its core business, the basic Connecticut Telephone Business, through a number of changes and achieved the best financial year in its recent history. Revenues reached nearly $1.2 billion.

SNET president and CEO Walter H. Monteith, Jr., emphasizes that "while our new developments have received the most media coverage, we remain fully committed to providing service to 1.3 million Connecticut customers." To meet large Connecticut businesses' need to move vast quantities of voice, data and video images over the same circuits, SNET has pioneered in the installation of state-of-the-art fiber optic transmission. By the end of this month, a $15 million fiber optic route, providing high-quality digital transmission in a cost-effective way, will be in service from Stamford to Hartford, the corridor along which Connecticut's large businesses are clustered. This network will reach 60 to 70 percent of SNET's customers.

SNET's initial unregulated venture was its Sonecor Systems division. The firm has a carefully planned strategy, described by Monteith. "We believe that to move too slowly amid tumultuous change and intense competition in the communications industry represents a greater risk than any other we would encounter." In September of 1983 Sonecor Systems introduced the first information management system that completely integrates computer and communications technology. The Sonecor System 2001 is designed for firms with 200 to 22,000 users.

To date, there are about 25 of these systems on order or in place. Two of SNET's first customers were Olin Corporation in Stamford and Stanley Works in New Britain. A 2001 will also provide communications for New Haven's Science Park. A second key 1983 development was LightNet, a joint venture with the CSX Corporation, the nation's largest transportation and natural resource company. LightNet combines SNET's experience with fiber optic technology with 5,000 miles of CSX Railroad right-of-way.

Another important SNET offering is cellular mobile radio service, which is a series of short-range radio transmitters covering geographic "cells." This advanced technology makes high-quality phone service also highly portable. SNET has received its first construction permits from the FCC for the Hartford and New Haven areas and expects to be in business before the end of 1984.

Monteith, summing up SNET's passage into a new competitive era, says, "We have *relearned* that as our company moves into the future, we cannot move away from the fundamentals that have given Southern New England Telephone its strength. We enter into new ventures with the full understanding that our first responsibility is to Connecticut. We go forward with the same commitment to quality that has characterized our business for the past century."

In Connecticut, innovation is a tradition. But even Connecticut Yankee ingenuity can benefit from financing to turn that spark of genius into reality. In Connecticut, help for the entrepreneur can come from CPDC—the Connecticut Product Development Corporation, the first state agency of its kind in the nation.

Through specially tailored programs, CPDC helps Connecticut entrepreneurs meet the ever increasing costs of designing, developing and marketing new products and processes. CPDC Risk Capital Financing can cover the costs of developing a new product or process from initial concept through fabrication of a prototype. CPDC Innovation Development loans provide low-cost working capital to get products manufactured, marketed and distributed.

CPDC is a not-for-profit state agency; it does not require equity participation or a management position in exchange for financing. Risk Capital investments by CPDC are repaid by limited royalties on successful sales of financed products. Innovation Development loans are direct loans made by CPDC at below-market interest rates. Either or both programs may be utilized.

New products equal new jobs. Since its formation in 1973, CPDC has played a key role in the state's aggressive efforts to expand Connecticut's job base through economic diversification. CPDC is the centerpiece of Governor O'Neill's high-technology strategy for the 1980's: keep Connecticut industry competitive, growing and important for new technologies.

Millions of CPDC dollars have made possible new Connecticut products as diverse as computer programs and bathroom scales, robot cutting instruments and car-top ski carriers, all resulting in hundreds of new jobs.

As of mid-1984, CPDC has delivered good performance to match its economic promise. Royalty income more than equals CPDC's operating-overhead expenses and is drawn from a score or more of developed products on the market. The corporation is enjoying an ever growing flow of new applications from companies that have learned that being in Connecticut is advantageous.

George Martin, president of OWL Electronic Laboratories of Old Saybrook, approached CPDC with a proposal for a new project two years ago. His firm was then four years old. "The members of CPDC's board of directors were all people in business or finance or the universities," Martin recalls. "In their regular jobs, they're subject to rules and influences that don't affect them at CPDC. Our proposal was weighed in a straightforward manner and the arrangement has worked out well for all of the parties involved."

David Coffin, chairman of Dexter Corporation of Windsor Locks, is the seventh-generation descendant of the founder of the firm; Dexter was founded in 1767 and is the oldest company listed on the New York Stock Exchange.

Harold V. Fleming is Dexter senior vice president for corporate development. "We work closely with the state," he says, "to review ideas and seek out new technologies appropriate for Dexter Corporation. We'll go anywhere to look at a promising commercial idea." Stiles Twitchell, a Yale graduate, reports to Fleming as manager of technical development. "We're in frequent contact with the Connecticut Product Development Corporation," Twitchell states. "They know us as an excellent prospective resource and we are always ready to talk with them."

The Connecticut Development Authority (CDA) is in its 11th year of developing public financing for private-sector job-generating investments.

Chaired by commissioner of economic development John J. Carson, CDA has arranged approval of $1.5 billion for 1,100 projects, which have created or retained nearly 125,000 jobs. CDA's excellent performance of its task is exemplified by Connecticut's jobless rate—one-third lower than the national average, and eighth lowest in the country.

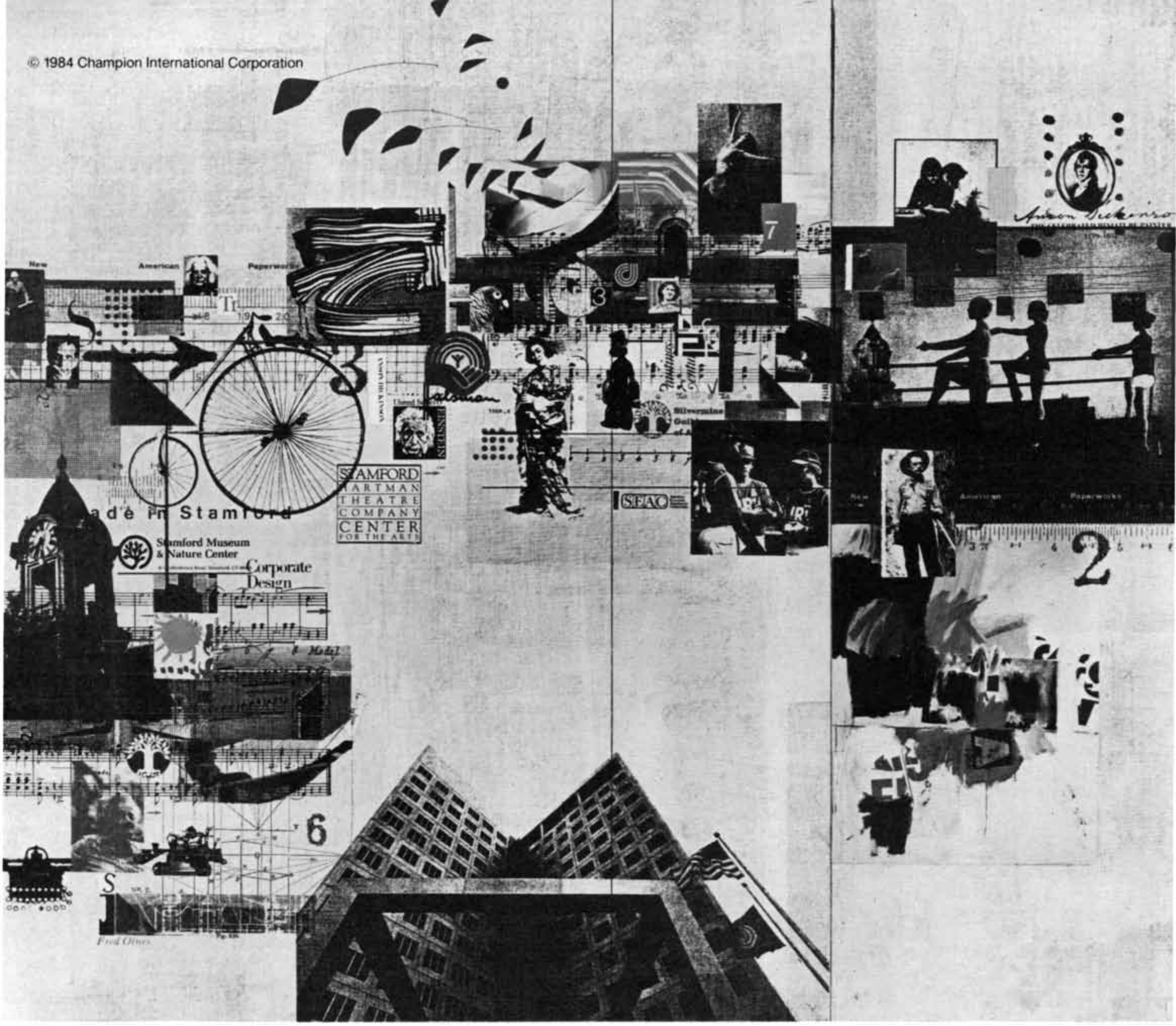
"Though the support of Connecticut's financial community may not be highly visible to the public, its commitment behind the scenes has made the whole job-creating process work," says CDA executive director Richard Higgins. "Connecticut's banks and insurance companies ... are, in many cases, the purchasers of CDA bond issues, and in other cases they are the lenders extending mortgage credit or construction, interim or matching-fund program financing."

TIE/communications has expanded in 12 years from a Greenwich garage to sales of nearly $300 million as a manufacturer of advanced-telecommunications equipment. Gerald Poch, president of its subsidiary Technicom International, attributes CDA's "aggressive assistance" as a key factor in TIE's corporate growth. Gerber Scientific employed CDA partial financing to add nearly 200 people to its work force in Manchester and South Windsor in just seven years. During the single year ending June 30, 1983, CDA financing programs for over 50 Connecticut companies totaled in excess of $400 million and 18,500 jobs.

Zygo Corporation, based in Middlefield, started up in the bedroom of a house on Wesleyan University's nearby campus. The company designs, manufactures and markets high-performance, laser-based, noncontact electro-optical measuring instruments and systems. Zygo president Paul Forman describes his company's beginnings:

"Our funding came partly from Wesleyan, partly from Canon in Japan and later from the Connecticut Development Authority." Zygo leases its 100,000-square-foot Middlefield facility under a net lease with CDA.

Most business and industry in Connecticut is electric-powered by Northeast Utilities, a holding company based near Hartford. The United Illuminating Company services the Bridgeport-New Haven coastal area. NU has concentrated heavily on proper management of the power needs of Connecticut industry; the utility has standing plans to use fuel cell technology, its existing and successful nuclear facilities and conservation to ensure that the state's present and future



Why should a forest products company be concerned about the quality of life in Fairfield County?

Although it's a long way from our forests, mills, and plants, Fairfield County is home to the 700 Champion people who work at our corporate headquarters in Stamford–and to their families and friends. In Fairfield County, and in all communities where Champions live and work, contributing to a healthy, vital social and cultural environment is, we believe, more than a nine-to-five job.

So Champion and Champion people are involved: in social services, in education, in community organizations, in the arts.

While we recognize that our first obligation is to remain a strong and profitable producer of building materials, paper, and packaging, we also believe a company's responsibilities include how the whole business is conducted, every day. In our complex and demanding world, that means corporations must strive to rise above the bottom line and consider thoughtfully the impact of their actions: on the communities where they operate and on the society as a whole.

The economic future of the nation–including Fairfield County–depends on strong and responsive business enterprises. And, in turn, the long-term viability of business is linked to how well it meets all its responsibilities to the society of which it is part.

That's why our company and our people are concerned about the quality of life in the communities where they live and work. Champion and Champions: Planting seeds for the future in Fairfield County.

Champion

Champion International Corporation

One Champion Plaza
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electric power needs will be met.

"I am interested in fresh, new ideas," says NU's young (44) chairman, Bill Ellis. "There is no inertia at Northeast when it comes to applying industrial methods to utility operations."

Chairman Ellis is also president of the Connecticut Economic Development Corporation, a consortium of industry leaders who work to keep Connecticut at the forefront of American economic growth.

"For technological growth to continue in Connecticut," says Lane DeCamp of General Electric's GEVENCO venture-capital unit, "the fundamentals must be there. Connecticut tends to attract the kind of advanced-technology firm that needs the state's triad of adequate financing, excellent management and access to markets."

GEVENCO is the largest of the fraternity of Connecticut venture-capital firms.

Bob Sorenson is chairman and CEO of Norwalk-based Perkin-Elmer and also a member of Governor O'Neill's High Technology Council. "Our company depends not on what we have been but on what we can become," Sorenson says. "Advancing the frontiers of technologies is the name of our game." Perkin-Elmer's Connecticut facilities extend from the manufacture of analytical instruments to computerized chemistry to optics for NASA's space telescope.

The Connecticut Technology Institute at the University of Bridgeport has been established to help incubate new advanced-technology industry. Both Perkin-Elmer and the High Technology Council were instrumental in building CTI, the only such facility in Fairfield County.

CTI is an attempt to provide a critical mass of personnel, research grants, financing, ideation and product development.

CTI's Technology Council includes 100 of the state's senior scientists and encourages the free flow of information about what is on the frontier of development between the laboratory, the classroom and the private sector.

Paul Phelpo, project director of the U.S. Congressional Office of Technology Assessment, says New Haven's Science Park "has all the best features .... In fact, if there's anything that's unique about it, it's the degree to which all of the parties to the game are participating." In Connecticut, cooperation among industry, academia and government is looked on as good business sense, with the Park as one case in point.

An interested and powerful coalition was assembled from among strong organizations already working within the state. The Science Park Development Corporation was created with two important goals: to create a center for high-technology economic activity and expansion, and to upgrade disadvantaged surrounding New Haven neighborhoods. Governor O'Neill, the Connecticut Office of Economic Development and New Haven mayor Biagio DiLieto hammered out a system of tax-based incentives that created an "enterprise zone" in the area. A $5 million venture-capital pool was formed. Yale University, which adjoins the new Park, contributed its own human and financial resources.

Yale made its Office of Cooperative Research available. Companies associating themselves with the new Park have access to Yale's research, libraries, student interns, laboratories and faculty. Linkages to advanced-technology industry are likely to prove substantial given the university's strength in computer science, medicine and the physical sciences. Says Mayor DiLieto, "The dynamism and creativity demonstrated by the entrepreneurs who will develop their businesses here represent the highest ideals of our free-enterprise system."

Olin Corporation, one of three dozen major international corporations headquartered in Connecticut, is responsible for much of what Science Park will become. Olin faced a problem common to other industrial leaders: departure

Scientific instruments are important to Connecticut's economy. Perkin-Elmer optics technology made NASA's space telescope possible.

Quality of Life

"Quality of life" is often cited by Connecticut companies recruiting managerial and technical personnel. Visitors find themselves surrounded by 300 years of living history amid some of New England's stunning scenery, ample recreational opportunities and a diversified cultural atmosphere. Along the Sound, one can spend days exploring Mystic Seaport with its *Charles W. Morgan*, last of the great wood whaling ships. There is live theater year-round at the Hartman in Stamford, the Long Wharf in New Haven, the Westport Playhouse and more.

The Berkshire foothills in northwest Connecticut offer excellent skiing and golf. One can spend the night at historic Under Mountain Inn near Salisbury, where enterprising Yankees hid naval supplies for the King's Rangers before the Revolution, and then canoe along the Housatonic.

One can walk the trails through the Mianus Gorge Reservation in northern Stamford and see woodlands that have remained untouched for three centuries.

"Of all the beautiful towns it has been my fortune to see, this is the chief," said Hartford resident Mark Twain. The capital city's huge insurance industry and several colleges and universities support a wide range of restaurants, opera, ballet, the Wadsworth Atheneum art museum, a symphony orchestra and acres of parkland.

"I was drawn first to the miles of rivers and streams, the glowing forest pools, and the meandering marshes and coastal inlets," writes photographer Steve Dunwell in *Connecticut—A Scenic Discovery*, whose cover photograph of the *Charles W. Morgan* appears above. Connecticut's coastline gives access to Manhattan's Broadway theatre district, less than an hour's drive from Stamford, and to the America's Cup races in Newport, Rhode Island, an equal distance from eastern Stonington.

One night during the War of 1812, British forces moved up the Connecticut River, pausing for their officers to dine comfortably at the Griswold Inn. Having paid their bill, they then set fire to the elements of the American navy anchored in Essex Harbor.

Save only for that last act, a Connecticut Yankee might duplicate both the trip and the dinner this very weekend.

from a community with which it had shared three-quarters of a century of life and work. The solution came from Olin's resourceful chairman and president, John Henske. A Yale graduate and former manager of the New Haven operation, Henske was determined to move honorably and responsibly.

So Olin donated all its land and buildings to the Science Park Development Corporation. Olin will maintain and secure the property until the Park can assume such tasks and has also loaned the Development Corporation $500,000 to renovate and adapt the complex.

Henry Chauncey, Jr., former secretary of Yale and president of Science Park Development Corporation, says, "We are very pleased that the Sonecor Systems division of Southern New England Telephone Company will install its new telecommunications system in the Park. This will give entrepreneurs and established firms access to a modern telecommunications system."

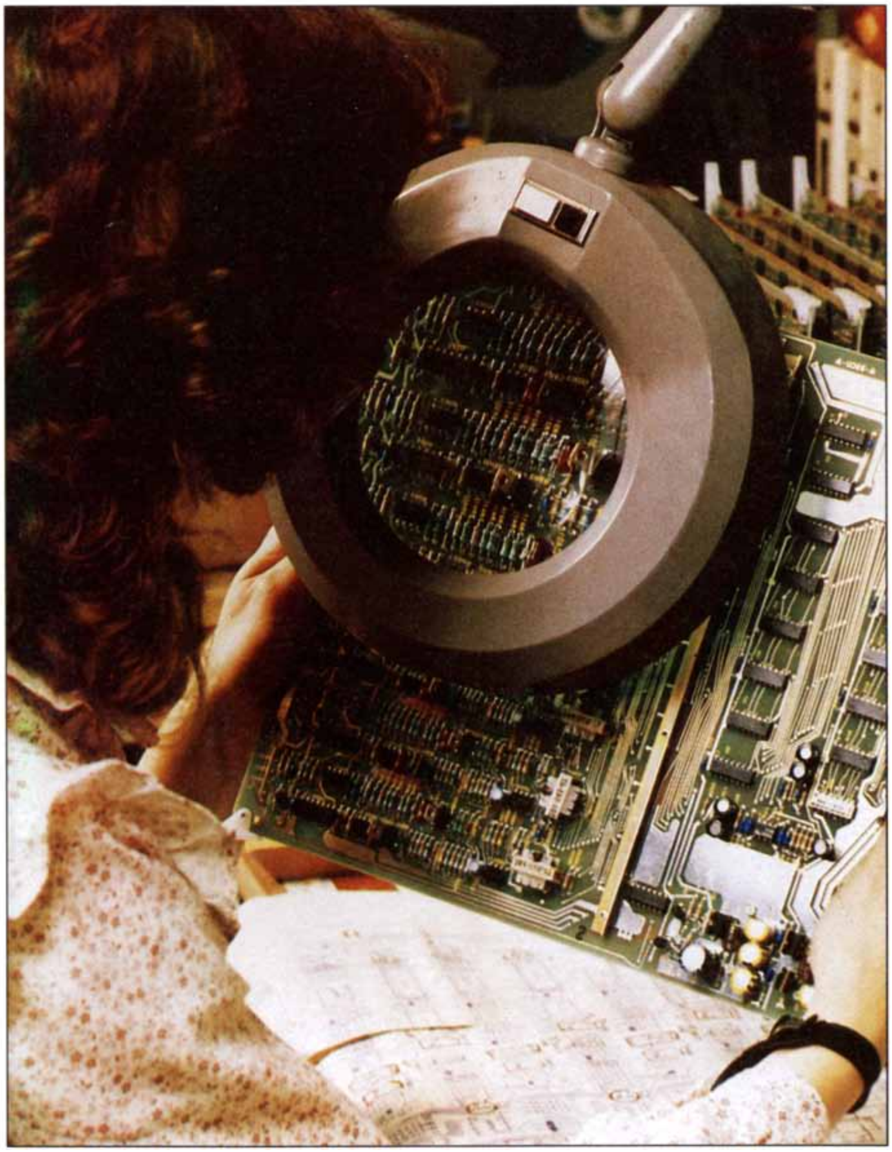
Says Hugo Kranz, Jr., of DataGraphics, another Park tenant, "We left Houston and chose Science Park to start up our company for three reasons: a university setting would encourage the interactive computer graphics technology in which we are interested, New Haven would provide a competitive operating cost advantage long term, and Connecticut would be an enjoyable place to live."

Science Park offers a variety of opportunities that demonstrate the O'Neill administration's commitment to strengthening the state's competitiveness in luring and nurturing advanced-technology industry and offering additional benefits to the high-technology firms already in place. Besides several million dollars for site improvement, the state Office of Economic Development has made marketing aid available. The state benefits as development attracts more and larger companies to the greater New Haven area.

"The relationship to Yale is key to our success," says Chauncey. "Virtually all of our embryo companies have some relationship to Yale—a faculty member, a laboratory, students—some sort of working together."

A. Bartlett Giamatti, president of Yale, agrees. "Science Park is a tremendously exciting venture that will help to revitalize the center of our city," he says.

The Rogers Corporation, founded in 1832 in Manchester, applies polymer chemistry and process technology to meet needs in electronics and other industrial markets for engineered



Connecticut's skilled people make advanced technology work. Above: Production under way at TIE/communications, Shelton.

materials and components. Rogers maintains a number of cooperative research programs with leading universities; a Rogers director, Leonid V. Azaroff, is also director of the Institute of Materials Science at the University of Connecticut, 20 miles from Rogers' corporate headquarters.

UConn's Institute of Materials Science represents a successful example of Connecticut Yankee ingenuity. "The mission of the Institute," writes Azaroff, "is to foster quality graduate programs in the materials sciences and to provide graduates suitably trained to meet the needs of Connecticut's materials-based industries.... Twenty-one chief scientific officers of Connecticut's leading technological corporations serve on the advisory board."

UConn has come a long way since its founding as a land-grant college in 1881. Some 24,000 students now populate UConn's main Storrs campus and regional campuses at Avery Point in Groton and at Hartford, Stamford, Torrington and Waterbury.

UConn president John DiBiaggio, a member of Governor O'Neill's High Technology Council, reflects on the university's role as a catalyst in Connecticut: "To really take advantage of our resources, we need more rapid technology transfer, a hand-in-glove process. I believe we will see the period of time between research and application abbreviated. There is incredible potential at UConn and I feel very positive about the new ways it's beginning to be used."

"There's obviously a broad awareness of the 'megalopolis' that stretches from Boston to Washington, but not so many people know there's a gap right in the middle of it," states Russ Meyerand, vice president for technology at United Technologies Corporation. "That gap is Connecticut, and there's room here for a lot of growth, activity and expansion."

United Technologies, based in Hartford, has become one of the world's largest companies, with over $14 billion in 1983 sales and over 190,000 employees worldwide. UTC's Pratt & Whitney division in East Hartford is a major state employer in the technologically sophisticated aero-engine industry. Norden Systems develops radar and guidance products in Norwalk. Hamilton-Standard manufactures astronaut space suits in its complex near Bradley International Airport. Otis Elevator is headquartered in Farmington. The famous Sikorsky helicopter is manufactured adjacent to the Merritt Parkway in Stratford. A new Building Systems division, merging the technologies of UTC's Otis people-movers and Carrier temperature-control operations, develops "intelligent buildings."

"High technology is in fact the common denominator of all we do," Meyerand states. A physicist himself and holder of 20 patents, Meyerand rapid-fires his firm's broad commitment to applied and basic research, in cooperation with academia and through UTC's own East Hartford Research Center. "We have a number of professional people who are adjunct professors at local colleges and universities. We're close to UConn's Institute of Materials Sciences. We've funded 10 science fellowships in Wesleyan's teaching program. I'm on the executive committee at the Hartford Graduate Center, which started several years ago as an extension of Rensselaer Polytech in New York but now has become a separate institution."

The United Technologies Research Center employs well over 1,000 scientists and engineers in four key areas: electronics and electro-optics, materials technology, power and industrial systems technology and manufacturing technology, particularly industrial lasers. The Research Center was founded in 1929 in support of UTC's aircraft operations and has since paced the company's expansion and diversification. The Center's charter is clear: conduct basic and applied research that will help to guide the corporation's technological future.

The Center resembles an engineer-

ing campus at a large university. Huge wind tunnels facilitate aircraft and engine design. Elsewhere, metals are tested against extremes of heat and stress. Diesel-engine research and experimentation, laser spectroscopy, computer-aided manufacturing and robotic automation, advanced ceramics and metals composites, and energy and communications systems for buildings are all subjects of ongoing research.

Five years ago, Meyerand received the Eli Whitney Award from the Connecticut Patent Law Association in recognition of his scientific achievements. United Technologies is the true successor to inventor Whitney in Connecticut. Through its R&D facilities, its manufacturing and other sites across the state and chairman Harry J. Gray's constant focus on well-managed technology, the Whitney tradition continues strongly in the 1980's.

Ridgefield, in upper Fairfield County, is a small, classically picturesque New England town. In late 1977 Ridgefield attracted Dr. Harvey Sadow, president of Boehringer Ingelheim, an American specialty pharmaceutical and health-care company. Sadow became involved in Connecticut education by renovating and occupying the columned, red-brick former Ridgefield High School as Boehringer Ingelheim's headquarters. By 1979 the company had completed a research center for the discovery and development of products to diagnose and treat disease on 193 acres of land at the Ridgefield-Danbury town line. At present some 225 chemists, pharmacologists and other scientific personnel staff the center, along with over 600 personnel at Boehringer Ingelheim's manufacturing and headquarters facilities.

Sadow encourages his people to undertake university research and service. Dr. Kurt Freter, head of the firm's chemistry department, is also adjunct professor of chemistry at Wesleyan. Other employees share their expertise with students at Fairfield University, Western Connecticut State and schools in nearby New York.

"Advanced technology in Connecticut is logical," says Dr. Sadow. "It's here because of the people—they're the attraction."

Fairfield County has displaced Chicago as the second most popular area for corporate headquarters in America. GE, Xerox, Olin and Champion International are among 20 of the largest U.S. industrial corporations headquartered in Greenwich, Stamford and surrounding towns.

Albert Phelps, Jr., owner-developer of Merritt 7 Corporate Park in Norwalk, has been part of Fairfield's growth for years. Merritt 7's strategic location 35 miles northeast of New York City has attracted firms such as IBM, GE and Merrill Lynch. The Park adjoins the Merritt Parkway.

"Every productive facility or amenity has been built into Merritt 7," Phelps says. "Business needs a lot of things beyond office space."

Champion International Corporation, one of the nation's largest paper and forest product companies, is headquartered in Stamford at One Champion Plaza, designed by the renowned architect Ulrich Franzen. About 40,000 people pass through the Champion headquarters lobby each year—not on company business, but to visit the Whitney Museum of American Art, Fairfield County. This branch of the Whitney is the first to be outside New York and is supported by Champion. "We believe the Whitney project represents the kind of partnership modern corporations need to establish with other institutions in our society," says Champion chairman Andrew Sigler.

The world's first passenger bus was manufactured in Sweden by Scania-Vabus in 1911; soon the latest models will be transporting people in cities across America. "We look to about 200 units per year," says Saab-Scania of America vice president and general manager Rolf Sundeman, "and we'll assemble them here in Orange."

Saab-Scania evaluated many North American locations before selecting Orange. "I received telephone calls while I was still in Sweden," Sundeman recalls. "Some Canadian developers flew over to talk to me.

"But Governor O'Neill assured me we would be both welcome and productive in Connecticut. And this has proved to be so."

New York City, Boston's Route 128, Albany, Long Island and Providence all fall within a 100-mile radius of Hartford's Bradley International Airport. The airport, equipped to handle over 160 scheduled flights daily plus corporate and charter service, benefits from its inland location: it rarely closes due to weather conditions.

Ray Fitzgerald is general manager of the growing Combs Gates service center at Bradley; Combs Gates, a division of Gates Learjet, provides fueling and other ground service for scheduled and private aircraft. "We're expanding to meet increasing demands from corporate and industrial customers," Fitzgerald states. "We maintain the arriving and departing corporate aircraft and service their crews. We've outgrown our current quarters; we're building newer, larger service facilities on the airport grounds nearby."

The Thames River flows from Norwich down to Long Island Sound, through quaint towns such as Uncasville and Gales Ferry and past the tall ship *Eagle* berthed at the U.S. Coast Guard Academy in New London. Across the Thames from New London, Groton's waterfront harbors a different sort of vessel: Trident-class nuclear submarines, built by the Electric Boat division of General Dynamics. EB, with a Connecticut staff of over 20,000, occupies about 100 acres of riverfront. Its first Groton-built submarine was contracted for by the Peruvian navy in 1924.

"New technology is obviously important to us," says assistant general manager Emmett Holt. "We work with universities in Connecticut and across the nation. We assign specific projects to UConn. We've even arranged for the University of New Haven to conduct degree programs on-site here, for our employees."

Pfizer Central Research has just formally opened a 110,000-square-foot, $50 million expansion of its Groton facility adjoining Electric Boat. The worldwide research-based company attained sales of nearly $4 billion in 1983, with research and development well in excess of $200 million at centers in England, France, Terre Haute and the important 137-acre Groton site.

Pfizer's presence in Groton dates to 1948, when Connecticut's economy was adapting to the falloff of war-related industry. Formerly a shipyard, Pfizer's Groton compound now encompasses 75 buildings and employs 3,000 people in the firm's chemical, central research, quality-control and Howmedica divisions. Howmedica makes orthopedic implants.

In the new expansion, 86 biology and chemistry laboratories have been added to Pfizer's Groton complex. Scientists can jog through the campus-like facility at noontime and extend their exercise to the adjacent Avery Point campus of UConn's Marine Sciences Institute.

The presidents of the University of Illinois and the Memorial Sloan-Kettering Cancer Center serve on Pfizer's board. Pfizer president Gerald Laubach, himself a chemistry Ph.D., has encouraged support of chemistry research at New London-based Connecticut College. "The relationship with Pfizer has been a wonderful one for us," says college president Oakes

Ames. "We hope Pfizer has found benefits here as well."

Connecticut has emerged as a site of preference for a growing number of biotechnical companies and institutions. Richardson-Vicks and Chesebrough-Pond's are both Fairfield County-headquartered firms with sales in excess of $1 billion. Bristol-Myers' world-known Clairol products have been manufactured in Stamford for years. The $3 billion firm is becoming a world leader in pharmaceuticals as well. In December, the architectural design was decided for the firm's new consolidated pharmaceutical research center in Wallingford. The $45 million first stage of the center will house basic research for anti-infective, anticancer and central nervous system therapeutic areas; it will be completed next year.

Wallingford is just 10 miles north of the Yale University School of Medicine, with which Bristol-Myers signed a unique agreement in 1983. For the next five years, Yale scientists will share with Bristol-Myers researchers their insights into the mechanism of cancer cell development and spread. "We want to develop some entirely new approaches," says Dr. Alan Sartorelli, chairman of Yale's department of pharmacology and director of Yale's Comprehensive Cancer Center. "We have many new leads."

Connecticut technology means submarines, electronic computing equipment, optics, industrial controls, telecommunications, surgical appliances, office machines, scientific instrumentation, guided missiles, guidance technology, helicopters, chemicals, fiber optics, semiconductors, photo equipment, control instrumentation and ophthalmic equipment, made by Connecticut-based companies whose names are a kind of litany of technology leadership. Burndy (electrical connectors), Olin (industrial chemicals), Pitney Bowes (mailing devices and office machinery), Alderson Research (medical equipment), Bunker-Ramo, Vitramon, Frigitronics, Branson Ultrasonics, Notsuko America, Samarius, Kaman, Emhart, GE, General Digital, Loctite, Data Switch, Gerber Scientific, Ex-Cell-O, Mite, Combustion Engineering, Union Carbide, Colt, Surgicot, Echlin, Sigma Instruments, American Cyanamid, Unholtz-Dickie, General Data-Com, Unimation, Holgrath, Arrow Hart, Boehringer Ingelheim, Qualitron, Canberra, Bicron Electronics—some are household words, others are known only in limited fields.

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Connecticut's corporate concentration results from good location, amenities and the "hiving" of already well-established industrial activities.

It is the Connecticut Yankee's unusual ability to turn things around, to take the familiar and bond it to new ideas and markets, that makes Connecticut's advanced-technology industry work. Old Eli Whitney would have been impressed.

"Connecticut: Catalyst for Corporate Growth" was written by Charles Stokes with contributions from Henry Chauncey, Jr., and David Driver of the Connecticut Department of Economic Development. Graphics: Sherin & Matejka, New York. Photo credits: Conn. DED, Steve Dunwell.

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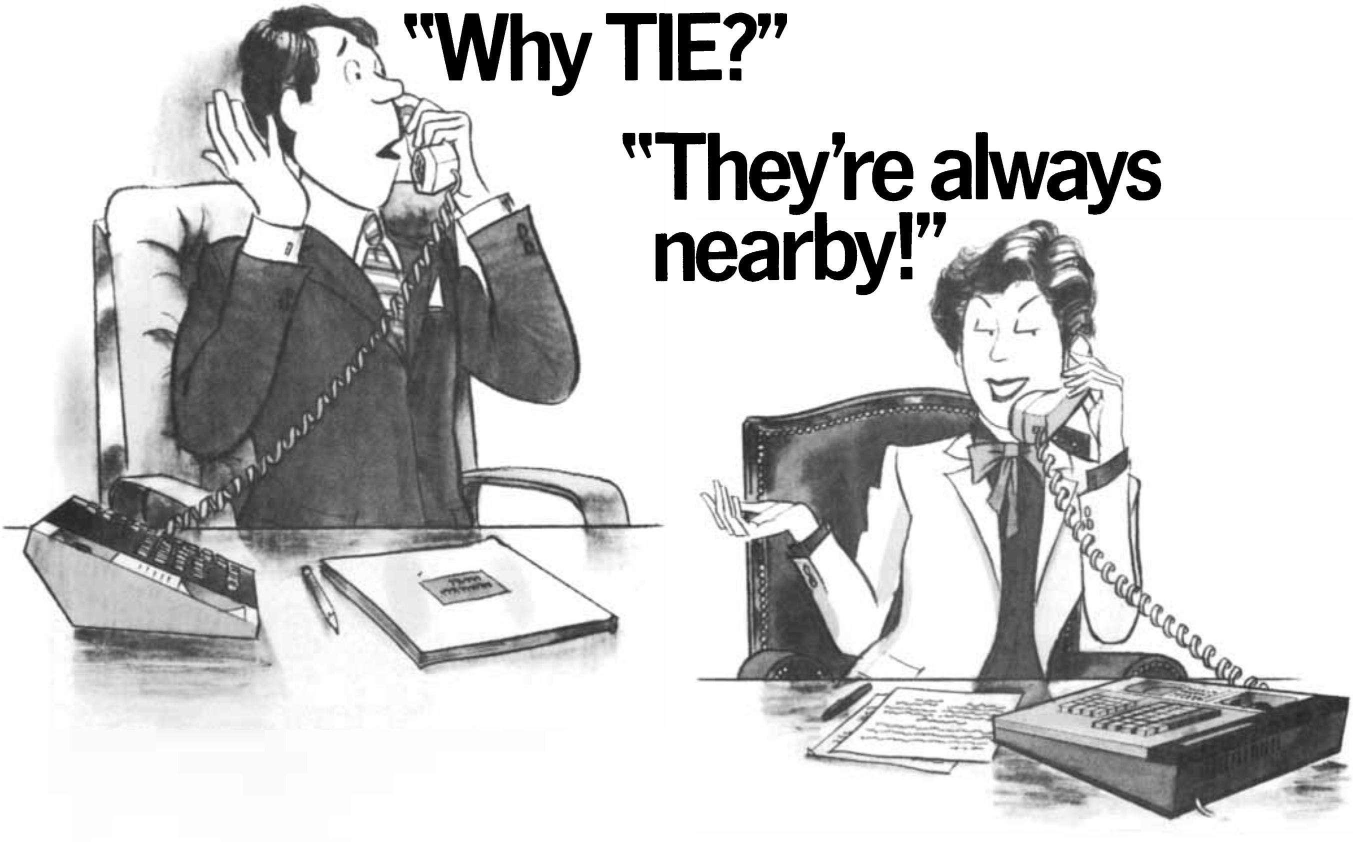

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BOOKS

Trace elements and nerve, Rutherford, sculpturing surfaces, a world of beers

by Philip Morrison

NEUROBIOLOGY OF THE TRACE ELEMENTS, VOLUME 1: TRACE ELEMENT NEUROBIOLOGY AND DEFICIENCIES; VOLUME 2: NEUROTOXICOLOGY AND NEUROPHARMACOLOGY, edited by Ivor E. Dreosti and Richard M. Smith. The Humana Press, Inc., Clifton, N.J. 07015 ($49.50 per volume). The rubric CHONPS—six single-letter symbols for six of the lighter elements—catchily sums up all the atomic constituents of the decisive polymers of life: the nucleic acids, most proteins, the sugars, structural substances such as collagen, cellulose and chitin, the lipids of cell membranes and even the simpler common currency of metabolism, such as the energy donor ATP and all the gears of the Krebs chemical engine producing that ubiquitous active fuel. Other elements do play an indispensable role in the fabric of living forms and have done so back at least to ancient bacterial ancestors. They include chlorine, sodium, potassium, calcium and magnesium, and some elements of the peak in the cosmic abundance curve around iron: stable iron itself along with manganese, cobalt, copper and zinc. They may enter as single atoms held in a complex and specific cage of fused organic rings, as in those vital reds and greens we call heme and the chlorophylls, or they may be built into widespread specific enzymes, such as catalase, or may simply reside in the ionic fluids within and without the cells. In all, 25 of the 83 long-lived elements are known to be required by one or another animal species.

Fourteen of those required elements are found in the organism at the level of one part in 10,000 by weight or less. These are the trace elements. In a sense they are invisible nutrients, found in the human diet or body only on knowing inspection; often a milligram is an adequate daily intake, and a dietary deficiency is apt to go long unnoticed. Obvious medical concern has led to including with these essential traces their opposites: atoms whose presence in small amounts is pathological rather than necessary, particularly when the elements enter our modern industrial environment. If traces of zinc are essential to tissue growth, it is no great wonder that traces of cadmium, a kind of poor chemical mimic of zinc, generate embryonic defects not unlike those that follow a deficiency of zinc. Such substitution is only the first step in explanation of these looped and subtle interactions.

Within the past decade the sensitivity of analysis, the power of modern biochemistry and a new awareness of medical need have fused into something close to an explosion of research on trace elements—clinical, experimental and epidemiological. The authoritative technical volumes reviewed here single out a special class of trace-element effects: consequences for the neurological system, the master control electronics of vertebrates. This is no arbitrary limitation of subject matter; many distressing pathologies associated with trace atoms are neurological. Mercury-induced shakes and the endemic cretinism of severe iodine deficiency are examples known for so long that they have become almost proverbial.

Among nearly 20 detailed technical-review chapters here, one chapter by two Australian experts concerns iodine deficiency, much the most important of all trace-element deficiency diseases. The classical goiter of the mountain peoples of Europe has long been managed by the addition of iodine to salt, bread and water; the unhappy condition is easily reversed. But throughout the populous developing lands, wherever people feed themselves by tilling soils grossly lacking in iodine, a rare water-soluble ion leached away by ancient ice or modern rainfall, there is widespread cretinism, in general quite unresponsive to iodization or even to treatment with thyroid hormone.

The *bon chrétien,* as the retarded innocent was long called in the French Alps, presents a pitiable syndrome of deaf-mutism, vacant stare and spastic reflexes, often without any visible goiter. In China alone there may be a million or two such people today. Although the syndrome has declined in Europe, the absence of direct correlation with the iodization measures raised doubts that its cause was in fact iodine deficiency. That correlation was entirely clear in the less common hypothyroid dwarfism, often called cretinism, which is strikingly responsive to thyroid hormone.

There is no doubt left. The neurological damage is the legacy of an iodine-deficient mother. A decade ago a harshly austere study was carried out along the Jimi River in the western highlands of Papua New Guinea. Women in alternate families were given either a single injection of iodized oil, supplying two grams of iodine, known to prevent iodine deficiency for about five years, or a control injection of saline. Each child of nearly 700 born there over five or six subsequent years was examined for motor retardation and deafness by a physician who did not know which injection the mother had received.

A graph records the results. The data are grimly exemplary: the dots marking the ages of deaf and retarded children march down the page year by year. Mothers who had received iodized oil bore seven diagnosed cretins, but not one of them could be reckoned to have been conceived more than a month after the trial injections. In those iodized families the dots then stop short. The alternate series begins in the same way, with six early births, but thereafter the dots continue randomly down the years, two dozen mute and retarded children. The saline injections had had no effect, but one cheap dose of iodine ended the syndrome. That missing milligram a day blights a lifetime.

It can also burden a society. Although cretinism is not common anywhere, there is today strong evidence that the children of iodine-deficient mothers who escape cretinism suffer nonetheless from measurably impaired motor performance, perhaps as many of them as the majority of the population at risk. Massive programs of iodization are wisely now under way in China, India, Indonesia and Zaire. A great deal of searching animal experimentation has confirmed the induction of a close analogue to the hypothyroid form of cretinism in iodine-deficient fetuses in rats, monkeys and sheep. The origin of the neurological form, however, "remains quite unclear." Fetal brain damage in the iodine-deficient lamb is often remarkably well reversed by the administration of thyroid hormone, just as it has been in the similar human condition. Yet so far we cannot produce deaf or spastic lambs, whether by the control of iodine intake (the flock is fed well, but with maize grown in a low-iodine area) or removal of the ewe's thyroid. We do not know why; we can prevent the disaster but cannot yet peer into the black box of human development.

The human brain, particularly during development, is "vulnerable to either a deficit or an excess of available copper." It is nearly 50 years since it was recognized that paralysis among lambs in western Australia was associated with subnormal copper levels in their wide pastures. (It was probably this discovery that recruited Australian interest in trace-element medicine, conspicuous in the expert editors of this international collection, in the foreword by F. Macfarlane Burnet and in many contributions to the extensive literature cited.) It is startling to learn that the very enzyme deficiencies and loss of the neurotransmitter dopamine that are so characteristic of Parkinson's disease in human beings are found in the brain of rats with a severe copper deficiency, particularly a certain type of mottled mutant.

The case is not closed: the drugs that help the Parkinson victim apparently have not yet been tried in the mottled rat. A connection with the dark pigment melanin is involved somehow through the pathways that metabolize the amino acid tyrosine, and the high concentration of copper found in two small pigmented areas of the brain stem in rat and human alike is one more of the tantalizing but inconclusive hints seen throughout this complex research. A powerful line of biochemical argument seems to show that copper is implicated in the brain's growing dependence after birth on oxidative metabolism. Oxygen is both essential and toxic; if the copper supply does not match the physiological program both for protection against oxygen and for the increased demands for oxidative energy, there is likely to be permanent damage.

Zinc and selenium, manganese and cobalt, lead, cadmium, mercury and aluminum (even lithium, an added starter as a mysteriously therapeutic trace element) are discussed at length. Epidemiology, spontaneous genetic diseases in human and animal, histochemical analyses to localize the special elements, a heavy dose of enzyme biochemistry in all its maturity, quantitative study of animal behavior through operant-conditioning techniques, and careful anatomizing of the neural net and its major centers all enter this technical, jargon-rich but telling and up-to-date account. The recent flood of interest in neurotransmitters and their complex chemical controls is now lapping also at this shore. Theories are in plenty, confirmations few. Management is ahead of insight, thanks both to accident and to therapeutic energy.

The editors generalize plausibly that each trace metal "has emerged as essential because it filled a niche in evolutionary progression and the niches are not related." Consider manganese, long known to be an occupational poison. Chronic overdose can produce a psychosis, "manganese madness," with hallucinations and unaccountable laughter leading on to speech disorders, tremors and a staggering gait. Yet we all require a milligram or so of manganese per day. In rats one effect of manganese deficiency was a severe loss of orientation. That turned out to be the result not of some subtle trouble with synaptic transmission but of failure of normal growth of the otoliths of the inner ear. The final story of trace-element neurobiology will be a pied wonder!

RUTHERFORD: SIMPLE GENIUS, by David Wilson. The MIT Press ($25). Ernest Rutherford was a big, strong country boy, well educated mainly through a series of earned scholarships. At 23 he was a graduate student in physics at Canterbury College in Christchurch, New Zealand, who had just won a brilliant "double first," top honors for the M.A. both in mathematics and in physical science. There he had last worked on an original magnetic detector for Hertzian waves. Anxiously waiting out the uncertain award of a scholarship to England, he spent an unhappy year or so in schoolteaching and farm work. A vacancy luckily arose, so that "he was in the garden at Pungarehu digging potatoes... when his mother brought out the telegram. He flung down his spade and declared, 'That's the last potato I'll dig.'" Likely it was.

Young Rutherford arrived at the Cavendish Laboratory at Cambridge to work with its Professor, J. J. Thomson, in October, 1895. For a few months his radio detector, with a clear note of practical invention about it, made impressive progress. But in January, 1896, a rocket of a scientific paper unexpectedly signaled the opening of the physics of the 20th century, a little prematurely, when Wilhelm Röntgen published his startling discovery of X rays.

The new radiation seized the minds of physicists everywhere, J. J. Thomson among the first. By the end of the Easter holiday Rutherford had joined his Professor in work on X rays in gases, his radio relegated to second place, left for assiduous inventors such as Marconi. Then for the 40 years until his death in 1937 Rutherford rode high on the wave of nuclear discovery. ("Well," he once said, "I made the wave, didn't I?") It crested in the large-scale release of nuclear energy he did not live to witness.

This first full-length biography of Rutherford gathers and orders the many excellent personal accounts already given by many of his colleagues, full of color and scientific appraisal. It makes good use of several interesting studies we owe to professional historians of modern science. More than that, the author, a BBC science journalist of long experience, has found his way to archives and memories held in New Zealand, in Montreal and most of all in the University of Cambridge library. There are many unpublished sources cited, including some for which it was necessary to gain the consent of the Russian Academician Peter L. Kapitsa, in his youth a fiery force for big physics at the Cavendish, a man long an intimate of Rutherford, whom Kapitsa called the Crocodile. (It is only a half-truth of Kapitsa's that the term is used in Russian with the sense of the father of the family.)

Wilson makes an admirable point in the conclusion of this meticulous and sensible book. He observes that the powerful mystique of Albert Einstein, reinforced to some degree by a similar air around Robert Oppenheimer and a few European participants in the atomic-bomb project, left at the end of the war an image in the American public mind of nuclear physics, and of nuclear energy in particular, as being the outcome of what was essentially progress in theory. Against this surely misleading view there was no adequate British counterweight, as there might have been. Rutherford, the master experimentalist, was nearly 10 years dead, his best-known boys were seen mainly as players on a large team in an American-based project and the once-glorious Cavendish itself was by the end of the war "old and dirty and run down."

Wilson recalls that he himself was a disenchanted physics student at Cambridge in those days. He has now constructed a compelling demonstration of decades of leadership by those insightful experimenters, Rutherford at their head, who step by surprising step built nuclear physics—finding random decay, transmutation, the tiny charged nucleus, isotopes, nuclear reactions and finally the neutron—without great aid from the theorists. The Cavendish story since the war will have to wait for another book, but of course the laboratory returned in glory. Far from the nucleus, its newer triumphs are diverse and already proverbial: the double helix and the pulsar.

The well-told narrative is chronological in form. Only a few selections can stand here for the 600 documented pages. Let Sir Mark Oliphant, himself then an enthusiastic young student from the antipodes, describe the personal impact of Rutherford around 1930, in the years of undoubted Cavendish mastery: "I entered a small office..., the desk cluttered.... It was raining and drops of water ran reluctantly down the grime-covered glass of the uncurtained window.... I was received genially by a large, rather florid man with thinning fair hair and a large moustache, who reminded me forcibly of the keeper of the general store and post office in a little village in the hills behind Adelaide.... Rutherford made me feel welcome and at ease at once."

In an epoch of all but unmitigated prejudice against women in science the bluff, conventional Rutherford "treated women very much as equals..., actively encouraging [them] to pursue scientific careers in his laboratories." He was a quiet support to Marie Curie

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through many troubles; theirs was a long, strange, "fond but sexless relationship." Perhaps it flourished because alike they were deeply in love with the laboratory. But the young Niels Bohr as well, deepest-dyed of philosophical theorists, made his revolutionary way first beside Rutherford at Manchester, to become a lifelong friend. It fell to Bohr, eyes filled with tears, to announce Rutherford's death. When the Third Reich began to exile its scholars, Rutherford, never concerned with politics in any partisan sense, took on with conviction and energy the task of head of the Academic Assistance Council in Britain, whose good offices had by 1936 helped 1,300 German scholars.

There is an excerpt from a paper written half a dozen years before the days of Hans Geiger and Ernest Marsden, who measured the single scattering of alpha particles by the patient counting of tiny flashes in the dark to establish the nuclear atom. Rutherford had noticed that his strongest magnetic fields could deflect the alpha-particle beam by about the same angle as the diffuse scattering noted when the beam passed through a thin sheet of mica. To bend the beam electrically, however, "would require over that distance an average transverse electric field of about 100 million volts per centimeter.... Such a result brings out clearly the fact that the atoms of matter must be the seat of very intense forces." Laboratory proof waited, but the leading idea was in place. In the same way he sought the neutron fruitlessly, but with a clear understanding of what its reactive powers would be, from 1920 until James Chadwick found it at last in the year of wonders 1932.

This is an honest and comprehensive study of the life and mind of a man who was a genius of the laboratory, although not a simple one, in spite of the catchy subtitle. He was, rather, an artist in a demanding and unfamiliar medium, a man of self-conscious sensibility dressed in the clothes and manners of a self-satisfied country squire. The issues he raised, from the role of theory in physics to the use of big machines, are treated here in a fair and informed way, much enriching with evidence the stereotypes of casual folklore. The people are made quite real, and never by caricature. Rutherford would have liked this book, one feels, for its straightforward yet sensitive narrative, and its patent care more to be understanding and kind than merely to seem polite.

Rutherford was caught up in the embryonic participation of the physicists in World War I. He may be counted as at least the coinventor of sonar. That his mind was also on other matters at the time is preserved in lapidary style in a famous remark he made to apologize for his absence from a meeting of an international antisubmarine-warfare committee: "If, as I have reason to believe, I have disintegrated the nucleus of the atom, this is of greater significance than the war."

SCULPTURED SURFACES IN ENGINEERING AND MEDICINE, by J. P. Duncan and S. G. Mair. Cambridge University Press ($39.50). Ships and shoes, although not sealing wax, are two significant examples of artifacts whose physical surfaces cannot be generated by simple mechanical motions, as a lathe generates a cylindrical surface or a planer generates a flat one. In order to produce the more complex shapes in diverse materials, and indeed often to replicate them by cutting, molding, casting or plastic deformation, master forms are first made. They can be cavities, dies shaped neatly to enclose the wanted form, or masters that resemble the wanted form itself, or even the fitted pair, fully enclosing both inside and out. The task of turning the designer's choices on paper into such objects, often required in hard steel, has been the handwork of the tool- and diemaker, traditionally the most skilled of all the craftsmen engaged in modern manufacture.

Professor Duncan was a toolroom apprentice in that expert environment 40 years ago; in this book he and a programming colleague at the University of British Columbia offer a modern replacement for the old skill, a computer-aided method for automatically producing surfaces of all but arbitrary shape. (Undercutting escapes the algorithm.) They present a simple but powerful scheme transparent to the user, aimed at workman and designer alike, suited to the low-cost and widely used open-loop digital machine tools. The book offers examples and case studies in variety.

The first step is specification of the form. Curved engineering forms, although hardly sculptured heads, are often described partly analytically. From the analytic boundaries thereby set up the more complicated forms were produced by interpolation or by trial and error. The surfaces of ships, aircraft and automobile bodies were laid out at full size, with the designer's set of points specified on paper. The craftsmen then smoothly joined the points with such aids as splines, thin elastic rods. Finally the sculptor, whose surfaces were generally the most varied and complex but whose tolerances were at his own disposal, used the most general scheme. It is called "pointing." With or without simple mechanical aids the carver fixed the position of a discrete set of points on the surface of a rough-hewn massif, often scaling up mechanically from a small model made by hand in some easier material, such as plaster. He then touched each of the dominant surface points by forming a small cavity at and around it. More points would add detail, until interpolation could be made directly. The final step was the local smoothing of the surface asperities necessarily left between the fixed points.

By 1940 there were ingenious automatic machines, not for making the initial complex form but for copying any complex surface in a harder material. The Keller copying machine of those days was a three-dimensional milling machine. It operated a tracer that scanned the full-size model. As the spherically tipped probe followed the curved surface a four-way microswitch sensed the increase or decrease of force when the scanning end tilted slightly with any inclination of the master surface. The signal caused a slight advance or retreat of the probe to reestablish the threshold pressure, and a strong power-driven metal cutter followed the motion of the probe as it scanned a similar path over a cast-iron massif. The copy was formed by the series of tracks cut in the iron; the ridge asperities between them were smoothed by hand. Design of complex form was freed. A twisted turbine blade, say, might have been specified earlier only in a simple approximation, as the volume enclosed between "two skewed circular cylinders, each generated by straight milling."

The theme of this original and interesting volume is the authors' computer-based system of programs called POLYHEDRAL NC. The NC stands for numerical-control machining, in wide use today for simple surfaces of every kind. The new software is a kind of computer-controlled pointing; the digitally controlled machine it directs acts like a Keller machine following without feedback a set of points defined only informationally. The concept is nicely understandable. The system generates a complex irregular polyhedron, like some magic gem with thousands of tiny plane facets, each vertex one of the assigned points. The points are ordinarily assigned through a set of three Cartesian reference planes. Then a program embodying a good deal of mathematical logic orders the positions of a spherical end-milling cutting tool, which is intended to visit and work in turn each facet of the polyhedron.

A key point is interference: a spherical tool might touch and cut away the neighbors of one small facet, ruining the form. The logic precludes this; a cutter of smaller radius must be used when such interference is present. The program orders the position and the choice of successive sizes of tool that guarantees interference-free touching of all the facets of the imaginary polyhedron. The control tolerances required and the tool choice are of course dependent on the size and the finish wanted. A very wide range of local curvatures can be handled; for good texture the tool must touch the surface at many points to limit the size of the cusps left behind.

The book includes much more detail, for example on clever means of optically mapping surfaces to allow digital specification and on admirable general methods of interpolation. A shoe last, an artificial leg, a pottery jug, molds for a Klein bottle to be built up out of four curved panels of fiber glass, the relief map of a Welsh island and even a head of a model of Michelangelo's David are sample products followed in some detail and visually documented. So far the scheme is supported on a mainframe computer with virtual memory, but transfer to the nimble microprocessor, the authors say, lies not far ahead.

THE WORLD GUIDE TO BEER, edited by Michael Jackson. Running Press, 125 South 22 Street, Philadelphia, Pa. 19103 ($9.95 plus 75 cents postage and handling). For many readers the season of hot, thirsty days and carefree travel is at hand. This attractive field guide compiled by an English savant is commended to those among them who look forward to cool draughts of bitter beer.

Labels, the blossoms of the cultivated flora, are reproduced here in large numbers, mostly in color. Along with them one sees the entire ambience of a cosmopolitan industry: draft horses, bottles, tankards, vats, posters, proper glasses, connoisseurs and images, some only period drolleries and some painted by artists such as Édouard Manet and Pieter Bruegel the Elder. These visual features of the human ecology of beer complement the main text, which describes hundreds of species of beers country by country, with fine maps of range and appropriate history.

Appraisal is gently offered, but the book is more descriptive than normative. The author knows the virtue of behaving in Rome as the Romans do, whatever odd winding paths they follow. (Indeed, if you do that in Utica, N.Y., very near Rome, you may have a pleasant surprise.) Beer in the European mode is brewed now on all continents; India's Black Beard lager and the lively bright foaming Star of Nigeria might serve to sample the long annotated lists. Of course, four-fifths of the text deals with Europe, the home of modern beers as it is of soccer and the automatic rifle, all enthusiastically adopted across the world for good or bad.

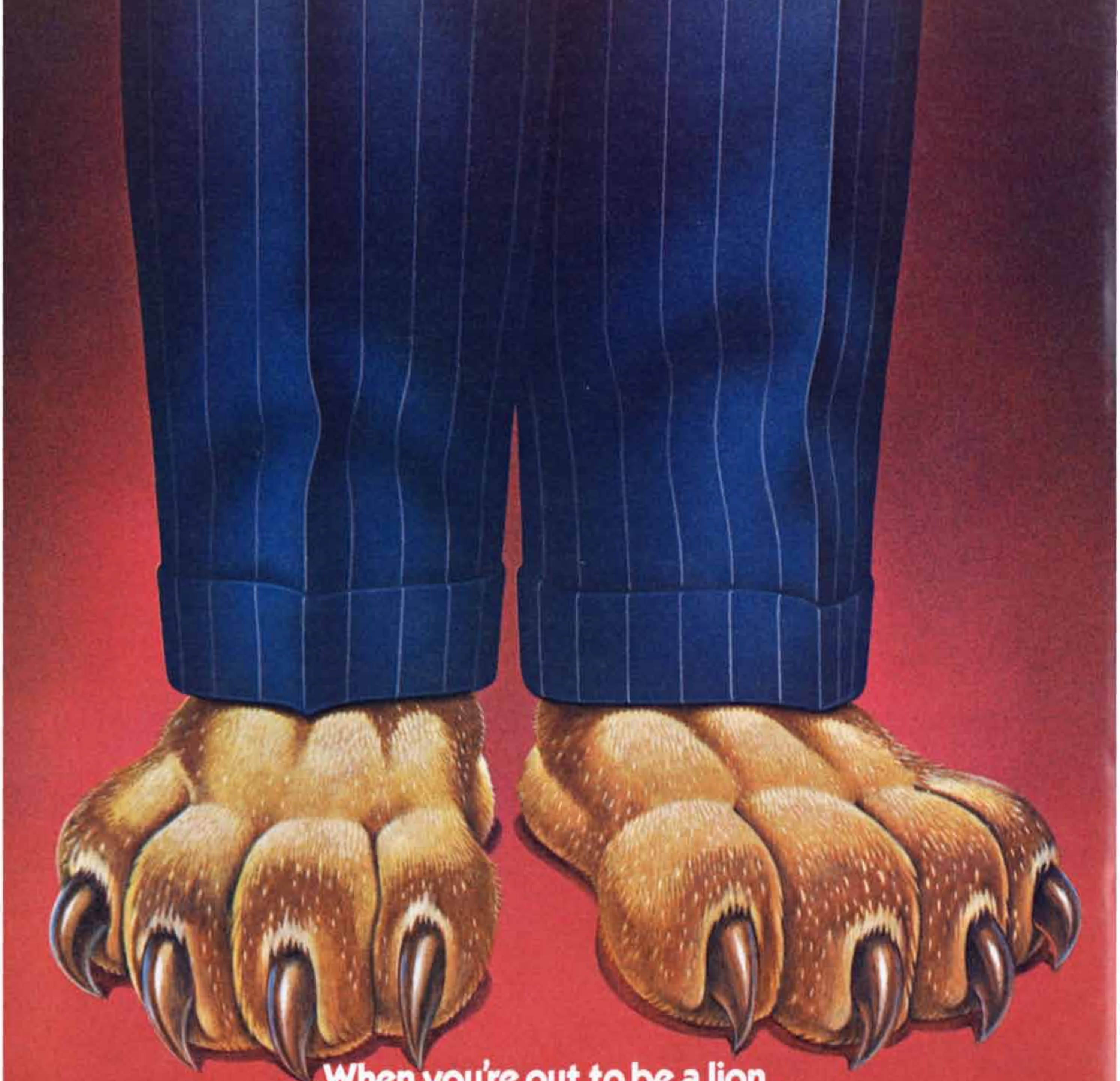
The first tenth of the book, as in many field guides, offers the basis of the taxonomy and draws the generalizations given concrete form in the geographic text. A couple of splendid prints represent two botanical essentials of modern beer: two-row barley, traditional source of the carbohydrates, and the bacteriostatic and bitter hops plant; a counterpart image is not earned by the third indispensable, yeast. Today the yeast is a carefully cultured single-cell strain. There are variants: Belgium remains the sole home of manufactured wild beers, fermented by volunteer airborne microorganisms and based on wheat and even cherries.

The more domesticated wheat beers are prized in many places, particularly from Berlin south to Vienna. American brewers, in a country where economic concentration is at its highest but the concentration of the beer itself is typically light, thriftily augment the malted barley with rice and corn as the chief sources of carbohydrate. Of the 10 biggest brewers in the world six are American or Canadian, two are British, one is Japanese and one is Dutch. But the site map of brewers in southern Germany, say, bears dots by the hundreds.

Beers are common in prehistory. Barley-based beer is probably Mesopotamian, older, it may be, than bread. As barley is to beer, so wheat is to bread. The two grains predispose to the two products; barley makes indifferent bread. The yeast enzymes generate carbon dioxide gas and alcohol, both removed in baking bread; the vitamins remain. Beer today is worldwide the hop-flavored barley-based type, probably a medieval innovation somewhere around Bohemia, although the aromatic hop plant was known in antiquity.

The two great divisions of beer are by the habit of the yeast. The perishable older beers, such as the true ales of Britain today, are made with yeast that floats at the top of the fermenting fluid, with oxidative souring always a risk. In the newer beers the yeasts sink to the bottom and the whole is kept at low temperature; such a brew will not sour for months. Bottom-fermenting beers enter the record in Bavaria in the 15th century, when they were kept cold by storage in caves or with natural ice. Their dominance in this epoch of easy refrigeration, under the name of *lager*, a German word for storage, is evident.

Finer-spun categories, the bocks, ales, porters and more, are also found in this detailed guide. The world's average beer is a mild approximation of a golden Pilsner style of lager, its original content of fermentable materials 5 percent by weight, its final concentration of alcohol 4.0 to 4.5 percent by weight. The popular drink unites today's indulgent world, from the next corner to Tombouctou. (When there, try Bamako Beer.)



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Antisatellite Weapons

Unless some action is taken soon to restrain the further development of such weapons the positive contributions of satellites to international security will be threatened

by Richard L. Garwin, Kurt Gottfried and Donald L. Hafner

The remarkable evolution of military technology in the nuclear age has resulted in a precipitous drop in global security. Four decades ago an all-out attack could not bring a major power to its knees in anything less than several months; today entire civilizations could be extinguished in a matter of hours. Artificial earth satellites are a rare example of a new military technology that on balance has improved global security. Nevertheless, if no political initiatives are taken promptly, developments in antisatellite (ASAT) weaponry will soon carry the arms race across the threshold into an era in which satellites will lose the comparatively secure status they now enjoy.

Satellites are coming under threat because they play a dual role. In peacetime they provide both the U.S. and the U.S.S.R. with prompt and virtually irreplaceable intelligence about each other's military forces and operations. As a consequence they are essential to many aspects of military planning, and they are indispensable to the verification of compliance with strategic arms-control agreements. In a political crisis involving the superpowers the prevention of armed conflict would depend to a considerable degree on satellites as tools in assessing the actions of the other side. If hostilities were to break out, whatever chance there might be of averting a catastrophic escalation could rest on the continued flow of surveillance information and communications from satellites. The extraordinary ability of satellites to see, to listen and to communicate would, however, greatly amplify the effectiveness of military forces in wartime. For that reason satellites would become particularly tempting targets as soon as hostilities seemed imminent. Accordingly both sides have long shown an interest in the development of antisatellite weapons.

In the 1960's both the U.S. and the U.S.S.R. developed weapons with an antisatellite capability. The U.S. eventually dismantled its antisatellite system and adopted the position that its security would be best served by abstaining from any further competition in antisatellite weaponry. The U.S.S.R., however, continued sporadic testing of its antisatellite system.

In the mid-1970's the U.S. altered its approach, although maintaining that a weapons-free space environment continued to be its ultimate goal. The new policy had two linked components: on the military front it called for the development of a new, more sophisticated antisatellite weapon; on the diplomatic front it called for negotiations toward a treaty that would eventually ban all such weapons. Bilateral discussions on the issue began in 1978, but they were suspended by the U.S. in 1979, following the Russian intervention in Afghanistan. Since then the U.S.S.R. has, in 1981 and 1983, submitted draft treaties to the United Nations calling for the control of weapons in space, but the U.S. has not responded to these initiatives.

Meanwhile both nations have continued to work on antisatellite weapons. What is more, the competition in space-based weaponry is likely to accelerate if the U.S. follows the recommendation of President Reagan and embarks on a large-scale exploration of the feasibility of a space-based antiballistic-missile (ABM) system, officially named the Strategic Defense Initiative and commonly known as the "Star Wars" program. Indeed, because of the close technological link between antisatellite weapons and ballistic-missile defense, even the early stages of such a program would be impossible if the existing ABM Treaty were to be complemented with a similar agreement limiting antisatellite weapons.

The advent of antisatellite weapons would seem to imply that the beneficial role of satellites in arms control, confidence building and conflict resolution had been judged less important than their ability to support actual military operations. In what follows we shall take issue with this assessment. Furthermore, we shall argue that there is still an opportunity to negotiate a militarily significant and verifiable constraint on the growth of antisatellite technology that would be in the security interest of the U.S. and the world as a whole.

Many issues must be examined before one can judge whether it is desirable or feasible to constrain the evolution of antisatellite technology by negotiation. The roles of the existing military satellites and their vulnerability to antisatellite weapons must be assessed, and the probable impact of antisatellite weapons on various kinds of crisis and conflict must be evaluated. This article is devoted to an examination of these questions and related ones.

It is important to distinguish among the different types of military satellites and among the ways in which the U.S. and the U.S.S.R. are dependent on them. The orbits of most of these satellites fall into four broad categories: (1) low orbits, which are roughly circular, have a period of about 100 minutes and have altitudes ranging from about 100 kilometers up to several thousand kilometers; (2) geosynchronous orbits, in which the satellite circles the earth at the same rate as the earth's rotation and remains above a fixed point on the Equator at an altitude of about 36,000 kilometers; (3)

highly elliptical orbits, which descend to an altitude of several hundred kilometers at their perigee (lowest point) over the Southern Hemisphere and rise to an apogee (highest point) of some 40,000 kilometers over the Northern Hemisphere, and (4) semisynchronous orbits, which are roughly circular in an inclined plane at an altitude of about 20,000 kilometers [*see illustration on page 48*].

The altitude of a satellite is pertinent to its mission. A satellite in a low orbit has the most detailed view of the earth's surface and can also detect weak electronic signals from sources on the ground, at sea or in the air. Accordingly photoreconnaissance, ocean-surveillance and most electronic-intelligence satellites are in a low orbit. When the mission is to continuously survey large areas, to communicate with large areas or to communicate with a fixed ground station, a geosynchronous orbit is preferred. Thus U.S. satellites whose infrared sensors are designed to provide early warning of a Russian missile firing are in such orbits, as are virtually all U.S. communications satellites.

Because the U.S.S.R. has important facilities in the Arctic region, where it is difficult to have a clear line of sight to a geosynchronous satellite above the Equator, the Russians have introduced highly elliptical orbits for many of their Molniya-class communications and early-warning satellites. The U.S. Satellite Data System (SDS) satellites, which handle communications with forces in the Arctic, are in similar orbits. A satellite in such an orbit, with its apogee high over the Northern Hemisphere, remains visible to its ground station for eight hours or more of its 12-hour period.

Precise global navigation is another important military task that is being assisted by satellites. The earliest navigation satellites were in low orbits, but the improved U.S. Global Positioning System (GPS) and a similar Russian system are now being deployed at an altitude of about 20,000 kilometers, where comparatively few (18 or 24) satellites suffice to have at least four in view simultaneously from any point on the earth. The Integrated Onboard Nuclear Detection System (IONDS), for detecting and locating nuclear explosions, will also be carried by the GPS satellites.

Although the military satellites of the U.S. and the U.S.S.R. have similar missions, they also have characteristic differences that affect their eventual vulnerability to antisatellite weapons. The persistent U.S. lead in microelectronics and other advanced technologies has led to U.S. satellites that are much more sophisticated, more reliable and longer-lived than their Russian counterparts. Longevity is particularly important for high-altitude satellites because of the high cost of launching a satellite into such an orbit. As a result the U.S. has been able to sustain a variety of satellite functions with fewer satellite networks, and it has operated them with less frequent replacements. Although some U.S. military satellites are still in low orbits and hence are potentially vulnerable to the present Russian antisatellite system, most U.S. satellites are at altitudes far beyond its reach.

The military satellites of the U.S.S.R., on the other hand, are predominantly in low orbits, and they also have much shorter lifetimes. This circumstance presumably reflects both operational choices and technological weaknesses. The latter factor is suggested by reports that malfunctions kept the Russians from monitoring the critical phases of the recent Falkland Islands conflict in spite of their major commitment to ocean-surveillance satellites. As for vulnerability to antisatellite weapons, a much greater fraction of the Russian satellite fleet is threatened by the current generation of low-altitude antisatellite weapons, although the higher rate at which the U.S.S.R. launches replacement satellites offsets this vulnerability to some extent.

U.S. Department of Defense officials and publications have often asserted that the far greater frequency of Russian satellite launches demonstrates that the military space program of the U.S.S.R. is much larger than that of the U.S. The disparity in launch frequency, however, is entirely accounted for by the much shorter lifetime of the Russian satellites. Similarly, many comparisons of the gross weight put into orbit ignore the U.S. space shuttle; only two shuttle flights are needed to exceed the 660,000 pounds lofted into orbit annually by the U.S.S.R. Comparisons based on expenditures devoted to the two military space programs should also be treated with caution; the same methodology would lead to the conclusion that the U.S.S.R. is a more abundant food producer than the U.S.

U.S. ANTISATELLITE WEAPON is designed to be launched into space from an F-15 fighter plane at high altitude. The two-stage booster rocket carrying the miniature homing vehicle is seen here on an early test flight aimed at demonstrating the compatibility of the missile with its host aircraft. The insignia visible on the tail of the aircraft heralds the antisatellite mission of the weapon system.

Military satellites have quite different roles in peacetime, in a low-level conflict and in a strategic nuclear exchange. In peacetime low-orbit photoreconnaissance, ocean-surveillance and electronic-intelligence satellites provide information essential to arms control and to routine military intelligence. If a crisis arose, these satellites would be particularly valuable in crisis management, but as soon as non-nuclear hostilities began they would assume a dual role because they would also enhance the effectiveness of the combatants. Once a political crisis or a low-level armed conflict was in danger of provoking a strategic nuclear exchange, the high-altitude early-warning and communications satellites would display the same duality: they would be significant factors in the attempt to prevent the exchange, and yet they would be important assets to the strategic forces if the attempt were to fail.

TEST	DATE	INTERCEPTOR (KOSMOS NUMBER)	INTERCEPT ALTITUDE (KILOMETERS)	ORBITS BEFORE INTERCEPT	TEST RESULT
1	OCT. 20, 1968	249	525	2	FAILURE
2	NOV. 1, 1968	252	535	2	SUCCESS
3	OCT. 23, 1970	374	530	2	FAILURE
4	OCT. 30, 1970	375	535	2	SUCCESS
5	FEB. 25, 1971	397	585	2	SUCCESS
6	APR. 4, 1971	404	1,005	2	SUCCESS
7	DEC. 3, 1971	462	230	2	SUCCESS
8	FEB. 16, 1976	804	575	1	FAILURE
9	APR. 13, 1976	814	590	1	SUCCESS
10	JULY 21, 1976	843	1,630	2	FAILURE
11	DEC. 27, 1976	886	570	2	FAILURE
12	MAY 23, 1977	910	1,710	1	FAILURE
13	JUNE 17, 1977	918	1,575	1	SUCCESS
14	OCT. 26, 1977	961	150	2	SUCCESS
15	DEC. 21, 1977	970	995	2	FAILURE
16	MAY 19, 1978	1,009	985	2	FAILURE
17	APR. 18, 1980	1,174	1,000	2	FAILURE
18	FEB. 2, 1981	1,243	1,005	2	FAILURE
19	MAR. 14, 1981	1,258	1,005	2	SUCCESS
20	JUNE 18, 1982	1,379	1,005	2	FAILURE

TEST RESULTS for the antisatellite-weapon system adopted by the U.S.S.R. are summarized in this table. The overall success rate for the system has been 45 percent (nine interceptions in 20 attempts). In tests conducted with the original radar-directed homing device the weapon has had a 50 percent success rate on first-orbit intercepts and a 70 percent success rate on second-orbit intercepts, for a net success rate of 64 percent. All six of the reported tests with a more sophisticated optical/infrared sensor have failed (*entries indicated in color*). The timing of the tests and the orbits chosen for the interceptor have lent support to the speculation that the Russian antisatellite weapon might be intended for attacking Chinese satellites rather than U.S. ones. The data are from *The Soviet Year in Space: 1982*, by Nicholas L. Johnson.

All antisatellite weapons currently deployed or undergoing field tests have a maximum altitude of several thousand kilometers or less. Hence they could attack satellites only in low orbits or in highly elliptical ones. Since the early-warning, navigation, attack-assessment and communications satellites essential to the U.S. strategic forces are all in very high orbits, they are not at risk in the near term. The U.S.S.R. faces a somewhat greater potential threat, since some of its essential communications satellites and all its early-warning satellites are currently in highly elliptical Molniya orbits.

To what extent is the present generation of antisatellite weapons likely to have an impact on crisis stability? In a full-scale nuclear war space-based systems for command, control, communications and intelligence (C^3I) would be seriously threatened whether antisatellite weapons existed or not, because their air- and ground-based communications facilities and control centers would be highly vulnerable to nuclear attack. The parts of the C^3I system essential to the strategic forces of each side are largely immune to antisatellite attacks for the time being, and low-orbit satellites that survive such attacks would be of questionable utility in the havoc created on the ground by a strategic nuclear exchange. It would therefore appear that the antisatellite capabilities likely to be operational in this decade will have little impact on the superpowers' ability to wage full-scale nuclear war, no matter what one may mean by that term.

The same low-altitude antisatellite capabilities, however, could have a substantial impact on the prospects for containing low-level armed conflicts up to and including hostilities involving small numbers of nuclear weapons. The sophistication of low-orbit satellites is increasing steadily and so is their ability to supply all-weather, real-time intelligence of unprecedented quality and coverage. Ships, aircraft, drones and sounding rockets will not be able to serve as a fully adequate replacement for the space-based systems. The ability to destroy low-orbit military satellites, coupled with the fear that the opponent may at any moment attack one's own satellites, could therefore create an irresistible temptation to remove the opponent's satellites. As a consequence the ability to destroy low-orbit satellites promptly could inflame a political crisis or a minor conflict that might otherwise have been resolved by diplomacy if there were no antisatellite weapons. Since it is widely believed that general nuclear war is most likely to start as a low-level confrontation, the current generation of antisatellite weapons is clearly more than just another minor hazard in an already very dangerous world.

An antisatellite weapon can attack its prey in various ways. The current Russian antisatellite weapon, for instance, is a co-orbital interceptor: it is launched into an orbit similar to that of its target, and as it approaches its target it explodes in a swarm of pellets. The U.S. antisatellite weapon is a direct-ascent interceptor: it is projected into the path of its target satellite by a rocket, which in turn is carried to high altitude by an airplane. Destruction is by direct impact; there is no explosion.

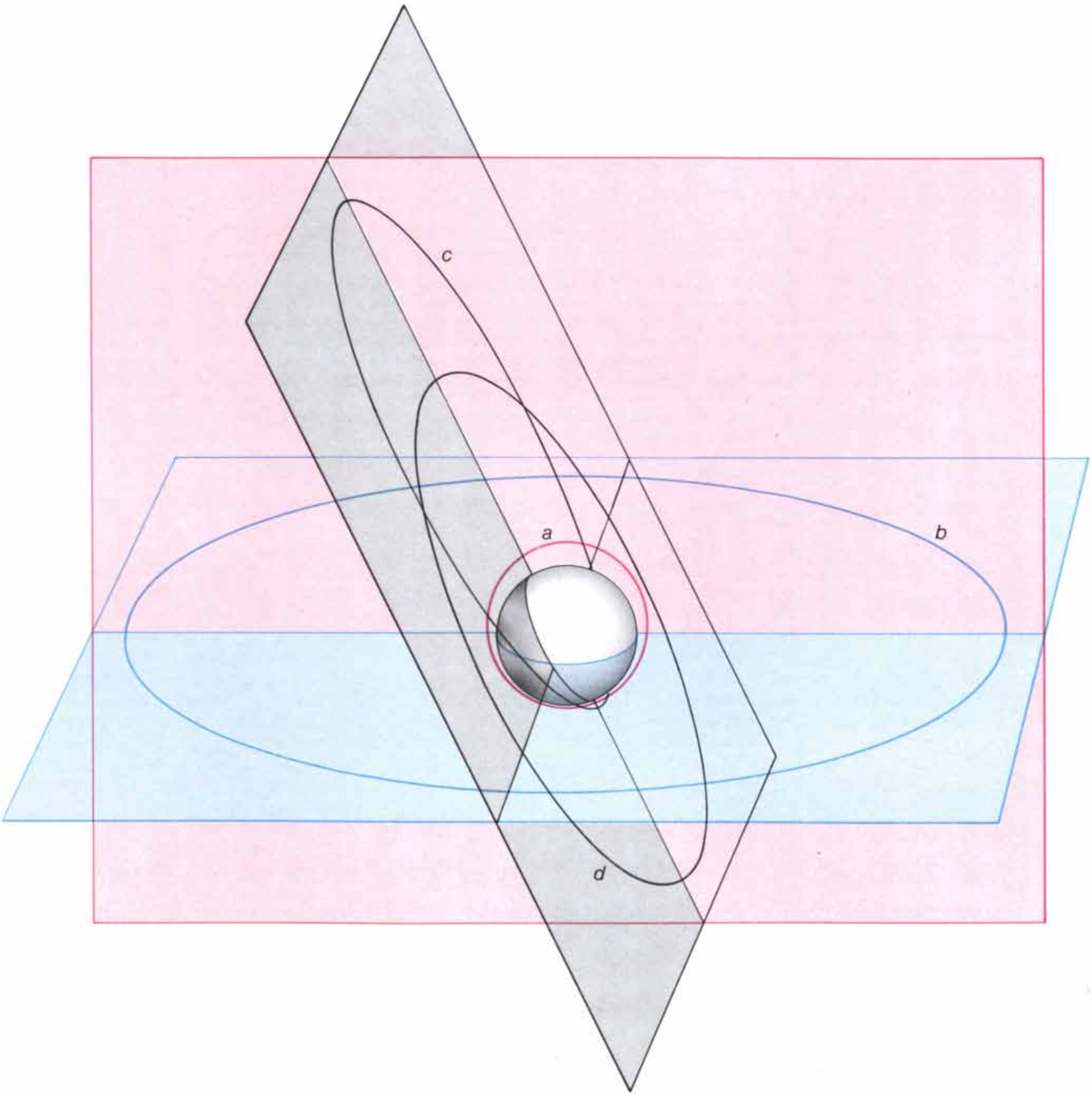
Other kinds of antisatellite weapon have been proposed, but we shall describe here only two weapons that are of particular significance. The first weapon is a space mine: a small satellite carrying an explosive charge that accompanies its potential victim for weeks or months and is fired by remote command. The second is a laser system, which can be based on the ground, in the air or in space.

All these weapons are non-nuclear. The U.S. and the U.S.S.R. could also resort to nuclear-armed missiles as antisatellite weapons, but the use of such weapons would have serious disadvantages: it would breach the nuclear threshold at a critical moment, and it would generate an electromagnetic pulse that could disrupt one's own communications system.

The current Russian antisatellite weapon was introduced in 1968. It is lofted into orbit atop a modified SS-9 booster rocket, a large liquid-fueled intercontinental ballistic missile (ICBM) first deployed in the 1960's. The interceptor itself weighs more than 2,000 kilograms and is about six meters long. In all tests the antisatellite weapon has been launched from Tyuratam in Kazakhstan into orbits within a narrow range of inclinations: between 62 and 65 degrees with respect to the Equator. Target satellites have been launched from Plesetsk in the northwestern part of the U.S.S.R. into orbits with the same narrow range of inclinations. Interception occurs after the antisatellite weapon has completed one or two trips around the earth at a point where its orbit crosses that of the target. The antisatellite weapon maneuvers close to its target under the guidance of an on-board homing device: either an active radar or a passive optical/infrared sensor.

The lack of variation in orbital inclination in the Russian test program, and the fact that there are so few U.S. satellites at these inclinations, has led to the speculation that the Russian antisatellite weapon might be intended for attacking Chinese satellites rather than U.S. satellites. Indeed, there are notable parallels between the launches and orbits of Chinese satellites and the Russian antisatellite test program.

Detailed reports on the Russian test program have been made available by a number of authoritative observers, including U.S. military officials. According to these sources, the U.S.S.R. has conducted some 20 tests since 1968. (The most recent test was on June 18, 1982, as part of a strategic exercise in-



TYPICAL ORBITS traveled by the military satellites of the U.S. and the U.S.S.R. are drawn to scale on a set of intersecting planes to distinguish their orbital characteristics. Satellites whose mission requires them to be in a comparatively low orbit (between 150 and 2,000 kilometers, say) tend to be in a roughly circular, more or less polar orbit with a period of about 100 minutes and an orbital inclination of between 65 and 115 degrees with respect to the Equator (*a*). Satellites in a geosynchronous orbit circle the earth at an altitude of some 36,000 kilometers and remain above a fixed point on the Equator (*b*). Satellites in a highly elliptical orbit, typically inclined by about 63 degrees, descend to an altitude of several hundred kilometers at their perigee (lowest point) over the Southern Hemisphere and rise to an apogee (highest point) of some 40,000 kilometers over the Northern Hemisphere (*c*). Satellites in a semisynchronous orbit generally follow a roughly circular path with an altitude of about 20,000 kilometers and an inclination of between 63 and 65 degrees (*d*).

volving a variety of ballistic missiles and two ABM interceptors; the antisatellite test was a failure.) The first series, which lasted from 1968 through 1971, relied on an active radar for homing after two orbits. Since 1976 the U.S.S.R. has explored two new techniques. One technique entails a quicker approach with the radar-directed homing device, in which interception is attempted in the first orbit; the other calls for interception after two orbits with the optical/infrared homing device. The latter system has failed in all six of its tests, and the quicker approach with the radar homing device has worked in two out of four tries. The original 1968–71 test series had a success rate of 70 percent.

Although the Russian 1968 design is fairly reliable, that version is susceptible to such countermeasures as jamming or deception of the radar homing device or evasive maneuvering on detection of the launch, since interception takes some three hours. The potentially defter homing and maneuvering techniques of the later tests have so far performed very poorly.

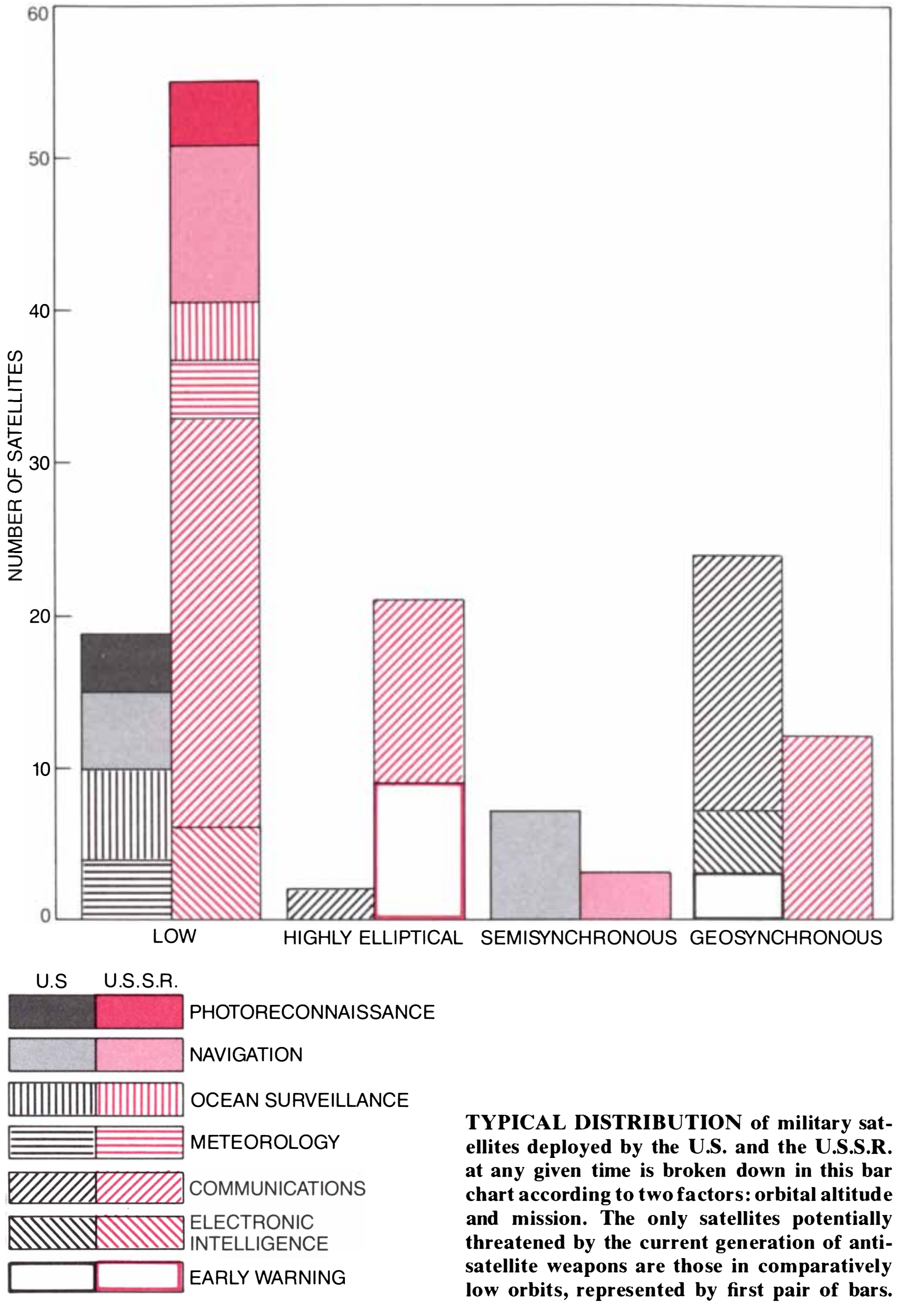
Apart from these shortcomings in execution, the Russian antisatellite system suffers from several basic conceptual flaws. First, a satellite can be attacked only when its ground track runs close to the launch site of the antisatellite weapon, a condition that is satisfied only for satellite orbits with inclinations higher than the latitude of the antisatellite weapon's launch site. This happens only twice a day, and so one must wait an average of six hours to attack a given satellite. Second, the heavy antisatellite weapon itself requires a massive booster rocket, which can be launched only from a limited number of facilities in the U.S.S.R. Third, it is difficult to fire such massive liquid-fueled boosters in rapid succession from a single launch site. Fourth, the highest altitude reached in the Russian tests (about 2,400 kilometers) is far below the orbits of the important U.S. navigation, early-warning and communications satellites.

Taken together, these factors lead to the estimate that it would take the Russian antisatellite force a week or more to destroy all U.S. satellites within its reach. If satellites at 20,000 kilometers or higher were to be attacked, a much more massive booster rocket would be required, and judging from the test record it is unlikely that the antisatellite weapon would have the maneuvering and homing capabilities to intercept at such altitudes.

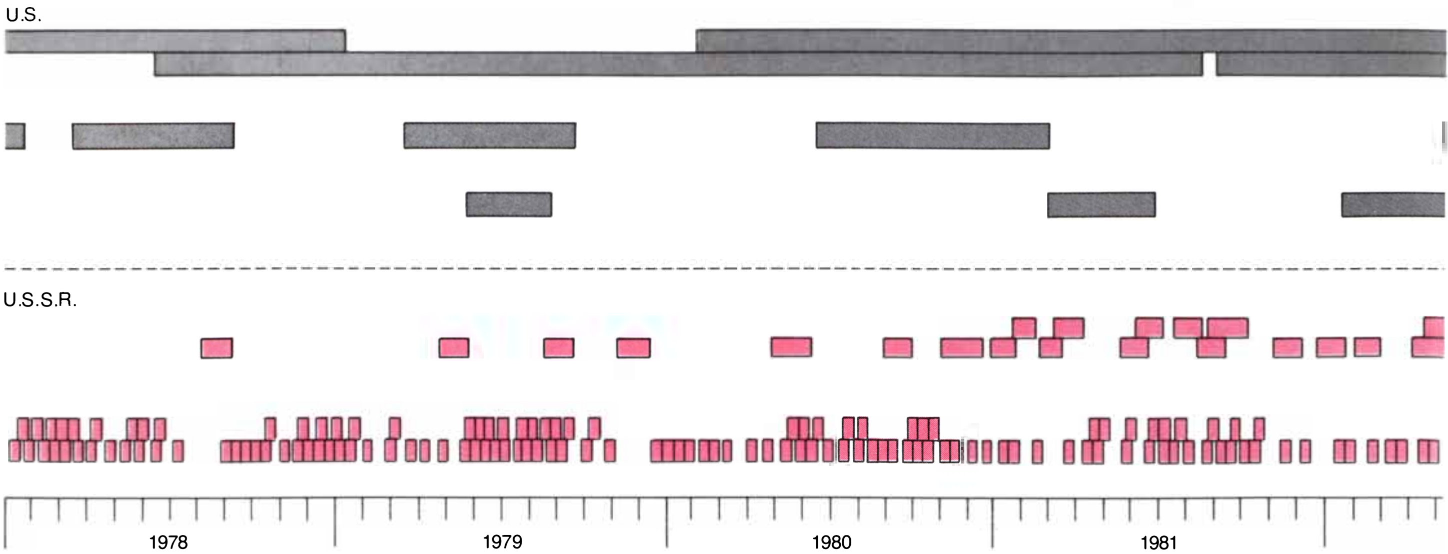
We therefore conclude that the current Russian antisatellite system presents a ponderous, inflexible and quite limited threat to the U.S. A similar assessment was given to the Senate by Air Force Chief of Staff General Lew Allen, Jr., on July 11, 1979: "I think our general opinion is that we give it a very questionable operational capability for a few launches. In other words, it is a threat that we are worried about, but they have not had a test program that would cause us to believe it is a very credible threat." Nothing has happened in the Russian test program since then to alter this 1979 assessment.

The U.S. direct-ascent antisatellite weapon is launched by a rocket small enough to be carried to high altitude by an F-15 fighter. The two-stage rocket boosts a device known as a miniature homing vehicle into the path of a target satellite on the basis of information supplied by the U.S. ground-based satellite-tracking network. The homing vehicle itself is a squat cylindrical object measuring about 30 centimeters in diameter and weighing about 15 kilograms. Homing is achieved through the combined action of eight infrared telescopes, a set of small thrusters and a laser gyroscope. The infrared sensors are able to see the target against the cold background of space. For stability the cylinder rotates, and the gyroscope determines when various thrusters are to be fired in order to bring the cylinder into the path of the target. The resulting high-speed collision suffices to destroy the target, but only extremely small homing errors are tolerable.

The maximum altitude of the U.S. antisatellite weapon has not been announced. Nevertheless, in congressional testimony it was revealed that the Joint Chiefs' highest-priority targets are satellites whose mission is to target U.S. forces—presumably photoreconnaissance



TYPICAL DISTRIBUTION of military satellites deployed by the U.S. and the U.S.S.R. at any given time is broken down in this bar chart according to two factors: orbital altitude and mission. The only satellites potentially threatened by the current generation of antisatellite weapons are those in comparatively low orbits, represented by first pair of bars.



CONTINUOUS COVERAGE by photographic reconnaissance satellites is achieved in two quite different ways by the U.S. and the U.S.S.R. In general U.S. military satellites are much more sophisticated, reliable and long-lived than their Russian counterparts; hence far fewer satellites are needed by the U.S. to maintain the same degree of coverage. In this illustration, covering the period from 1978 through 1983, U.S. photoreconnaissance satellites are represented by the gray bars and Russian photoreconnaissance satellites by the colored bars. The beginning of each bar marks the date the satellite was launched; the end of the bar marks the date it either returned to the ground or went out of operation. All photoreconnaissance satellites on both sides with an effective lifetime of three weeks or more are included.

and ocean-surveillance satellites at altitudes of 500 kilometers or less.

The first flight test of the new U.S. antisatellite system was conducted on January 21, 1984. According to the Department of Defense, an F-15 launched a rocket toward a point in space but without a miniature homing vehicle aboard. Further tests will include the homing interceptor itself, and the current test program will reportedly culminate in launches against target balloons in orbit. The system is supposed to become operational in 1987. The original plans called for two squadrons of specially equipped F-15's, to be stationed at McChord Air Force Base in Washington and Langley Air Force Base in Virginia.

The remarkably small size of the miniature homing vehicle means that the U.S. antisatellite system, if it is fully exploited, would be much more versatile than the current Russian system. In principle any F-15 can be adapted to carry the antisatellite weapon. Furthermore, carrier-based aircraft (or midair refueling of the F-15's) could carry the antisatellite weapon to an attack position almost anywhere in the world. If the U.S. were to invest in the required control facilities and bases, it could thereby acquire a force that could destroy all the low-orbit satellites of the U.S.S.R. in a matter of hours. Molniya satellites in highly elliptical orbits could also be threatened, but the U.S.S.R. would presumably put its early-warning and communications satellites into safer orbits before then.

In addition to the antisatellite weapons that are either deployed or well under way at least two other types can be expected in the next decade or so. The device that would appear to be most effective and most easily developed is the space mine. In principle it could threaten satellites in any kind of orbit. It could be on station for long periods, always parked close enough so that its detonation would destroy its victim. It could even be "salvage-fused" to explode if tampered with. The sophistication of a space mine would, however, depend on the type of satellite it is accompanying. A satellite that has poor maneuvering ability could be destroyed by a rather simple space mine. If the target satellite had on-board sensors and could maneuver effectively, the space mine would have to be a sophisticated device, perhaps one more complicated than current antisatellite interceptors, but it should always be cheaper than its quarry.

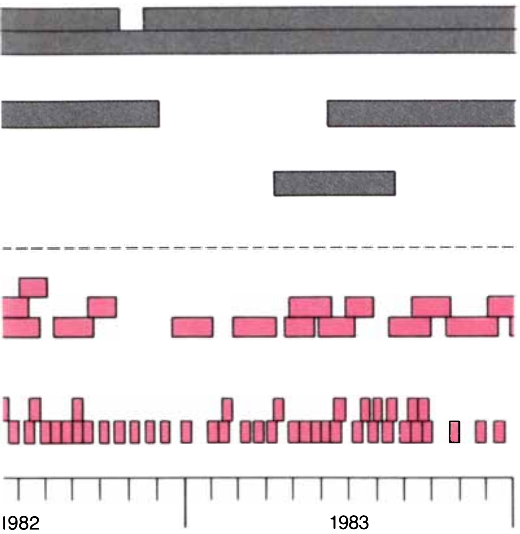
It is also possible to foresee antisatellite weapons that exploit "directed energy" beams. Indeed, the Defense Advanced Research Projects Agency is engaged in a demonstration program whose chief components are a two-megawatt infrared chemical laser and a sophisticated tracking and pointing system, which together could form the basis for an airborne antisatellite system. More speculative directed-energy concepts primarily intended for space-based ballistic-missile defense may also have a significant antisatellite potential in the more distant future.

With this overview of antisatellite technology in hand, we can now assess the threat antisatellite weapons could present in the future under a variety of assumptions. For the sake of clarity we shall focus on two distinct futures; the first future is one without any negotiated constraints on the development of antisatellite weapons, and the second is one in which all further flight tests of antisatellite weapons would be banned.

The characteristics of the U.S. antisatellite system demonstrate that in the unconstrained scenario it is entirely possible that by the end of the decade all low-orbit satellites could be threatened with virtually simultaneous prompt destruction. By that time space mines might be following geosynchronous satellites; eventually antisatellite weapons armed with lasers could also be available to attack high-altitude satellites.

As the antisatellite threat evolved, great effort would be devoted to protecting satellites. For example, satellites might be equipped with on-board threat-assessment equipment, jammers, deployable decoys and more powerful thrusters, enabling them to survive some attacks, although protection against intense laser beams would be difficult at best. Above all, the functions of satellites would have to be diversified; thus the current U.S. reliance on a small number of very complex multipurpose satellites would have to change. By the same token, the ability to quickly replace particularly valuable satellites would have to be developed. Such an elaborate effort is certain to be very costly and in all likelihood futile. A satellite with a sophisticated surveillance or communications mission is intrinsically fragile and expensive, and it cannot be expected to be a match for a simpler and cheaper device whose sole task is to destroy it.

Once antisatellite capabilities become too threatening, greater reliance would have to be placed on backup systems



The illustration was prepared by the editors on the basis of information compiled by the Stockholm International Peace Research Institute (SIPRI). The authors are not in a position to vouch for the accuracy of the data and so bear no responsibility for the illustration.

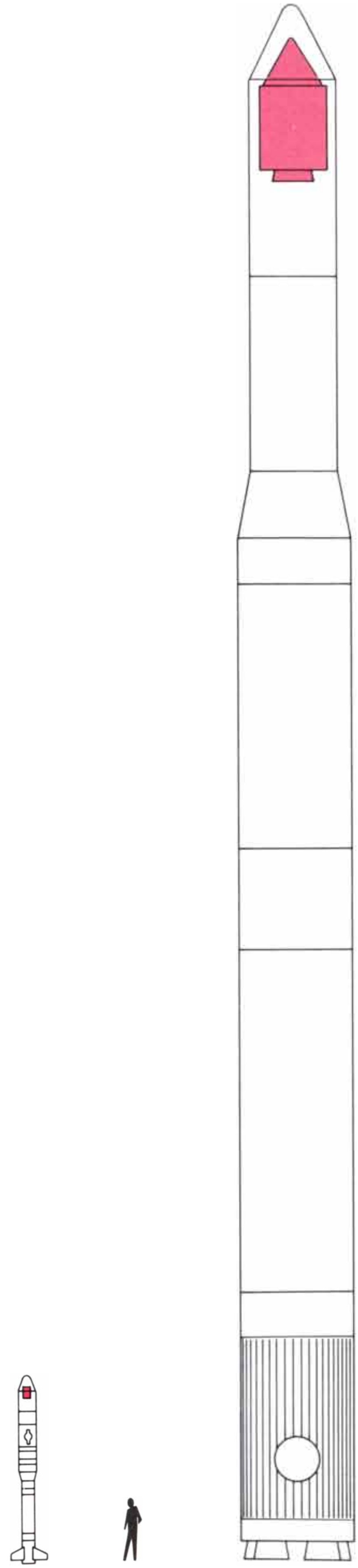
such as sounding rockets and airborne C^{3}I facilities. Such a development would be to the disadvantage of the U.S., which has its military forces spread around the globe and has come to rely heavily on space-based systems. For example, some 70 percent of long-range U.S. military communications are now relayed by satellites. The U.S.S.R., on the other hand, being essentially a continental power, has an elaborate land-based and airborne communications network. In the opinion of some experts, such as Stephen M. Meyer of the Massachusetts Institute of Technology, the Russians probably view their communications satellites as a backup to their terrestrial system.

Turning to the political and military implications of such a competition, we have already argued that an effective threat against satellites would reduce the chance that crises and conflicts at all levels could be contained. An antisatellite capability against geosynchronous satellites would have even graver implications, since it could enhance the likelihood of a strategic conflict and could destroy essential components of the system that supposedly would control a strategic nuclear war. In addition to these risks the competition in space weaponry would carry risks in itself. In an era of fierce technological competition, marked by numerous tests against objects in space, one must anticipate accidents and ambiguous events involving valuable spacecraft of one or both competitors. There would therefore be a serious risk that an unrestrained competition in space weapons could spawn grave crises and even armed conflict.

What about the second scenario, in which further flight tests of antisatellite weapons would be forbidden? This scenario would leave the U.S.S.R. with its existing system of very limited capability against low-orbit satellites. The U.S. would have a system that is potentially superior against the same targets; although the U.S. system would be only under development, it would be at a point where it could be deployed and operational within several years. Under this regime the U.S. would be free to enhance the security of its low-orbit satellites by diversifying their functions and increasing their maneuvering ability; if necessary, radar jammers could also be put on board. The result would be a modest Russian antisatellite capability whose reliability would erode in the absence of tests whereas the U.S. satellite fleet would become increasingly robust.

One must still ask whether a low-orbit antisatellite capability would be of such urgent importance to the U.S. military that the longer-term goals of crisis stability and arms-race stability should be ignored. To answer this question one must examine the targets that are cited for the U.S. antisatellite weapon. The first is the Russian antisatellite weapon itself. This is not a realistic objective, however, since the Russians could dispense tethered decoys near their antisatellite weapon for the comparatively short time it spends in space, thereby confusing the U.S. interceptor. Furthermore, the Russian interceptor may be able to maneuver enough to evade the U.S. homing vehicle.

Far more plausible targets are the Russian electronic-intelligence and radar-reconnaisance satellites, which have been of concern to the U.S. Navy. An assessment of the relative advantages and disadvantages of antisatellite weapons to the Navy has recently been given by Admiral Noel Gayler, formerly commander-in-chief of all U.S. forces in the Pacific and before that director of the National Security Agency. Admiral Gayler observes that it is fairly easy to jam or deceive a radar satellite, and that electronic intelligence can be denied



BOOSTER ROCKETS employed to launch the current antisatellite weapons of the U.S. and the U.S.S.R. are compared. The two-stage U.S. booster, which was test-fired from an F-15 fighter for the first time in January, is about five meters long; its payload (the nonexplosive homing vehicle) is some 30 centimeters long and weighs about 15 kilograms. The three-stage Russian booster, a modified SS-9 liquid-fueled ballistic missile initially deployed in the 1960's (and since then retired from the strategic nuclear forces), is approximately 45 meters long; its payload (the explosive antisatellite warhead itself together with its maneuvering engine) is roughly six meters long and weighs more than 2,000 kilograms.

only by circumscribing the signals sent out from ships, since if no special precautions are taken, such signals can be detected by other listening posts that need not be in space. High-data-rate communications from ships to satellites by means of sharply focused beams are now feasible, however, and they are difficult to intercept. According to this assessment, the safety of the U.S. satellite fleet is therefore of greater importance to the Navy's security than the ability to destroy Russian ocean-surveillance satellites.

Between the two scenarios we have just described—unrestrained competition and a test ban that constrains further development—there lies another possibility. It would allow both sides to keep and test their current low-orbit antisatellite weapons, but it would forbid the development and testing of all weapons that could reach satellites in geosynchronous or other high orbits. In such a situation satellites that are of importance to conventional military operations would be at risk, but those that are crucial to the strategic forces would still be secure.

An unrestrained competition in antisatellite weapons would also have an important impact on strategic weapons, because antisatellite weapons and ballistic-missile defense are closely related. This kinship is illustrated by the U.S. antisatellite system, since the miniature homing vehicle is essentially the same device designed for midcourse interception of ICBM's in the U.S. Army's Homing Overlay program. A detailed examination of the relation between antisatellite weapons and ballistic-missile defense has been presented in a recent paper by Donald M. Kerr, Jr., the director of the Los Alamos National Laboratory. The relation has also been invoked by George A. Keyworth II, the president's science adviser, who suggests that a laser antisatellite weapon be developed as a first step toward a space-based ballistic-missile-defense system.

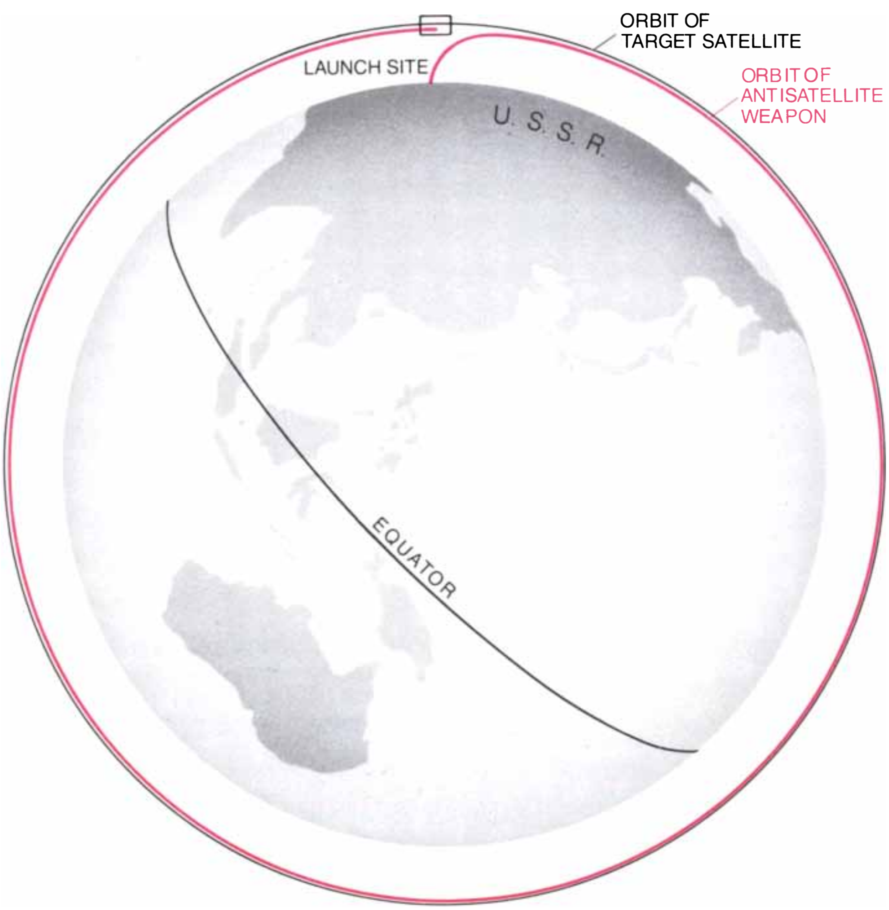
The technological kinship between antisatellite weapons and ballistic-missile defense has important political implications, because it exposes the most important loophole in the 1972 ABM Treaty. As the president's Arms Control Impact Statement of April, 1983, puts it, "the ABM Treaty prohibition on development, testing and deployment of space-based ABM systems, or components of such systems, applies to directed-energy technology or any technology used for this purpose. Thus when such directed-energy programs enter the field-testing phase, they become constrained by these ABM Treaty obligations." The ABM Treaty, however, does not forbid the development or testing of antisatellite technology; all it forbids is actual interference with "national technical means" of verification, namely satellites used for that purpose.

Until the ABM Treaty is complemented by a treaty restricting the development of antisatellite weapons it will be possible to claim that a weapon under development is intended to be an antisatellite weapon even though its ultimate purpose is for ballistic-missile defense. Unlike satellites, missiles are hard, small and readily surrounded by decoys, and they move along trajectories that must be determined at the time of interception. Therefore most putative ballistic-missile-defense systems would be effective antisatellite weapons long before they achieved any capability against ballistic missiles, and it would be difficult to refute such a claim for years.

This is particularly true of directed-energy weapons, which may be able to destroy a target at long range and therefore present a potential threat to geosynchronous satellites. Such a weapon, in a ballistic-missile-defense mode, must damage its target in a minute or less, whereas it could dwell on a satellite for hours. For all these reasons a weapon that is intended to have only an antisatellite capability would almost inevitably be perceived as a nascent ballistic-missile-defense system by the adversary. Since the cheapest and most effective response to ballistic-missile defense is a buildup of offensive strategic forces, such a buildup is a likely by-product of a vigorous and innovative antisatellite program.

A treaty on antisatellite weapons could have one or more of the following objectives: it could ban the testing, possession or use of such weapons; it could limit nondestructive interference with satellite functions; it could prohibit any tampering with satellites that would change their trajectory or attitude or permanently damage their ability to function; it could restrict rapid close approaches between any two space objects, no matter whose they are, in order to impede the practice of maneuvers having an antisatellite potential; it could institute "rules of the road" that would minimize unintended (or possibly intended) close encounters.

It would take us too far afield to examine all these useful measures. Instead we shall concentrate on those treaty provisions that in our view are essential if one intends to constrain the growth of the actual antisatellite threat with adequate verification of compliance. In broad outline these objectives were reportedly the ones sought by the U.S. in



CO-ORBITAL INTERCEPTION is the mode of attack adopted by the U.S.S.R. for its antisatellite system. The weapon is launched into an orbit roughly the same as that of its target but generally either slightly higher or slightly lower; in this case the antisatellite weapon is in a slightly lower orbit and so it catches up with the target rather than the other way around. In the

the negotiations that were suspended in 1979.

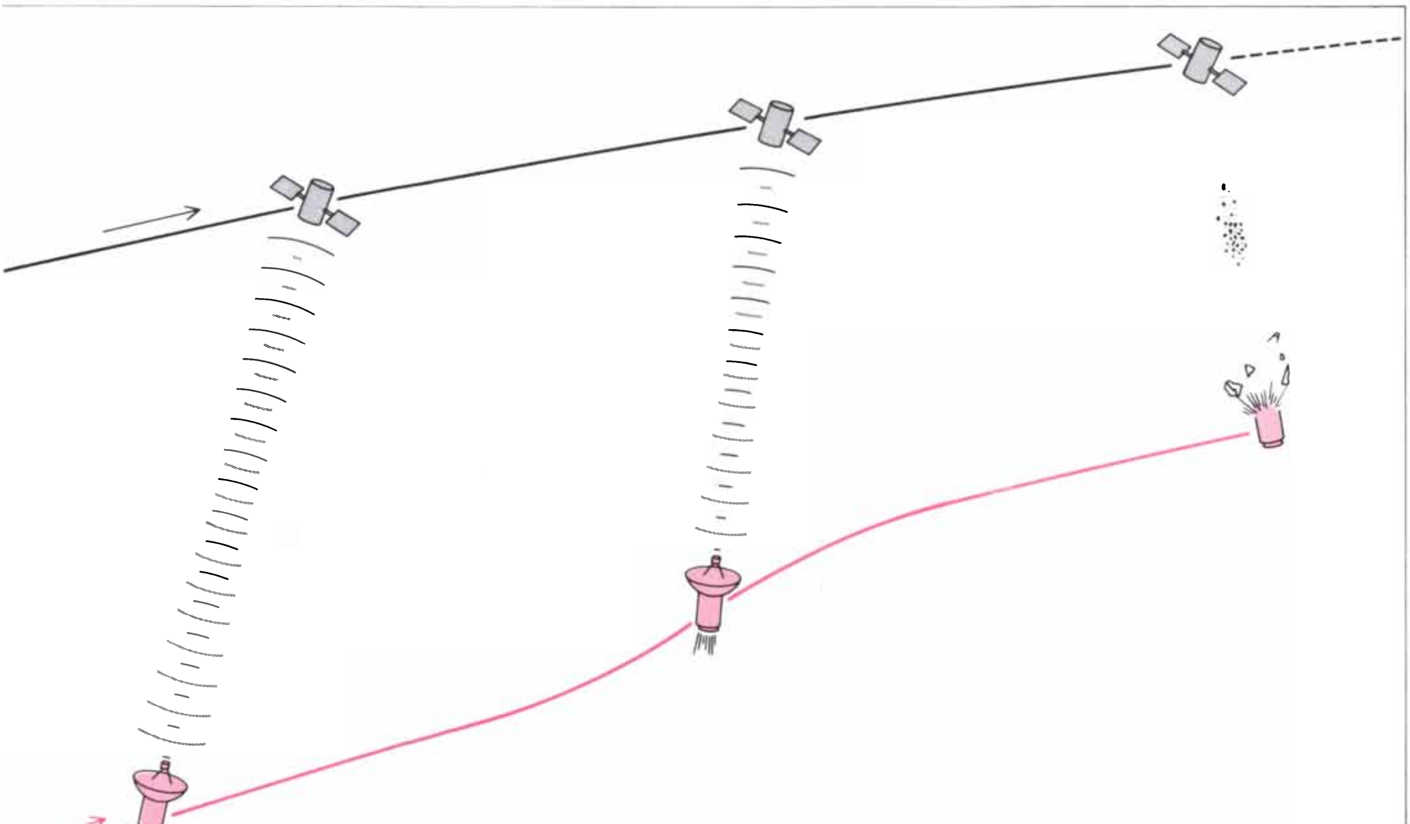
The growth of the antisatellite threat would be most effectively hindered by a ban on all tests of such a weapon against any object in space, no matter what the weapon's basing mode may be. Verification would be made reliable by forgoing a ban on the possession of antisatellite weapons, by placing no restrictions on countermeasures against satellites (as long as these activities cause no damage) and by forbidding tests of weapons from space against targets on the ground or in the atmosphere, since such activities could disguise antisatellite tests. Naturally a treaty would also forbid the use of weapons against the satellites of other nations.

A model treaty along these lines, drafted by a panel convened under the auspices of the Union of Concerned Scientists, was presented by two of us (Garwin and Gottfried), accompanied by Admiral Gayler, at a hearing held for that purpose by the Senate Foreign Relations Committee in May, 1983. The draft treaty submitted by the U.S.S.R. to the UN in August, 1983, is similar in key respects to our model treaty. The Russian draft treaty also calls for prompt dismantling of all antisatellite weapons, and it no longer contains most of the elements of the 1981 Russian draft treaty that were criticized by us at the Senate hearing. In his last public appearance President Andropov announced a moratorium on antisatellite tests by the U.S.S.R., which was to last as long as the U.S. refrained from testing.

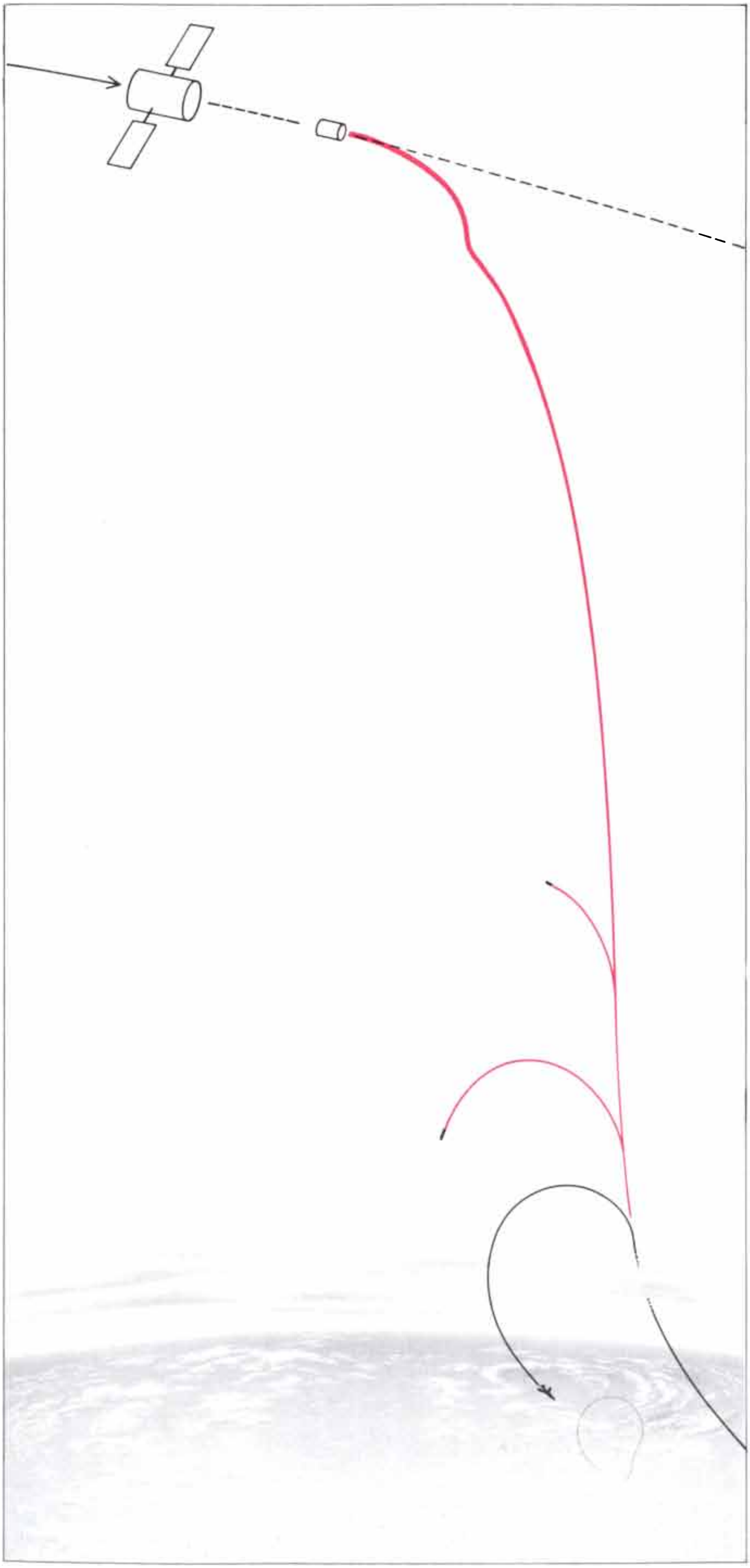
Could such a test ban be adequately verified? The U.S. has a global network of space-tracking radars and telescopes that enable the Air Force to keep track of all Russian space launches and space objects. Since the U.S. already has 15 years of experience in monitoring undisguised Russian antisatellite tests, clandestine tests of the present system could only hope to evade detection if they attacked a point in space instead of a target, and if they avoided unusual maneuvers characteristic of antisatellite weapons. In view of the record of the U.S.S.R. in this area it is unlikely much could be gained from such a highly constrained test program.

Monitoring of covert tests of new kinds of antisatellite weapon must be examined on a case-by-case basis, but all such tests would face an ever growing battery of surveillance facilities. The U.S. radar network has recently been upgraded to provide greater tracking accuracy and improved coverage. The Ground-based Electro-Optical Deep Space Surveillance (GEODSS) system, when it is completed in 1987, will provide highly detailed optical and orbital data on space objects ranging as high as those in geosynchronous orbits. Furthermore, under a test ban one might decide to develop space vehicles designed expressly for enforcing the ban. Such vehicles could photograph and track suspicious objects, measure their infrared emission to see whether they were being heated by lasers and monitor legitimate space and ground activities that have an antisatellite potential.

Although a test ban would put substantial obstacles in the path of antisatellite development, it would leave both sides free to protect their satellites against the remnant threat presented by whatever antisatellite capability continued to exist. Why not remove this residual threat by a ban on the possession of antisatellite weapons, particularly in view of the Russians' offer of such a ban? Naturally a ban would be helpful, but it should be recognized that it would be difficult to verify. Even the larger Russian interceptor could be secretly stored, not to mention the far smaller



final stages of the engagement, depicted in the enlarged view at the right, the antisatellite weapon and the target are in what are referred to as grazing orbits; the antisatellite weapon, relying on a radar-directed or optical/infrared homing device, closes in on the target in both the lateral direction and the along-track direction. The warhead then explodes, firing a shotgunlike blast of pellets toward the target. In all 20 tests since 1968 the weapon has been launched from a site in Kazakhstan. Interception has been on either the first or the second orbit.



U.S. weapon. Furthermore, if the Russians were to dismantle all the facilities capable of launching their antisatellite weapon, they would impede their space program.

Hence a ban on the possession of antisatellite weapons and the dismantling of facilities that have already been used in Russian antisatellite tests should be primarily viewed as a valuable confidence-building measure, not as a verifiable primary treaty provision. In any event, if the performance of the Russian antisatellite system were constrained to its present level by a test ban, the 1979 assessment of the Air Force Chief of Staff shows that the U.S.S.R. could not gain a significant military advantage by hiding a number of interceptors.

The Administration's attitude toward antisatellite arms control has at last been clarified by a report that was transmitted to Congress on March 31. The Defense Appropriations Act for Fiscal Year 1984 contains a provision that some $19 million for the antisatellite program can not be spent unless the president provided a report that would describe the "specific steps [he] contemplates undertaking . . . to seek a verifiable agreement with the Soviet Union to ban or strictly limit existing and future ASAT systems."

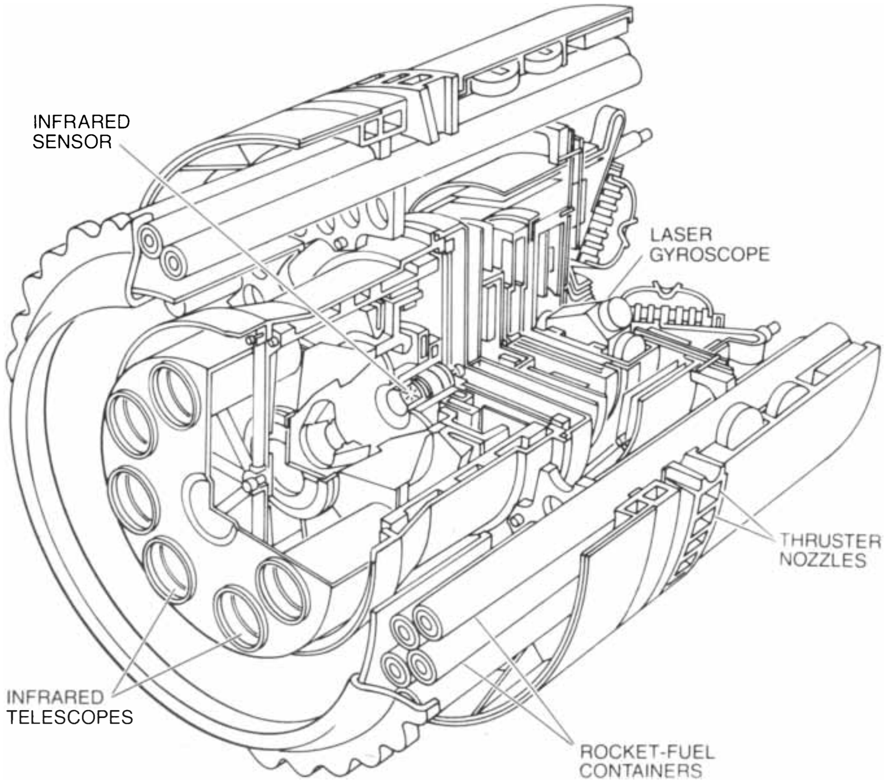
The essential conclusion of the president's report is that "no arrangements or agreements beyond those already governing military activities in outer space have been found to date that are judged to be in the overall interest of the U.S. and its allies," and that there is consequently no purpose in entering into negotiations at this time. Various arguments are cited in support of that conclusion: the possibility that the U.S.S.R. might retain a supply of antisatellite interceptors; the difficulty of monitoring antisatellite tests; the related threat of a sudden Russian deployment of weapons that had been developed clandestinely; the possibility that weapons not primarily intended for antisatellite purposes, such as ICBM's, could be used to attack satellites and their ground stations; the

DIRECT-ASCENT INTERCEPTION is planned by the U.S. for its antisatellite system. The F-15 launches the two-stage booster rocket in the general direction of the target on the basis of tracking information supplied by a control station on the ground. The miniature homing vehicle is propelled to orbital altitude by the boosters, which separate and fall away in succession as they exhaust their fuel. The weapon then follows a ballistic trajectory until it approaches its target, at which point the infrared homing system takes over and brings the vehicle into collision with the target. Destruction is by high-speed impact alone. The current test program will conclude with launches against target balloons in orbit.

problem of defining a space weapon (in the context of electronic countermeasures, maneuvering spacecraft and certain unspecified commercial systems), and the threat presented to U.S. forces, particularly the Navy, by Russian reconnaissance and targeting satellites.

Many of the issues raised by the Administration—the military significance of existing interceptors that could well remain in the Russian arsenal, the verification of a test ban, the vulnerability of the Navy to Russian satellites and the credibility of deterring attack on our satellites by threatening retaliation on Russian satellites—have already been dealt with here. We have not discussed the vulnerability of satellites and their support systems to attack by strategic weapons because that is a danger that can only be averted by remaining at peace; nor have we concerned ourselves with ill-defined and marginal threats. Nevertheless, several points deserve further comment.

First, there is the Administration's contention that adequate verification of a test ban is not possible. This contention rests on a comparison between an evolving weapons technology and a static verification capability, and it ignores the fact that the U.S. Government has revealed a detailed knowledge of the existing Russian antisatellite program. A treaty-constrained regime could, indeed should, be accompanied by appropriate investment in more powerful surveillance technologies. Congressional testimony on March 1 by Undersecretary of Defense for Research and Engineering Richard D. DeLauer in support of the "Star Wars" program describes ambitious plans for a space-based tracking and target-acquisition facility involving radar, laser and other techniques. This vast complex is supposed to achieve the ability to observe and track tens of thousands of space objects simultaneously, to discriminate among them and to automatically decide how they are to be attacked. It "must operate reliably even in the presence of disturbances caused by nuclear weapons effects or direct enemy attack." Obviously a far cheaper and simpler system could collect and analyze the data from the sporadic and isolated events that must be monitored in peacetime to retain confidence in an antisatellite test-ban treaty—a task that can be done at a leisurely pace by men and machines.



MINIATURE HOMING VEHICLE at the heart of the U.S. antisatellite system is a squat cylindrical device incorporating eight infrared telescopes, a laser gyroscope, a computer and a set of 56 small thruster rockets around the periphery. For stability the cylinder rotates about its axis of symmetry. The gyroscope determines when the thrusters are to be fired to adjust the vehicle's trajectory. Prime contractor for the weapon is LTV Aerospace and Defense Company.

Second, one must compare the cost of maintaining a given level of secure satellite capability in both the presence and the absence of antisatellite weapons. If such weapons are being developed and deployed, one must have a space-surveillance system that is far more versatile, quick-acting and robust than it would be if one is only monitoring a test ban. Satellites must be supplied with much better protective measures, and with a more elaborate backup system, if tested weapons are legitimately ready to attack them than would be the case in a situation where one only fears that a tightly constrained antisatellite threat may exist. In reckoning the cost of an antisatellite procurement program one must not forget the cost of these elaborate space-surveillance facilities, protective measures and backup systems.

Third, the Administration's statement draws no distinction between systems that potentially present a prompt and simultaneous threat against an entire constituent of a satellite fleet and systems that could attack only one or a few satellites in a way that would give warning for evasive action or replacement. The U.S. interceptor and future directed-energy weapons belong in the first category; the Russian co-orbital interceptor, maneuvering spacecraft and commercial satellites belong in the second. It is the first category that represents a significant military threat and is also most readily constrained by a test-ban treaty.

In judging the value of any arms-control proposal one must recognize that no treaty can be verified to perfection. What finally counts is whether the activities that could plausibly escape detection present a greater risk than the perils a treaty-free regime would produce. With this observation in mind, let us strike the balance between the alternative futures we have postulated. The first regime, marked by unconstrained competition, would eventually expose all satellites to the threat of prompt destruction; hence there would be a growing risk that crises and conflicts would run out of control. In the second regime, constrained by a test-ban treaty, satellites would not be absolutely safe, but the dangers they would face would evolve slowly, would be quite well understood and could be countered by readily attainable measures at reasonable cost.

The unconstrained regime is to be favored only if one side or the other expects to attain a persistent advantage in weapons that can destroy satellites and ballistic missiles. We have no such expectation. The entire post-Hiroshima experience demonstrates that neither superpower can long maintain a military advantage in any technology presenting a grave threat to the other, and that the outcome of all such competition is a reduced level of security for both sides. There is no evidence that an unrestrained contest in space weaponry would be an exception to this rule.

Pre-Columbian Surface Metallurgy

The metalsmiths of Andean cultures knew how to plate copper with gold or silver and how to treat alloys of copper, gold and silver so that the surface of the metal consisted only of gold

by Heather Lechtman

When the Spanish conquistadors melted down the gold and silver objects they looted from the Incas, they were surprised to discover that the bullion they got was quite impure. Although the objects appeared to be made out of silver or gold, they were actually alloys of those metals with copper. At least a millennium before the rise of the Incas, Andean metalsmiths had developed these alloys along with procedures for treating them so that the finished objects presented a surface of pure silver or pure gold. The smiths also knew how to plate objects made entirely out of copper with a thin coating of gold or silver.

My colleagues and I at the Massachusetts Institute of Technology Laboratory for Research on Archaeological Materials have long been engaged in interpreting the development of metallurgy in the Americas during pre-Columbian times. One focus of New World metallurgy was the production of metals and alloys that could be specially treated to display colors highly valued in the culture of their makers. Therefore in recent years we have concentrated our efforts on describing the sophisticated processes Andean metalworkers devised to impart the colors of gold and silver to objects made out of other metals.

Through metallurgical examination of artifacts from many periods of Andean prehistory we have identified two main coloring techniques: electrochemical replacement plating (as distinct from electroplating) and depletion gilding or silvering. We have reproduced both coloring methods in the laboratory with only such materials and techniques as were available to the metalsmiths of the time. In every instance the materials and techniques were suggested by close examination of the artifacts themselves. The smiths who invented and elaborated these methods were members of societies in the central Andean area.

Among the high cultures of Andean South America known to us through archaeological investigation, the earliest were the most instrumental in the development of metallurgical technologies. They include Chavín, with its center in the northern highlands of Peru (about 800–400 B.C.), Moche, consisting of several river valleys on the desert northern coast of Peru (about 100 B.C.–A.D. 800), and Chimú, the large coastal state extending from the Moche heartland almost to the Ecuadorian border (about A.D. 1150–1476). Spanish records indicate that the Incas brought the best Chimú goldsmiths and silversmiths to the imperial capital at Cuzco.

Moche metalsmiths were by far the most sophisticated artisans within the Andean metallurgical tradition. Their virtuosity and the quality of their products were unequaled by any of the succeeding cultures, including the Inca. The Inca rulers relied heavily on the metallurgical technologies first established by the Moche, turning objects with the appearance of gold and silver to their political advantage in governing an empire that extended some 3,000 miles from Colombia to Argentina.

Recently a large number of metal objects of Moche style were found on the far northern coast of Peru near the Ecuadorian border. The site of the discovery is known as Loma Negra, and most of the objects are made out of hammered sheet copper. Sheet-metal work, as opposed to casting, is a key characteristic of Andean metallurgy. Individually shaped pieces of sheet copper had been joined to create three-dimensional forms and figures. When the Loma Negra pieces were unearthed, they were covered with characteristic green corrosion products, chiefly oxides and carbonates of copper, that had formed during their long burial. Removal of the corrosion products showed, however, that the copper had originally been covered with a thin coating of silver or gold, so that the objects would have appeared to be made entirely out of those precious metals.

Metallographic examination in our laboratory of small samples removed from some of the Loma Negra pieces revealed that many of the surface coatings were so thin, measuring between .5 micrometer and two micrometers in cross section, as to be nearly invisible at magnifications up to 500 diameters. Our studies led us to the following characterization of the surfaces. First, the coating on any one object was remarkably uniform in thickness and covered all its surfaces, including edges that were paper-thin. Second, a solid-state diffusion zone between the surface layer of precious metal and the underlying copper indicated heat had been applied to the objects at some stage in the coating process. Third, the Loma Negra artifacts showed no evidence of any familiar plating technique, such as mercury gilding, the application of gold foil or gold leaf, the flushing on of molten gold, sweat-welding or Sheffield plating.

The most impressive characteristic of the Loma Negra coatings is their extreme thinness and evenness. At the same time they could not possibly have been the product of what they most resemble: modern electroplating. In electroplating, precious metals, present as ions in an electrolyte bath, are deposited onto baser metals immersed in the bath. An external source of electric current, such as a battery, drives the plating process by reducing the ions to metal at the negative electrode.

Nevertheless, the quality of the Loma Negra surface coatings strongly suggested they had been deposited by some form of plating. What other techniques of deposition could have been available to the Moche metalsmiths? One such technique, of considerable antiquity in the Old World, is known as electrochemical replacement. The Romans exploited it to plate iron with copper, and by the ninth century of the Christian Era it was employed to prepare iron for gilding. Eighteenth-century European armorers relied on the same technique to decorate iron and steel armor with gold.

The 18th-century European procedure varied according to the metal to be gilded. When silver or copper were to be plated with gold, an aqueous solution of gold was prepared by dissolving the metal in a bath of aqua regia (a mixture of hydrochloric and nitric acids). When iron or steel were to be plated with gold, the gold was dissolved in a solution of common salt, saltpeter and alum. In either case once the gold was in solution the bath was heated to dryness. Gold chloride ($AuCl_3$) was extracted with alcohol (or, in the 19th century, with ether) from the complex mixture of desiccated salts, and the alcoholic solution was then applied to the object to be gilded. None of the distilled acids (nitric, sulfuric and hydrochloric) discovered in Europe between the 12th and 16th centuries and capable of dissolving gold and silver was known, however, to the Andean metalworkers.

At the same time the dry deserts of the Peruvian coast do not lack for corrosive minerals that were readily available to Andean metalworkers. We decided to attempt the dissolution of gold in aqueous solutions of corrosive salts that might have been used by the Moche. The simplest and most effective method we devised was to prepare a corrosive bath by dissolving in water equal parts of potassium aluminum sulfate, potassium nitrate and sodium chloride (common salt). Gold heated gently in this mixture for two to five days dissolves readily. (The mixture, incidentally, contains among other ions those present in aqua regia.) The solution is highly acidic, however, and immediately attacks any copper immersed in it. We had to neutralize it before any gold in the solution could plate out onto the copper. The salt we found most effective for this purpose was sodium bicarbonate ("baking soda"), and the optimum *p*H (the standard measure of acidity or alkalinity) for plating proved to be 9, or somewhat alkaline.

After five minutes of gentle boiling, a sheet of copper immersed in the neutralized solution was uniformly coated with gold on all its surfaces, edges included. The gold film was approximately one micrometer thick. The plating process by itself, however, was rarely sufficient to bond the gold to the copper permanently. Unless the copper was extremely clean and free of oxide the gold layer tended to pop off.

Our metallographic studies of the Loma Negra objects revealed a distinct zone of solid-state diffusion between the

MINIATURE MASK from Loma Negra, a site of the Moche culture in northern Peru, was covered with copper oxide after centuries of burial (*top*). Removal of the visor revealed that the surface under the oxide was gold (*middle*). After the oxide was removed the sheet-metal object shone brightly (*bottom*). The gold had been applied by electrochemical plating.

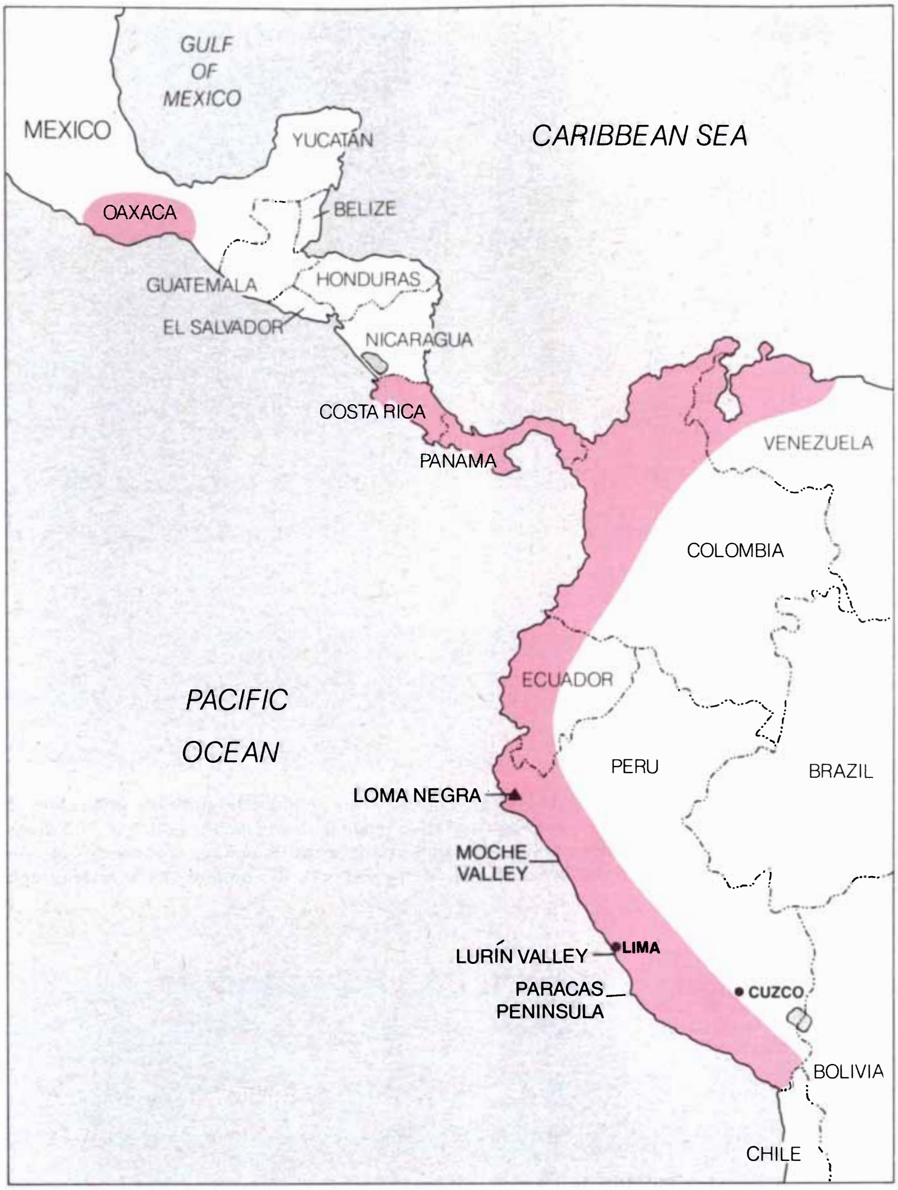
MUMMY MASK of the Chimú culture, the largest such mask discovered so far, is 74 centimeters wide and 40 centimeters high. The ingot that was hammered into the sheet metal for the mask was 40 percent gold, 48 percent silver and 12 percent copper. Such an alloy is known as tumbaga. The sheet was repeatedly hammered, annealed (heated so that it recrystallized) and pickled (chemically treated to remove copper oxide scale). The result was a surface that was depleted in copper. The silver in the remaining silver-gold surface layer was then removed with a corrosive paste. Finally the remaining gold surface layer was burnished. The method is termed depletion gilding.

PAIRED BIRDS from the area of the Quimbaya culture in Colombia were made by casting rather than hammering but were also produced from the gold-silver-copper alloy tumbaga. The copper on the original surface was probably dissolved away by acid plant juices.

gold layer and the underlying copper, indicating that the Moche smiths had heated their plated copper to achieve a strong metallurgical bond at this interface. When our laboratory-prepared samples were heated for only a few seconds in the temperature range between 650 and 800 degrees Celsius, we also achieved excellent bonding between the gold plate and the copper substrate.

Our experiments were eventually successful in producing electrochemically deposited gold platings that quite closely resembled those on the Loma Negra artifacts both in their surface visual characteristics and in their microstructure. These results strongly suggest the Andean smiths achieved their platings in much the same way, dissolving gold and silver in aqueous solutions of corrosive minerals common to the deserts of the Peruvian coast. It is possible their familiarity with these minerals had been acquired in the course of the development of other Andean technologies such as textile dyeing. Whatever the origins, it seems that utilization of natural corrosives was an early and dominant factor in Andean surface metallurgy.

Electrochemical replacement plating occurs when a metal at the "base," or negative, end of the electromotive series, such as copper, is placed in an electrolytic bath that contains ions of a metal at the "noble," or positive, end of the series, such as gold. The chemical reaction is a simple replacement one, the copper replacing the gold in solution: $2AuCl_3 + 3Cu \rightarrow 2Au + 3CuCl_2$. Such an equation does not, however, reveal the mechanism behind the plating process. That mechanism is identical with the one in the first simple cells devised by modern electroplaters. It requires anodic (electrically positive) and cathodic (negative) areas, both of which must be in contact with the electrolyte, and a circuit for electrons to flow from the anode through the metal to the cathode, balanced by the return flow of ions through the electrolyte. Unless the geometry is such that the anode areas are steadily in contact with the electrolyte, only an infinitesimal deposit will form before the electrode potential is the same everywhere and the plating action stops.



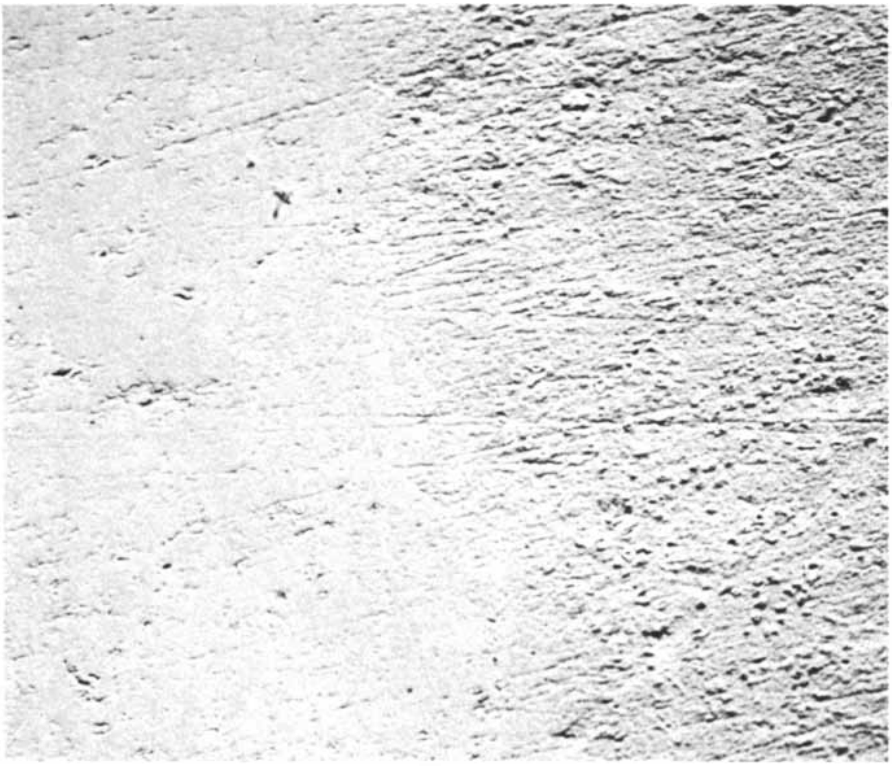
AREAS OF THE NEW WORLD where depletion gilding and silvering were practiced are indicated in color. Depletion methods were in use in Peru as early as the second millennium B.C. The Andean metalsmiths worked principally with sheet metal. The metalworkers from Colombia northward to western Mexico preferred to cast the tumbaga alloy by the lost-wax method.

When a metal is plated by the replacement method, both the anode and the cathode areas are provided by different parts of the same metal surface. In our own experiments, as must have been the case for the Moche smiths, small pits or irregularities on the surface of the copper sheet initially act as anodes. They continue their anodic activity until they are completely sealed off from the electrolyte by the gold that is plating onto adjacent cathodic surfaces. The anodic and cathodic areas remain in a delicate balance depending on the availability of ions, the rates at which ions diffuse through the electrolyte and the degree to which the areas are electrically polarized. A good deposit results only when the anodic areas have shrunk to the point of near-invisibility but are not yet completely sealed off from the electrolyte.

The Andean tradition of hammering out sheets of metal and joining them to produce three-dimensional objects may have led to the discovery of another method of enriching a surface with precious metal. The method, to which I shall refer as depletion gilding or depletion silvering, began with the casting of an ingot consisting not of copper but of an alloy of various proportions of copper and silver, of copper and gold or of all three metals.

Hammering such an alloy hardens it, and as the ingot is worked into a sheet, gradually reducing its thickness, the metal eventually becomes too hard and brittle to shape any further. When this point is reached, the smith must anneal the piece: bring the metal to a dull red heat so that it recrystallizes and regains its malleability.

The earliest of the Andean alloys known to archaeology is one of copper and silver. Its malleability allowed it to be shaped by hammering, and the toughness it developed on hammering ensured that once it was formed it would retain its shape. When in the course of being worked a sheet of copper-silver alloy is annealed to restore its malleability, copper at the surface reacts preferentially with oxygen in the air to form a layer of copper oxide scale. The silver is



SURFACE OF A SHEET electrochemically plated with gold in the author's laboratory at the Massachusetts Institute of Technology and then partially burnished is enlarged 500 diameters in a scanning electron micrograph. The underlying metal is copper. Boundary between the burnished area (*left*) and the unburnished one (*right*) is in the middle of the micrograph.

UNBURNISHED PART OF THE SHEET, enlarged 2,000 diameters in this scanning electron micrograph, is covered with craterlike pores. The pores are artifacts of the electrochemical plating process; each pore is at the site of an anodic (positively charged) pit in the underlying copper. In such plating the copper is immersed in an electrolyte in which gold has been dissolved. The gold plates onto the surfaces adjacent to the anodic pits; the surfaces are cathodic (negatively charged). In building up, the gold forms a slightly elevated ring around each pit.

less readily oxidized; hence after the repeated sequences of annealing, descaling, hammering and reannealing that are necessary to the manufacture of metal sheet, there gradually forms a surface layer much depleted in copper and correspondingly enriched in silver.

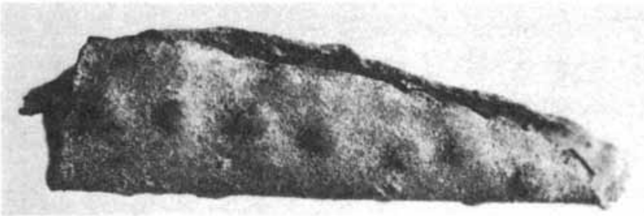
Indeed, after several such cycles the surface of the sheet looks like nearly pure silver, because that is what it has become. The copper oxide that forms in the course of each annealing is brown to black. To pickle the sheet, that is, to remove the scale by dissolving it, the Andean smiths could have applied to it stale urine (the urea in fresh urine degrades to ammonia) or the acid juices of certain plants. In either case the formation of a silvered surface was an inescapable consequence of annealing in air.

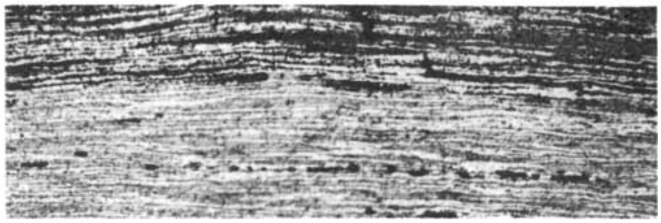
A few Andean objects made of copper-silver alloys are known to predate the flowering of Moche culture. Moche smiths, however, excelled in their utilization of these materials. They worked with alloys over a wide range of silver concentration: from more than 50 percent silver by weight down to about 20 percent. The objects they manufactured were hard and tough and looked like silver. In post-Moche times the same kinds of alloys continued to be used for the same reasons.

By far the most important alloy developed by the Moche, however, was a mixture of copper and gold known as tumbaga in the Caribbean, where the Spanish acquired the word. When copper and gold are melted together, they readily mix. When they cool and solidify, they remain mixed; they form a series of solid solutions throughout the range of possible proportions. Pre-Columbian copper-gold alloys vary widely in composition: some contain as little as 12 percent gold by weight. The color of the alloy depends on its composition. Tumbagas with a high concentration of copper are red or pink; those high in gold are yellower.

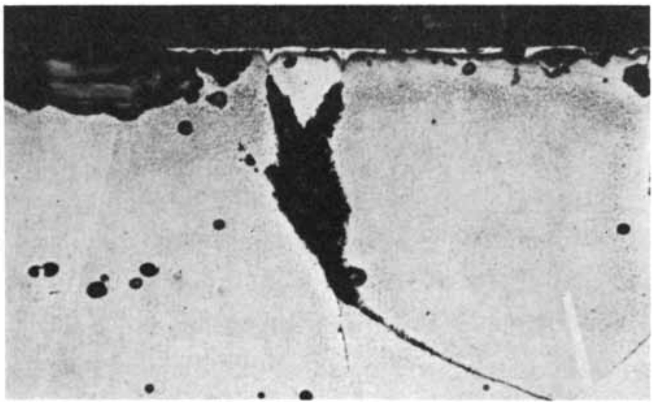
Silver is also found in many of these alloys. This may be because gold was added to a silver-copper alloy or because the gold already contained some silver, as gold nuggets from Andean stream beds often do. In any event the alloy, whether it consisted exclusively of gold and copper or contained silver as well, still went by the same name: tumbaga. Although tumbaga was first produced in the central Andes, it later became common to many parts of pre-Columbian South and Central America and was known as far north as Mexico.

The annealing of a copper-gold sheet, like the annealing of a copper-silver one, eventually yields a surface enriched in the precious metal as increasing amounts of copper are lost through oxidation. The surfaces look like pure gold. When silver is also a component of the

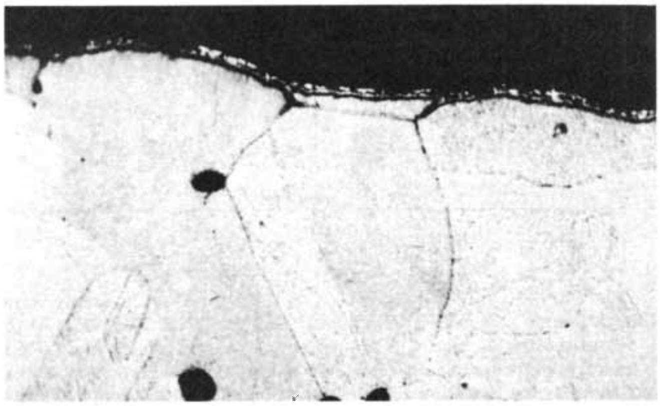




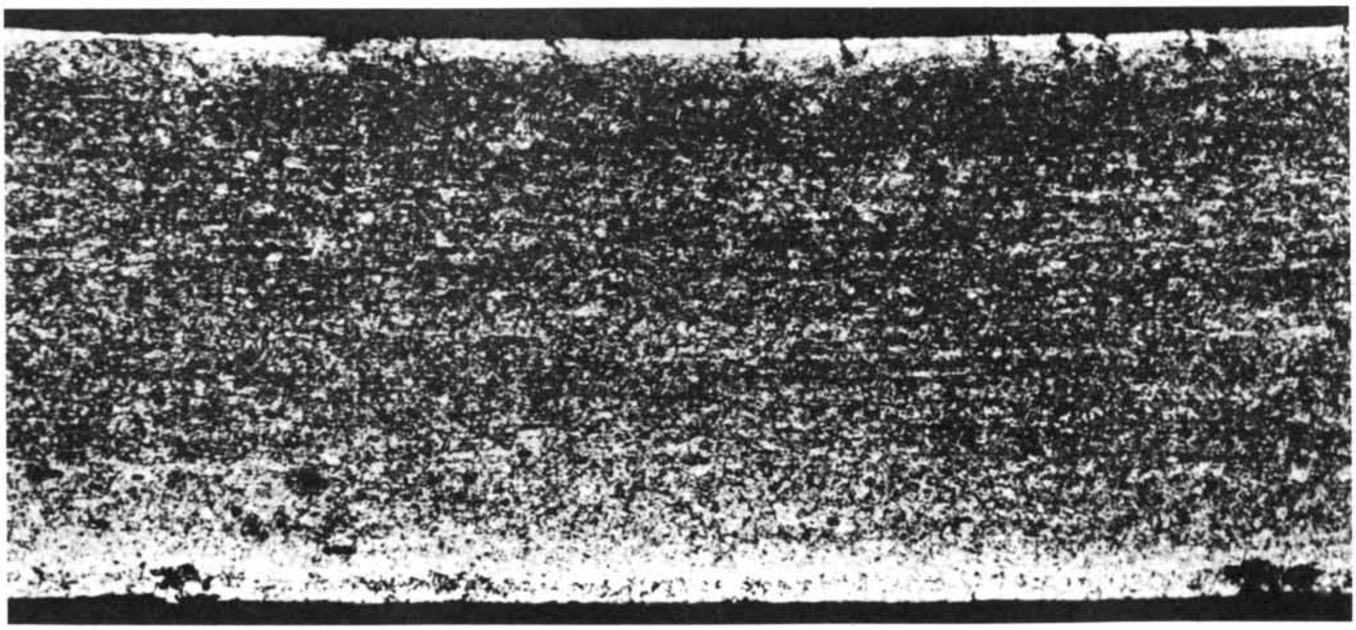
PERUVIAN BEAD at the left, from the Lurín valley site of Malpaso, is made out of an alloy of copper and silver. It was given a surface layer of silver alone by repeated hammering, annealing and pickling. Only 20 millimeters long, the bead is the earliest Andean example of a copper-silver alloy known. A cross section through the bead is enlarged 500 diameters in the light micrograph at the right. When the ingot from which the sheet metal was formed originally cooled from the molten alloy, it separated microscopically into a phase rich in silver and a duplex eutectic consisting of silver-rich and copper-rich phases. (A eutectic is the composition of an alloy that has the lowest melting point.) Subsequent hammering and annealing caused the silver-rich and copper-rich phases of the alloy to separate more or less completely, as is indicated by the alternating layers that are visible in the micrograph. The copper-rich layers have also corroded.



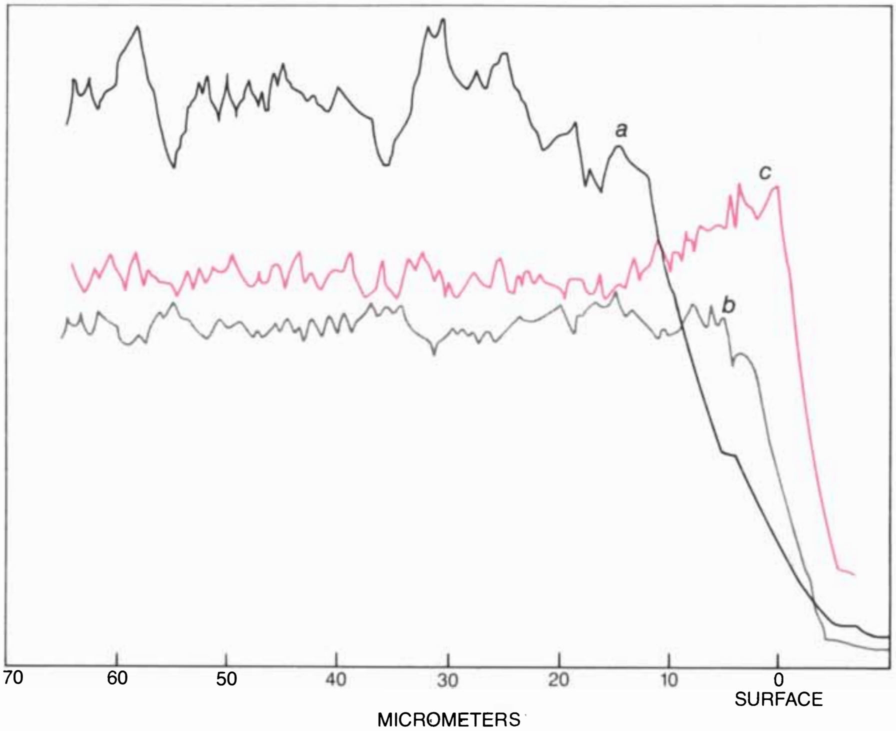
GOLD-PLATED COPPER SHEET from a Loma Negra figure is seen in cross section enlarged 500 diameters in a light micrograph. The thin light-color surface area is the even layer of gold deposited by electrochemical plating; in some places the layer is as little as .2 micrometer thick. The *V*-shaped line at the lower right marks the boundary of a crystal grain of copper. The much smaller *V*-shaped thickenings within the gold layer itself result from the diffusion of gold along the boundaries between the copper grains when the piece was heated to bond the two metals. The small round black areas in the micrograph are copper oxide; the larger black areas are zones of corrosion.



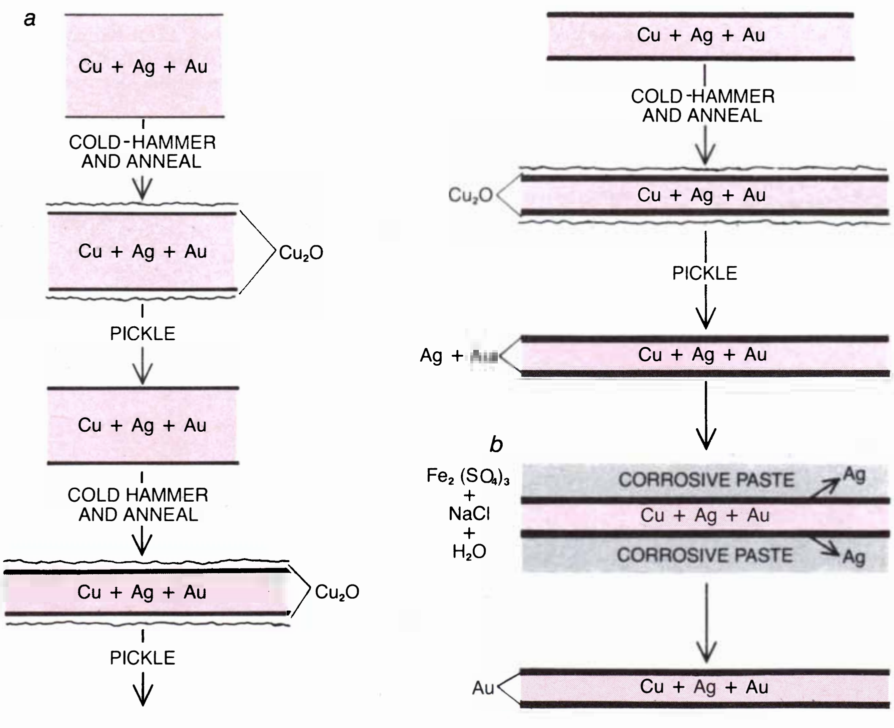
ANOTHER COPPER SHEET was electrochemically plated in the author's laboratory by immersing it in an electrolyte bath containing gold in solution. The bath consisted of an aqueous solution of corrosive minerals that would have been available to Moche metalsmiths; the minerals are found in abundance in the dry deserts of the Peruvian coast. In this light micrograph the surface of the sheet has been enlarged 1,000 diameters. After the specimen had been plated it was annealed for 15 seconds by the application of a hot flame. As with the Loma Negra sample, this heating made the gold diffuse along the boundaries of the copper grains, thus bonding the two metals.



SAMPLE FROM THE CHIMÚ MASK shown on page 40 is seen in cross section in a light micrograph enlarging the section 200 diameters. The two surfaces are lighter in appearance than the interior of the sample. This reflects the enrichment of the surfaces in silver and gold as the process of depletion gilding removed the copper in the alloy by subjecting it to repeated cycles of annealing and pickling. The striations in the sample represent phases of different compositions that have become elongated through repeated hammering.



CONCENTRATION PROFILES of the same Chimú sample show how the concentration of each metal (gold, silver and copper) changes from the middle of the cross section (at the left) outward to its surface. The copper concentration (*black*) remained relatively uniform until the analyzing electron beam came within about 12 micrometers of the surface of the sample (*a*). Here the concentration fell, marking the zone where copper had been removed from the surface. The silver concentration (*gray*) also remained relatively constant until the electron beam came within about five micrometers of the surface (*b*). At that point the silver fell off rapidly, corresponding to the depletion of silver from the surface. The gold, however, began rising in concentration at the same distance below the surface where the copper concentration abruptly fell. It continued to rise and peaked when the beam reached the edge of the sample (*c*).



DEPLETION GILDING is portrayed schematically. The first stage (*a*) consists of cold-working an ingot of copper alloyed with silver and gold, annealing the metal so that copper oxide appears on its surface and then pickling before resuming hammering. By the time the sheet has reached the desired thickness a surface layer has developed that is composed of a mixture of silver and gold. The next stage (*b*) calls for coating the surface of the sheet with a corrosive paste of ferric sulfate and salt. The paste dissolves the silver, leaving at the surface only the gold.

alloy, however, the surface becomes enriched in both precious metals and its color varies from silver-white to pale yellow. If the smith wants a richly golden surface, the silver must be removed.

Parting silver from gold without distilled acids is not simple, but the Moche were able to do it, probably by applying naturally corrosive mineral mixtures to the surface of the sheet. Indeed, our laboratory experiments showed that silver is quite effectively removed from the surface of a gold-silver-copper alloy sheet treated with an aqueous paste of ferric sulfate and salt. When ferric sulfate is so used, it is nearly as effective as sulfuric acid. The same procedure was continued by the Chimú, who later dominated the northern coast of Peru until their kingdom was conquered by the Incas in about A.D. 1476.

Of the large and impressively golden Andean mummy masks familiar to museum visitors many if not most are of Chimú manufacture. The largest example known, currently in the collection of the Metropolitan Museum of Art in New York, is made out of sheet metal and is 74 centimeters wide and 40 centimeters high. Its gold surface is dazzling, but our laboratory analyses revealed that the metal is a tumbaga alloy containing only 40 percent gold; the remainder is 48 percent silver and 12 percent copper. When we cast an alloy of the same composition, the ingot was pale pink in color. Yet this particular object is relatively rich in gold. Some Chimú smiths made gleaming gold sheet metal from ingots containing as little as 12 percent gold; the rest of the alloy was mainly copper.

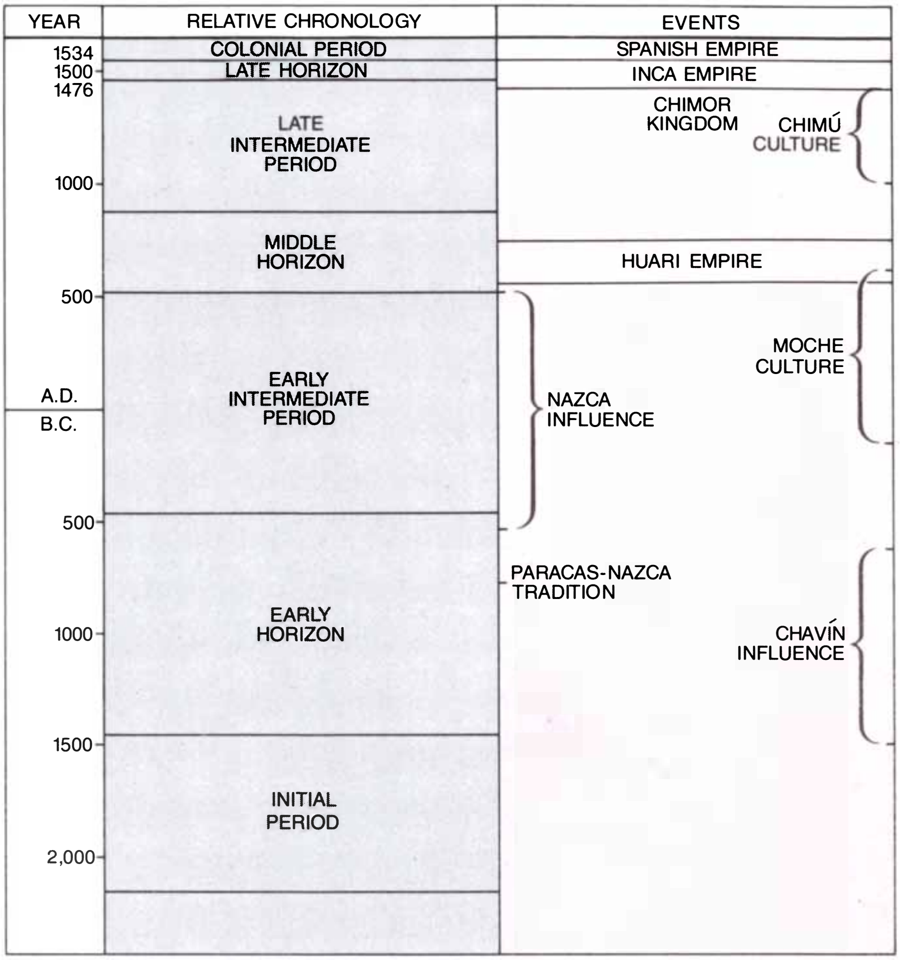
The tumbaga alloys, with their inherent properties for surface enrichment in gold, were in common use when the Spaniards established themselves in Mexico, Central America and South America in the 16th century. Whereas in the central Andes tumbaga was used primarily to produce gold-colored sheet metal, farther north in South America and in Central America and Mexico it was cast into three-dimensional forms.

Once objects made of tumbaga are cast, they can be depletion-gilded directly by dissolving the surface copper with a corrosive solution. No annealing is necessary. If the alloy contains little gold, however, repeated annealings and picklings are needed to produce a coherent enriched surface layer. Sometimes the smith juxtaposed different surface colors on the same casting by chemically treating only selected areas of the tumbaga; in this way it was possible to contrast the goldenness of the treated surface with the redder color of the untreated alloy. On occasion the smiths made single objects of tumbagas with differing proportions of precious metal, casting one alloy onto the other to enhance the surface-color contrast of various parts of the object.

Electrochemical replacement and depletion silvering or gilding were not the only methods of surface treatment devised in the pre-Columbian New World to give a base-metal substrate a precious-metal appearance. The smiths also flushed objects with molten gold and covered metal surfaces with gold foil, but they resorted to those methods far less often. Indeed, even electrochemical replacement plating (essentially a "cover and hide" technique) had no more than a local and brief impact on pre-Columbian metallurgical practices. It was depletion surface metallurgy (in contrast a "development and enhancement" technique) that dominated New World metallurgical technology for nearly two millenniums.

The explanation for this commitment to what can only be defined as a technological style can be sought in the realm of cultural attitudes and ideologies. Are we able to reconstruct what Andean attitudes toward metals may have been? To a certain extent we can. Consider the development of metallurgy in the Old World during prehistoric times. It is clear that the important metallurgies of the Bronze and Iron ages in Europe and the Near East received their greatest stimulus in the domains of warfare, transportation and agriculture. Weapons and tools were central to Old World metallurgy, and metalworkers sought and developed the mechanical properties that were necessary to the proper performance of such manufactures: hardness, sharpness, the ability to retain a cutting edge, strength on impact and strength in tension.

In the New World the emphasis in metal production was quite different. The objects that were at the center of metallurgical attention served in the domains of life associated with political power, the display of social status and the communication of religious belief. Such objects, the attributes of rank and power in the world of the living and the world of the dead, included elaborate earspools (a form of earring), nose rings, religious cult objects and death masks fitted onto mummy bundles such as those made by the Chimú. In anthropological terms, in New World societies metals served important symbolic functions. The impetus of Andean metallurgy lay in the development of those properties of metals and alloys that helped to achieve such functions. The most important property was color, and the two colors that were paramount in the New World metallurgical spectrum were silver and gold.



CHRONOLOGICAL TABLE presents major phases of Andean prehistory from 2000 B.C. (the Initial Period) up to the time of the Spanish conquest in A.D. 1534 (the Colonial Period).

We know from Spanish accounts of Inca religious and political life that the royal family claimed descent from the union of the sun and the moon. The Incas considered gold "the sweat of the sun" and silver "the tears of the moon." Thus both metals figured prominently in the origin mythology of the royal dynasty and were completely controlled by the emperor. The Spaniards marveled at rooms in Inca palaces filled with indoor gardens whose plants, flowers and birds all displayed the colors of these precious metals. Yet the Andean commitment to the colors of silver and gold was founded centuries earlier, in about 1000 B.C., with the spread of the Chavín religious cult through large regions of the central Andes. Gold religious objects functioned prominently in Chavín ritual, and the first use of copper-silver alloy came in this period.

If Andean metallurgy was color-oriented, it was also surface-oriented. The color of a metal object resides at its surface. Indeed, as we have seen, an object may have one color at the surface and a quite different one underneath. It is not remarkable, therefore, that the most innovative aspects of Andean metallurgy arose as a response to achieving the culturally desired colors of silver and gold. Both electrochemical replacement plating and depletion gilding and silvering conferred the appropriate colors on metal objects not entirely made out of either of the precious metals.

Within this general framework, how can one explain the persistence of depletion surface metallurgy as the coloring technique of choice in the New World? Why did it outlast all the others, spreading widely beyond the Andes? Perhaps because it was a technique that developed at the surface of an object the qualities already present inside it. Surface enrichment merely enhanced an aspect of the metal that was inherent to it; metallurgically speaking, the alloy out of which an object is made contains the metal (gold or silver) that is later enhanced or developed at its surface. It is the color developed at the surface that eventually becomes the visual hallmark of the object, communicating cultural messages of power, status and religious belief. Again, however, the surface color is simply the external manifestation of an internal condition. Although there may never be a definitive answer to the question, whatever economic or technological factors contributed to the development of Andean surface metallurgy, the factors that seem to have most strongly influenced the direction the technology took were ideological.

Mass Extinctions in the Ocean

During brief intervals over the past 700 million years many marine animals and plants have died out. Geologic evidence now suggests that most of the mass extinctions were caused by cooling of the sea

by Steven M. Stanley

Throughout geologic history plant and animal species have died out at a rate that has ordinarily fluctuated only slightly. At various times, however, there have been sharp peaks in the number of vanishing species. Such mass extinctions have affected terrestrial as well as marine organisms, but the fossil record documenting their occurrence is more abundant in the marine realm. During geologically brief intervals of several million years some of these events have eliminated most of the species in the ocean and as many as half of the families. Devastation of this magnitude could have been inflicted only by radical changes in the environment, on a regional or even global scale, and over the years some workers have suggested exotic causes, such as cosmic radiation from an exploding supernova. Others have looked to more mundane agents: drastic changes in the environmental "limiting factors," including temperature and living space on the sea floor, that ordinarily determine the distribution and abundance of species in the sea.

The most important factor limiting the geographic distribution of animal species in the ocean is water temperature. A particular species can survive only within a certain range of temperatures. Living animals provide striking confirmation of this fact: a discontinuity in temperature often marks the boundary of a species' geographic range. An episode of climatic cooling could extinguish any species that was not adapted to the new, cooler temperatures and that lacked a warmer refuge to which it could migrate.

In what follows I shall present recent evidence pointing to climatic cooling as the primary culprit behind most of the known marine crises. There are essentially three types of evidence. First, in some cases there is independent indication, such as the presence of glacial gravels, that cooling occurred at the same time as a mass extinction. (Cooling need not always have been accompanied by glaciation, however.) Second, the fossil record suggests that species adapted to warm water or to a narrow temperature range have tended to suffer most, as one would expect if the crises were brought on by a drop in temperature. Third, the record also indicates that most marine mass extinctions were gradual rather than sudden events, taking place over hundreds of thousands or even millions of years. This pattern is compatible with the usually slow and episodic pace of global cooling.

Even the most famous of mass extinctions—the disappearance at the end of the Cretaceous period, some 65 million years ago, of the dinosaurs along with many marine animal species—now appears to have been gradual. As I shall explain below, that is the main argument against attributing the entire Cretaceous crisis to an asteroid impact, as Walter and Luis W. Alvarez and their colleagues at the University of California at Berkeley have proposed. Since the environmental effects of an impact would have been relatively short-lived, it cannot completely account for a crisis that probably lasted for at least two million years. Furthermore, even if the Alvarez hypothesis should prove to be correct, there is little evidence that asteroid impacts might account for the many other crises in the history of the oceans.

Before examining in detail the evidence linking mass extinctions to climatic cooling, let me first discuss the flaws of a rival explanation that attaches primary importance to changes in a different limiting factor: area of the shallow sea floor, which decreases when sea level falls because portions of the continental shelf are exposed. The hypothesis assumes that vast areas of shallow sea floor are needed to sustain a diverse population of bottom-dwelling animals not adapted to conditions of the deep sea. This turns out not to be the case. A quite narrow continental shelf can harbor an enormous diversity of bottom-dwelling organisms. For example, approximately 3,000 species of shelled mollusks, representing hundreds of families, inhabit the tropical segments of the slender continental shelf along the west coast of the Americas. A thousand or so species of shelled mollusks occupy the small area of shallow sea floor that fringes the Hawaiian Islands.

Moreover, in recent years knowledge of sea-level changes in the distant past has improved considerably, and this new evidence shows that "biotic crowding" brought on by sea-level lowering cannot possibly have caused most of the known mass extinctions. Much of the evidence comes from the application of seismic stratigraphy techniques developed by investigators at the Exxon Corporation. By bouncing sound waves off ancient sediment layers under modern continental shelves it is often possible to detect discontinuities between the superimposed layers, which differ in density and therefore refract the sound waves in characteristic ways. For example, a discontinuity may reveal the boundary between mud deposited in deep water and alluvial sands that accumulated on a coastal plain at a later time, after the sea had receded to a level lower than its present level. Analysis of rocks exposed on land reveals other times when the sea level was higher.

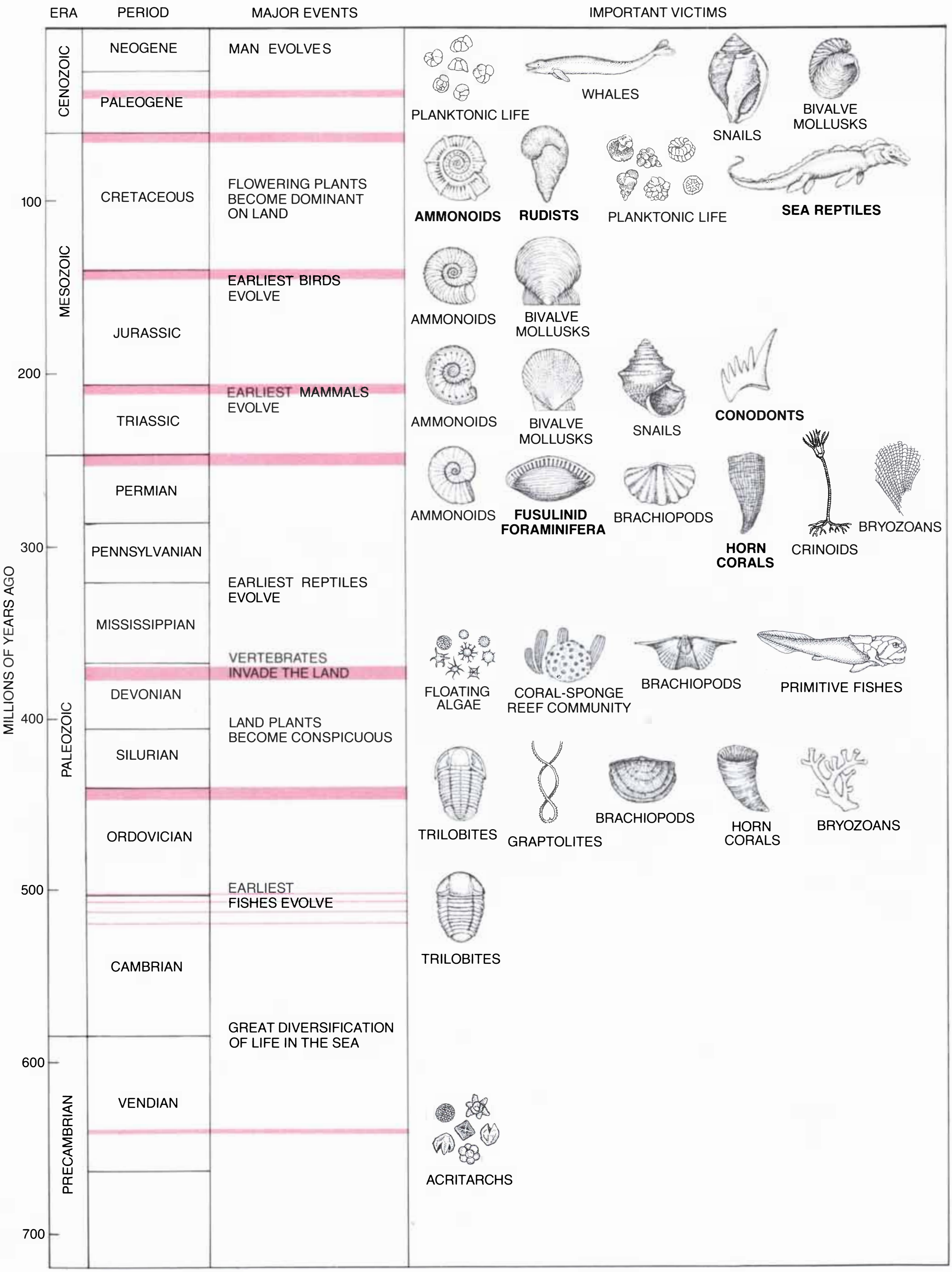
These studies have demonstrated that during many mass extinctions sea level was no lower than it is now. Conversely, when the sea level has fallen, there has often been no biotic crisis. Consider one example. Late in the Eocene epoch, about 40 million years ago, a crisis eliminated many European species of marine life at a time when Europe was extensively flooded by shallow seas. In the ensuing Oligocene epoch these seas were drained as the ocean withdrew to what may have been its lowest level of the past several hundred million years. Although sea level remained depressed for the next five million years, there was little or no excessive extinction of marine life in Europe or anywhere else. The availability of living space on the shallow sea floor must put some limit on the number of species that can live there, but the relation is weak.

More recently sea level dropped by as much as 100 meters on several occasions in the past three million years as expanding ice sheets removed huge volumes of water from the earth's hydrologic cycle. A large number of species did vanish from the oceans during these glacial periods, but the geographic pattern of the extinctions suggests they were caused by cooling rather than by shrinkage of the shallow sea floor. The connection is only now becoming clear, because for a long time paleontologists overlooked the Ice Age mass extinctions. Lacking accurate methods of assigning ages to fossil marine faunas, they assumed that faunas including many extinct species were geologically old and that the extinct species had died out at a low, "background" rate. The study of microscopic fossils, such as those of planktonic foraminiferans (floating organisms like amoebas but with skeletons), has now produced more accurate age assignments showing that the extinctions were actually bunched in the Ice Age. In many fossil faunas only four million years old more than half of the species are extinct.

If the Ice Age extinctions had been the result of sea-level lowering, they would have struck shallow-water communities throughout the world. Workers studying fossil mollusks have instead found a concentration of excessive extinction only in regions bordering the Atlantic north of the Equator. Faunas of the western Atlantic and the Caribbean were hit hardest, losing about 70 percent of their species; in the Mediterranean and the North Sea about 30 percent of the mollusk species were wiped out. In contrast, the molluscan faunas on the Pacific coasts of California, Panama and Japan give no evidence of excessive extinction during the glacial periods.

This pattern fits the cooling hypothesis. The species that vanished were those adapted to warm water or to a narrow temperature range and that could not escape the cooling pulse associated with glacial expansion. The Pacific faunas could get away: they simply migrated north and south as temperatures fluctuated. A look at the map shows that the Mediterranean and the Caribbean offer no such easy escape route. When during glacial expansions these tropical basins cooled, many mollusks, trapped in the chilling seas, died out. The Pinecrest

FOSSIL MOLLUSKS, victims of the Ice Age, pour out of a shell bed in the Pinecrest sands near Sarasota, Fla. During glacial advances over the past three million years about 70 percent of the mollusk species in the region have died out. Among bivalve mollusks the species adapted only to tropical conditions have vanished entirely, whereas some species able to live in temperate waters have survived. The pattern suggests that climatic cooling caused the excess extinctions. Mollusks in the photograph are on the average a few inches in diameter.



MASS EXTINCTIONS (*colored lines and bars*) **have struck all kinds of marine life over the past 700 million years, from single-celled algae and plankton to huge swimming reptiles and whales. The most famous crisis occurred 65 million years ago at the end of the Cretaceous period, eliminating most marine species at about the time the dinosaurs became extinct on land. In many cases an animal or plant group has been able to recover after a crisis and evolve new species; in other cases the entire group has vanished from the sea (*bold type*).**

sands of central and southern Florida, which date from early in the Pliocene (about 3.5 or four million years ago), offer vivid testimony of this process. They contain an enormous fossil fauna of tropical mollusks, including many bivalve species, but all the bivalves surviving in the region today are ones able to live not only in the Tropics but also in warm temperate waters. All the fully tropical species disappeared.

How well does climatic cooling account for earlier marine mass extinctions? In the late Eocene crisis mentioned above, which spanned several million years, extinctions were more widespread than they were in the Ice Age. In addition to the European fauna, mollusks in the southern Pacific and along the northwest Pacific coast of what is now the U.S. suffered heavily, and for the latter region Carole S. Hickman of Berkeley has shown that species belonging to predominantly southern (warm-water) taxonomic groups suffered the most. Richard Cifelli of the Smithsonian Institution, who first noted the crisis, observed that it eliminated most types of planktonic foraminifera, but that one foraminiferan group, the globigerines, survived and went on to become dominant in the Oligocene. Today the globigerines are unique among planktonic foraminiferans in that they are common in cool water; the species now found in warm seas have for the most part evolved since the Eocene. The flourishing of the globigerines while their warm-water relatives vanished makes sense if the crisis is assumed to have been caused by cooling.

There is strong evidence that the extinctions were accompanied by a temperature drop. Fossil leaves found near Puget Sound document a shift from rain forests nearly tropical in character to temperate forests at about the same time that mollusks were disappearing from nearby coastal waters. By analyzing the change in the proportion of plant species with smooth leaf margins to those with toothed leaves in a given region, it is possible to estimate the change in mean temperature; leaves with smooth edges are commonest in tropical climates, while toothed leaves dominate in temperate zones. Using this method, Jack Wolfe of the U.S. Geological Survey has calculated that the mean annual temperature in the Pacific Northwest fell by about 10 degrees Celsius in the late Eocene. A similar analysis has documented substantial cooling in Britain.

As in the Ice Age, the Eocene cooling seems to have emanated from the poles and spread toward the Equator in an irregular fashion. Fossils in deep-sea sediments near the Antarctic reveal that glaciers there expanded late in the epoch. One result, as Richard H. Benson of the Smithsonian Institution and other workers have shown, was a drastic change in the thermal structure of the ocean. As water off Antarctica cooled, some of it sank because of its greater density and flowed northward, forming a cold layer in the deep sea, called the psychrosphere, that has persisted to the present. The plate-tectonic separation of Greenland from Europe during the Eocene may also have helped to create the psychrosphere by allowing frigid Arctic water to escape into the Atlantic.

There is no reason to assume that major cooling events earlier in the earth's history would necessarily have spread from the poles, and indeed they seem to have been more global, with temperatures dropping significantly in equatorial regions as well as at higher latitudes. Such worldwide cooling should do the most damage to tropical biotas. Whereas biotas of higher latitudes should, unless they are obstructed by geographic barriers, be able to migrate toward the Equator along with the climatic zone to which they are adapted, there would be no warmer refuge for tropical species because they already inhabit the warmest areas. Furthermore, tropical species are in many cases less tolerant of temperature change than species of temperate regions, where seasonal fluctuations are generally stronger. A cooling event causing water temperatures to drop below about 18 degrees C. on a regular basis would eliminate many tropical marine species of the modern world. If global cooling contributed to the marine crises that preceded the Cenozoic era (the age of mammals, which began 65 million years ago), the mass extinctions should reflect a tropical bias. An examination of the fossil record for these events shows it does indeed bear this distinctive stamp.

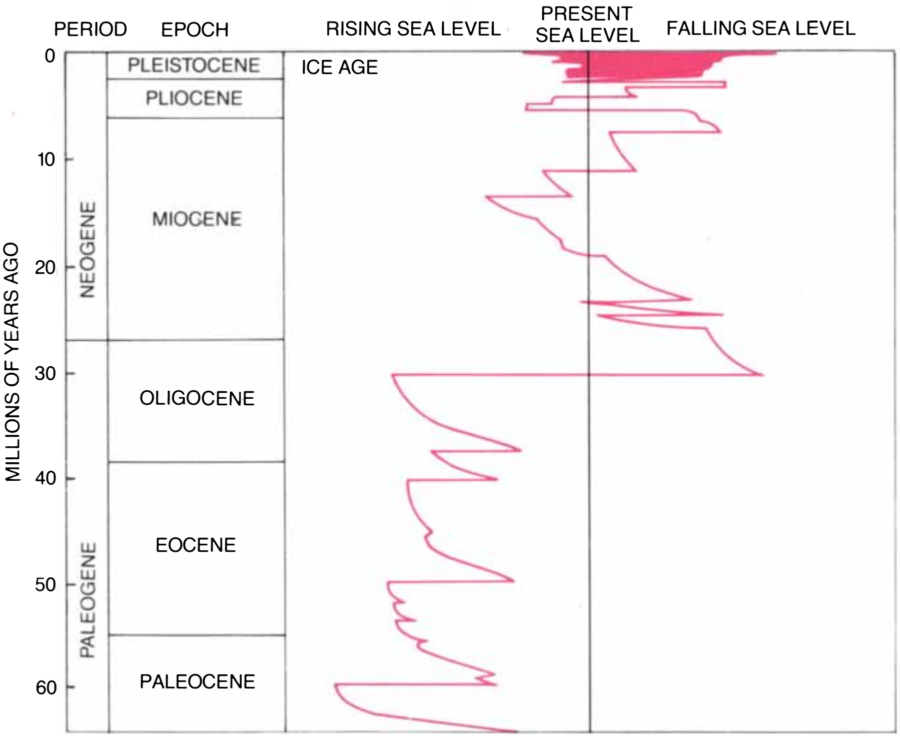
The best evidence is available for the mass extinction that ended the Mesozoic era (the age of dinosaurs) and began the Cenozoic. The last period of the Mesozoic was the Cretaceous. During the latter part of the Cretaceous shallow seas flooded large continental areas that are now exposed, and a belt of tropical oceans, known as the Tethyan Seaway, spread across southeastern Asia, the Mediterranean region and the Gulf of Mexico. Among marine organisms it was Tethyan faunas that suffered the most in the terminal Cretaceous crisis.

Many groups of minute floating algae were decimated, including most of the coccolithophores—spheroidal, single-celled organisms that secreted shieldlike structures of calcium carbonate, which were released when the organisms died. Before the crisis this calcium carbonate rained down on the sea floor at a tremendous rate, producing the thick deposits of chalk—the white cliffs of Dover are an example—to which the Cretaceous owes its name (from *creta*, the Latin word for chalk). The coccolithophores have never fully recovered their prominent position in tropical seas. Planktonic foraminiferans also endured heavy casualties: their sole survivors were the globigerines, the same group that became dominant after the Eocene crisis and that today thrive in cool seas.

The disappearance from the Tethyan Seaway of the reef-building rudists, bivalve mollusks similar to corals with cone-shaped skeletons, was particularly dramatic. So successful were these animals during the Cretaceous period that they seem to have pushed corals into a subordinate role on tropical reefs. Were it not for the sudden extinction of the rudists, they rather than corals would undoubtedly dominate the reefs that dot the shallow tropical seas of the modern world. Elsewhere on the Tethyan Seaway floor other groups of bivalves and gastropods (snails) also vanished, as did families of large bottom-dwelling foraminiferans. Most unfortunate, in view of their great beauty, was the total extinction of the ammonoids: swimming cephalopod mollusks whose chambered, spiral shells, like those of their living relative the pearly nautilus, housed squidlike bodies. The ammonoids are one group whose elimination did not reflect the general tropical bias of the terminal Cretaceous crisis; nontropical as well as tropical species were lost.

The bias is nonetheless real, as the confusion over the correct dating of certain rock formations of high latitudes illustrates. For years some paleontologists have assigned rocks in Denmark of Danian age to the Cretaceous period, because the rocks contain Cretaceous fossil groups. Most workers now believe the terminal Cretaceous crisis actually preceded the Danian. Its effect in Denmark was so weak, however, that many Cretaceous species persisted into the Paleogene period, the first period of the Cenozoic era. (The Cenozoic has traditionally been divided into the Tertiary period, beginning 65 million years ago, and the Quaternary, beginning two million years ago and extending to the present. Many paleontologists, however, now prefer to split the Cenozoic into more equal parts: the Paleogene period, which ended with the Oligocene epoch 26 million years ago, and the Neogene period.) Similarly, the Cannonball Formation in North Dakota, once assigned to the Cretaceous, is now known to be of early Paleogene age. Although the Cretaceous crisis wiped out most bivalve species in the tropical Gulf of Mexico region, about 60 percent of the bivalve species found in the Cannonball Formation are also known from Cretaceous deposits several million years older. This is roughly the survival rate seen in intervals in which no crisis occurred.

Not only were Tethyan biotas much more strongly affected than nontropical



DRAMATIC LOWERING OF SEA LEVEL about 30 million years ago caused no evident mass extinction, contradicting the hypothesis that reductions in sea level precipitate marine crises by reducing living space on the shallow sea floor. During the Oligocene epoch the ocean surface fell to what may have been its lowest level of the past 600 million years and remained below the lip of the present continental shelf for about five million years. The absence of excessive extinction in the Oligocene contrasts sharply with the crisis that eliminated many marine species in the preceding epoch, the Eocene, at a time when shallow seas flooded large areas of the continents. Sea-level falls associated with Ice Age glacial advances have coincided with pulses of extinction, but the pattern of the extinctions suggests they were caused by cooling.

ones but also biotas from cool northern latitudes seem to have shifted southward, taking the place of disappearing tropical flora and fauna. Tethyan snails, for example, were decimated by the mass extinction. Heinz Kollman of the Natural History Museum of Vienna has found that during the early Paleogene the snails in a large region extending from Greenland to North Africa belonged to groups that during the Cretaceous had lived only in northern seas.

Leo J. Hickey of Yale University has recently demonstrated, by analyzing the margins of fossil leaves, that the Wyoming region experienced a pulse of cooling during the transition from the Maastrichtian, the last epoch of the Cretaceous, to the Paleocene. The Maastrichtian has long been recognized as the coolest interval of the Cretaceous, but in Wyoming the early Paleocene floras attest to a climate with a mean annual temperature that was as much as 10 degrees C. colder still. The low temperatures appear to have persisted in Wyoming for several million years.

So much for the evidence linking the Cretaceous crisis to climatic cooling. In the past few years public attention has been drawn to the Alvarez hypothesis that the impact of an asteroid about 10 kilometers in diameter killed off marine organisms as well as the dinosaurs. The impact supposedly threw up a dust cloud that quickly encircled the earth before settling out of the atmosphere. The main evidence for this scenario is the discovery in rock sequences around the world of a significant concentration of iridium in a thin sedimentary layer at the Cretaceous-Paleogene boundary. Iridium, a platinum-group metal, is rare on the earth but comparatively abundant in meteorites. Most meteorites are thought to be fragments of asteroids.

How might an impact have caused extinctions in the ocean? Various mechanisms have been proposed, including both a sudden rise and an equally dramatic drop in temperature. The Alvarezes have suggested the dust cloud might bring on a three- to six-month period of darkness, thereby stopping photosynthesis and eliminating the phytoplankton near the ocean surface. The effects of this extinction would then cascade up the food chain, killing off larger marine organisms.

The Alvarez hypothesis includes a testable prediction: if an asteroid impact caused extinctions at the end of the Cretaceous, they would have been quite sudden, indeed virtually instantaneous on the geologic time scale. Judging from recent evidence, that was not the case. The uppermost Cretaceous deposits at Stevns Klint in Denmark have been celebrated for their apparent documentation of sudden extinctions. The latest of these deposits, however, is a "hardground": an area of sea floor on which sediments that remained unburied for a long time—because no new sediments accumulated—were cemented into a hard crust by calcium carbonate precipitating out of seawater. As long as no sediment is accumulating, no fossil record is being formed. The hardground at Stevns Klint suggests the deposits there actually do not document the final few tens of thousands of years of the Cretaceous. If this is so, they cannot be used as evidence that the terminal Cretaceous extinctions spanned at most several millenniums.

At Zumaya, on the north coast of Spain, there is a rock sequence that appears to be more continuous. Deep-sea deposits brought to the surface by plate-tectonic motion span the Cretaceous-Paleogene boundary with no evidence of a gap in sediment deposition; they thus seem to provide a more accurate history of certain prominent Cretaceous extinctions. The extinctions that seem compatible with the asteroid hypothesis are those of the coccolithophores and similar plankton. According to Stephen F. Percival, Jr., and Alfred G. Fischer, then at Princeton University, the typical Cretaceous species of these plankton disappeared suddenly, at least as abundant forms, during an interval of less than 10,000 years just before the iridium-rich layer formed.

In contrast, Peter Ward of the University of California at Davis and Jost Wiedmann of the University of Tübingen have found that the rich ammonoid fauna at Zumaya suffered a gradual decline in the last part of the Cretaceous rather than a sudden extinction at the end of the period. The number of ammonoid species dwindled from 10 to none over an interval of approximately two million years, represented by about 120 meters of sediment. The youngest ammonoid was detected 12 meters below the iridium layer, implying that the last species may have died out some 100,000 years before the supposed impact of the asteroid.

Ward and Wiedmann have found a similar dwindling of the inoceramids, a group of bivalves that vanished near the end of the Cretaceous; the last inoceramid they collected at Zumaya was 60 meters—the equivalent of about a million years—below the iridium layer. Their results corroborate those of a global survey of the inoceramids by Annie V. Dhondt of the Royal Institute of Natural Sciences of Belgium, who has also reported that these bivalves dwindled during the Maastrichtian. Similarly, according to Erle G. Kauffman of the University of Colorado at Boulder, the rudists (which built their reefs in shallow tropical seas and are therefore not present in the deep-sea deposits at Zumaya) were decimated in mid-Maastrichtian time, perhaps two million years before the iridium layer formed. In late Maastrichtian rocks the rudist fossil community is impoverished and not represented by large reefs.

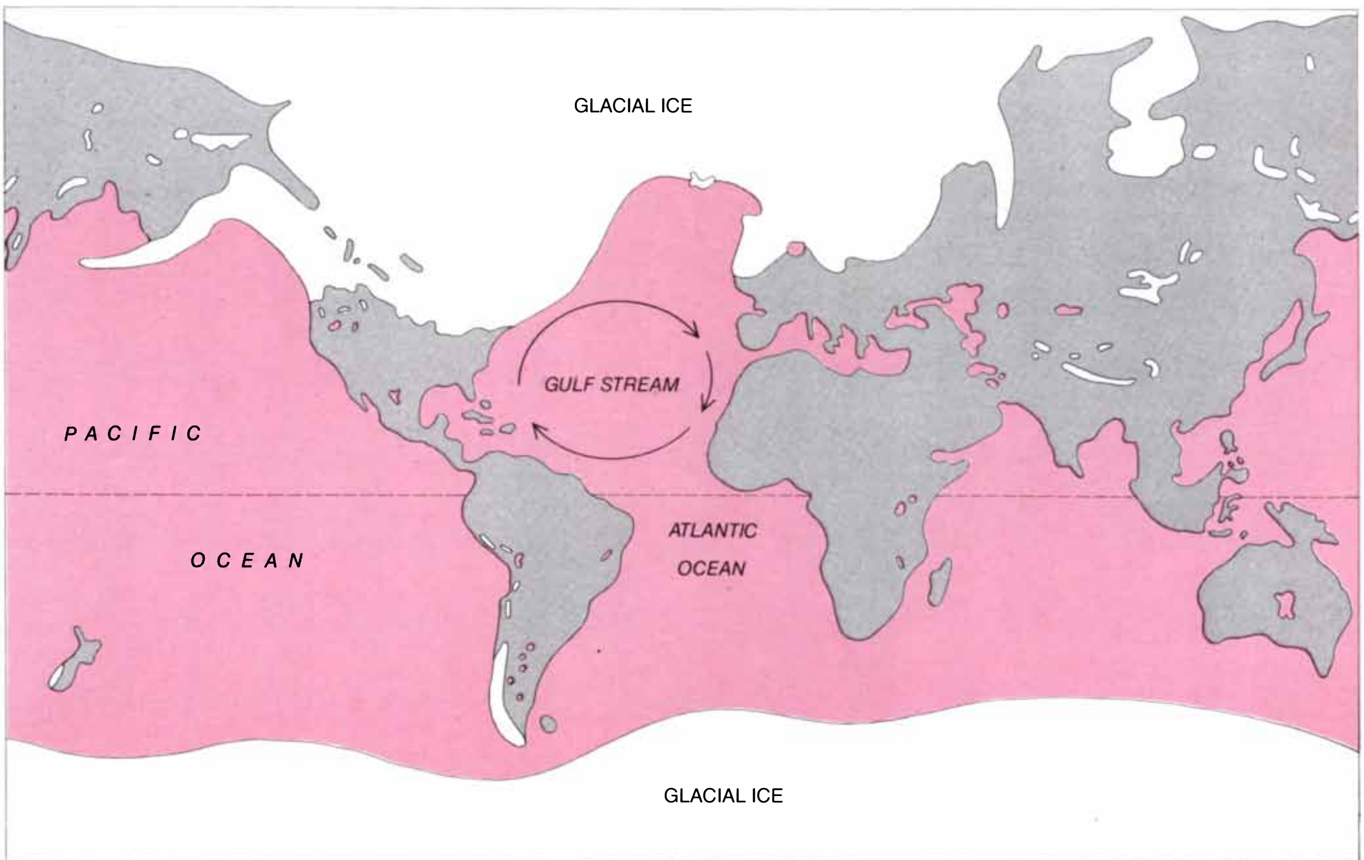
To summarize, the Cretaceous crisis was not a single brief event. Different groups of organisms declined and became extinct at different times, over a period of at least two million years. The sequence of the disappearances is also significant, because it contradicts the old idea, adopted by the Alvarezes, that extinctions might begin at the bottom of the food web and propagate upward in a kind of domino effect. The lowly plankton suffered at the very end of the Cretaceous crisis, after the decline of many plankton-eating mollusk groups and after the total disappearance of the carnivorous ammonoids.

In recent months several investigators have proposed variations on the Alvarez hypothesis that might account for the fact that the Cretaceous extinctions were not instantaneous. These new hypotheses, which at present are largely speculative, are designed to explain the conclusion of David M. Raup and J. J. Sepkoski, Jr., of the University of Chicago, who have suggested, based on a statistical analysis of the disappearance of more than 500 marine families, that mass extinctions over the past 250 million years have followed a 26-million-year cycle. According to one of the new hypotheses, a small, cold companion star might be circling the sun in a greatly elongated orbit. If this body were to pass close to the sun every 26 million years, it would perturb the orbits of comets, and over an extended period some of the comets might strike the earth, causing a mass extinction. Several workers are now trying to find such a companion star; others are examining craters on the earth that might come from comet impacts to see if the ages of the craters follow the same period as the marine mass extinctions.

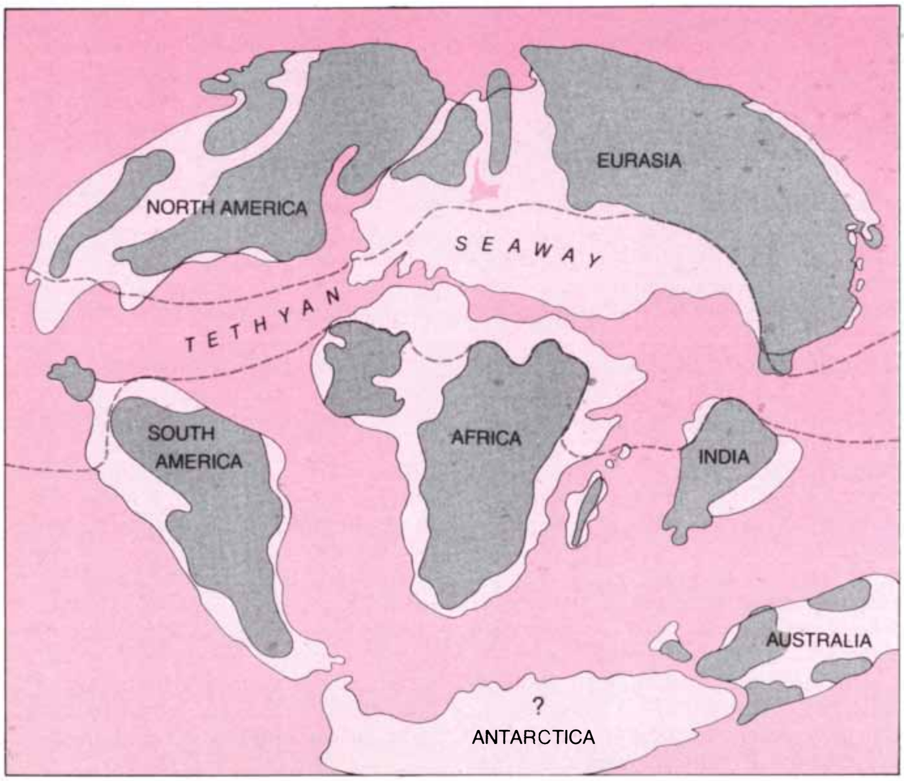
The alleged 26-million-year cycle itself needs further study. To begin with, the most recent extinction peak in the cycle, about 13 million years ago, is extremely weak and would probably go unnoticed if it were much older; further back in time there might be more such events that are obscured by the fossil record and do not fit the cycle. Moreover, the peaks older than 90 million years that Raup and Sepkoski did identify do not fit the cycle very well. It may be the peaks are not truly periodic but only somewhat closer to a 26-million-year cycle than they would be if they were distributed randomly over time.

Such a condition requires no extraterrestrial explanation; it would have arisen if after each mass extinction there had to be a lag before another crisis could occur. The environmental change that precipitated the initial crisis might have persisted for several million years, preventing the biotic recovery that would have had to precede the next pulse of extinction. Even if the environment did improve, the decimated biotas might have required millions of years to rediversify to the point where they included species that were particularly vulnerable to mass extinction. After the Cretaceous crisis, for example, and after a similarly large mass extinction in the late Permian, marine biotas remained impoverished for several million years.

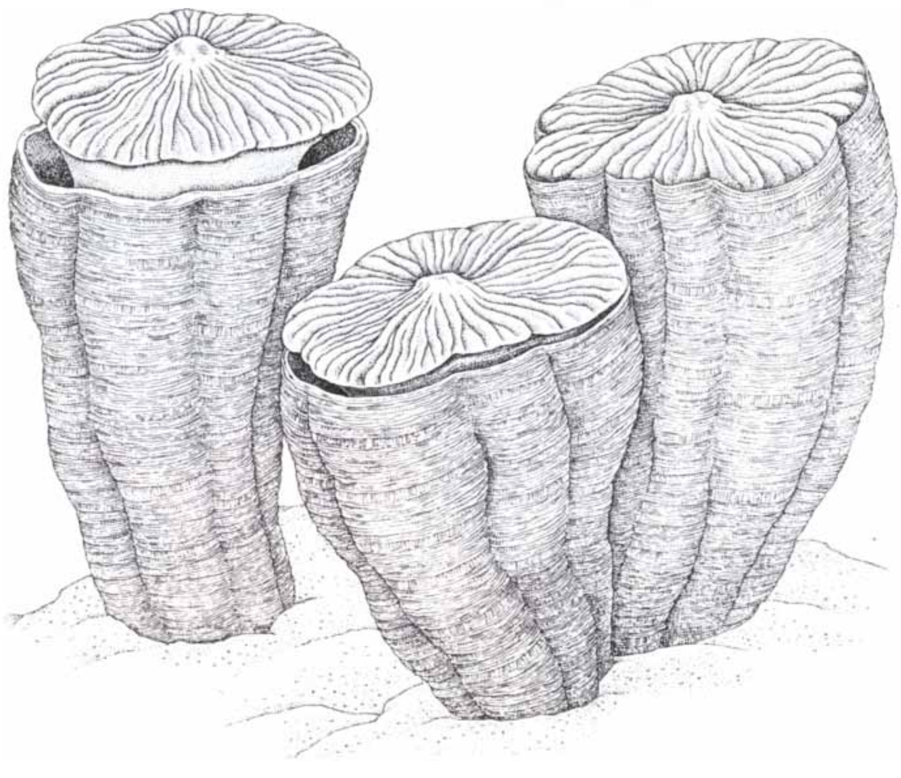
Whether or not marine mass extinctions are found to follow a cyclical pattern, there is ample evidence link-



ICE-AGE MASS EXTINCTION was confined to regions bordering the North Atlantic. About 70 percent of the mollusk species in the western Atlantic and Caribbean and about 30 percent of those in the Mediterranean and the North Sea were wiped out. During cooling episodes molluscan faunas in these basins were trapped and could not easily escape to warmer seas. In contrast, Pacific molluscan faunas could migrate southward as the water temperature dropped, and they thereby avoided excessive extinction. The path of the warm Gulf Stream, far south of its present position, indicates the extent of cooling in the Atlantic. Map shows the last glaciation, 18,000 years ago.



TROPICAL OCEAN BELT known as the Tethyan Seaway covered large portions of the continents in the latter part of the Cretaceous period. Tethyan species suffered the heaviest extinction in the crisis that ended the Cretaceous, and this tropical bias suggests the crisis was caused by cooling. The broken lines indicate boundaries between tropical and temperate conditions.



RUDISTS, bivalve mollusks that during the Cretaceous displaced corals as the dominant reef builders in the Tethyan Seaway, disappeared altogether at the end of the period. They had begun to decline in abundance as much as two million years earlier, however, which implies that their extinction was probably not precipitated by a sudden event such as an asteroid impact. Unlike corals, individual rudists were connected only by their shells, not by their soft tissue. Rudists, usually less than 20 centimeters tall, sometimes grew to a height of more than one meter.

ing the crises even before the Cretaceous to climatic cooling. The first event known took place about 650 million years ago, late in Precambrian time, when animal life was still sparse. At that time, according to Gonzalo Vidal of the University of Lund and Andrew H. Knoll of Harvard University, extinctions decimated the ocean's population of acritarchs, single-celled phytoplankton that apparently were the first organisms to evolve cells with nuclei. The mass disappearance of the acritarchs, which later recovered to become the largest group of fossil phytoplankton preserved in Paleozoic rocks, coincided with a period when glaciers covered many areas of the earth. The evidence for glacial activity includes gravelly formations containing large boulders that could only have been deposited by glaciers, as well as the scratches left by the boulders on older bedrock as they were swept along by the moving ice. Such evidence has been found on all the continents except Antarctica (whose surface is largely hidden by modern ice), suggesting that climatic cooling in the Precambrian was indeed global.

During the next period, the Cambrian, invertebrate animals with shells became abundant in the sea. The first dominant invertebrates were the arthropods called trilobites, so named because their segmented bodies were divided into three lobes (one central lobe and two lateral ones). Beginning roughly 530 million years ago the trilobites suffered a series of mass extinctions, of which the best-documented involved faunas occupying tropical sea floors in North America. Allison R. Palmer of the Geological Society of America has found evidence for three distinct crises, separated by intervals of from five to 7.5 million years; from the thickness of sediments deposited during one of these events he has concluded that it spanned at most from 4,000 to 6,000 years. Brief pulses of extinction thus seem to have been followed by long intervals during which the trilobites once again expanded, evolving many new species before the next crisis struck. In each case the new fauna evolved from the same ancestral group, the olenid trilobites, whose fossils are found in sediments from deep offshore waters that were presumably cool. This recurring pattern is readily explained by climatic cooling: when brief cooling events periodically decimated shallow-water tropical faunas, the cold-adapted olenids were left "waiting in the wings" offshore, from where they invaded the barren shallow sea and gave rise to new trilobite species that eventually adapted to restored tropical conditions.

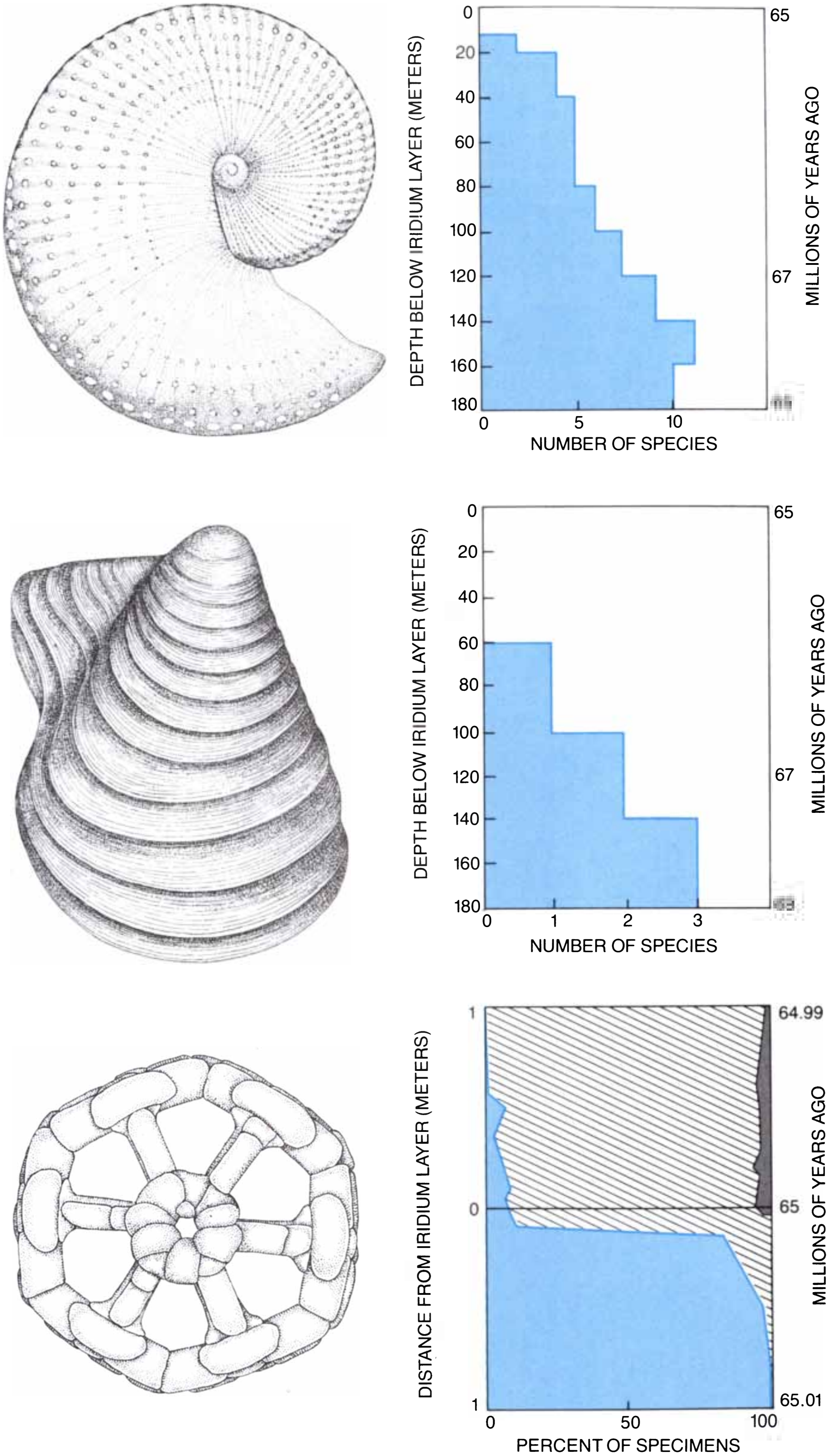
The trilobites were also victimized by the mass extinction at the very end of the Ordovician period, about 440 million years ago. Overall, the Ordovician crisis eliminated some 100 families of marine animals, again primarily in the Tropics. Its impact on the graptolites is particularly instructive.

The graptolites were a strange group: they lived as floating colonies of individuals that were attached to one another by stalks, and they presumably fed on plankton or other small food particles. Fossil deposits along the borders of the North Atlantic reveal that several million years before the end of the Ordovician different graptolite species lived in distinct ecological belts parallel to the Equator. By the end of the period, when the extinctions occurred, the belts had become compressed into a single biogeographic province in the equatorial region. At the same time glacial activity, which had begun somewhat earlier, reached its peak, with ice flowing outward in many directions from a center in North Africa. The geographic redistribution of the graptolites suggests their extinctions were related to cooling of their habitat.

Tropical species were again hit hardest by a marine crisis near the end of the Devonian period, about 370 million years ago. Primitive corals and sponges, builders of limestone reefs earlier in the period, endured a pulse of extinction from which they never fully recovered, and many other tropical marine groups disappeared simultaneously. In contrast, animal groups living near the South Pole fared quite well, as shown by the work of Paul Copper of Laurentian University in Ontario. South America was adjacent to the South Pole in the Devonian, and its unusual fauna, which lacked reef builders and other warm-water species, survived with few losses. Brachiopods—double-valved organisms (also called lamp shells) found in both tropical and temperate seas—suffered heavily but not randomly: 90 percent of the brachiopod families that died out had no representatives in the cold waters that flooded broad areas of South America.

From his study of fossil faunas in New York, which in the late Devonian lay near the Equator, George R. McGhee, Jr., of Rutgers University has found that the crisis in this area lasted for about seven million years. He has also reported another interesting observation: while other animal groups were vanishing, the glass sponges diversified. Then as the crisis subsided and the other groups recovered, the number of glass-sponge species dwindled again. The significance of this observation is that today most glass sponges are adapted to cool water. Their prosperity during the late Devonian crisis is circumstantial evidence that their less fortunate competitors were succumbing to the effects of climatic cooling.

Establishing a link between cooling



PATTERNS OF EXTINCTION in a rock sequence at Zumaya, Spain, provide evidence both for and against the hypothesis that an asteroid impact caused the terminal Cretaceous crisis. The main evidence for such an impact is a thin layer of clay at the Cretaceous-Paleogene boundary with an unusual abundance of the rare metal iridium. Taxonomic groups extinguished by an asteroid impact would be expected to vanish suddenly near the iridium layer. According to a study of the Zumaya formation done by Peter Ward of the University of California at Davis, both the ammonoids (*top*) and the inoceramid bivalve mollusks (*middle*) instead declined gradually in species diversity during the late Cretaceous; both groups disappear altogether well below the iridium layer and hence before the conjectured impact. In contrast, the demise of certain species of coccolithophore (*bottom*) and other calcium-carbonate secreting plankton was sudden. According to a specimen count by Stephen F. Percival, Jr., and Alfred G. Fischer, typical Cretaceous species (*color*) were replaced by opportunists (*hatching*) and new species (*gray*) in less than 10,000 years at about the time the iridium was deposited.

and marine crises of the late Paleozoic and early Mesozoic eras is more problematic. A long glacial episode in the Pennsylvanian and early Permian periods seems not to have caused excessive extinction, but there is clear evidence that tropical vegetation continued to thrive near the Equator, indicating that cooling was confined to higher latitudes. Species from these latitudes were therefore presumably able to seek refuge in the Tropics.

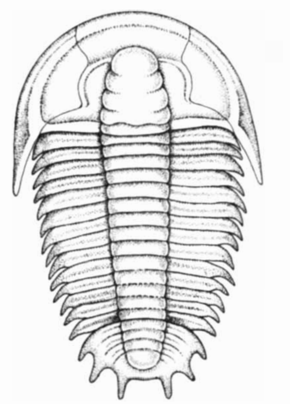
A mass extinction did mark the latter part of the Permian period, but it followed a complicated pattern. Cold-adapted polar marine animals, which died out first, appear to have succumbed to the spread of warm climates from low latitudes: in the Southern Hemisphere, at least, their extinction coincided with a shrinking of polar glaciers and a migration of warm-adapted land plants toward the pole. Conversely, the extinctions that struck the Tropics later, near the end of the Permian, may have been accompanied by widespread climatic cooling, although the evidence for cooling is still local. In the northern U.S.S.R. rock sequences of the late Permian contain coarse sedimentary debris, of the type dropped by sea ice, on top of limestone, which tends to be deposited in warmer waters. The sequence suggests that sea ice expanded at about that time. Moreover, in the Northern Hemisphere many of the marine species surviving into the Triassic, the first period of the Mesozoic era, were able to withstand a wide range of temperatures. Many of the earliest Mesozoic ammonoids, for example, lived in both Tethyan and cold-water regions, as did the conodonts, a group of eel-shaped swimming animals that apparently survived the late Permian crisis without suffering major losses.

Information on the mass extinctions at the end of both the Triassic and the Jurassic periods is still sparse. The Triassic crisis seems to have eliminated the tropical reef corals of southern Europe, whereas the fossil plant record suggests that significant cooling in Europe and northern Asia accompanied the Jurassic extinctions. More such evidence is needed, however, before these events can be said to have coincided with widespread climatic cooling.

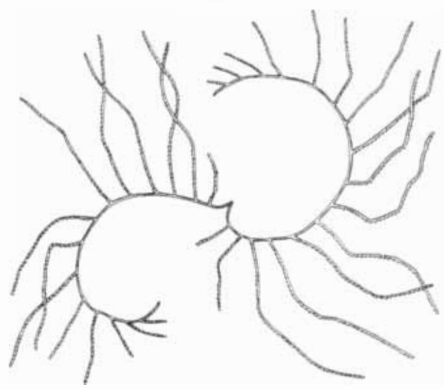
The oldest animal species in today's ocean are ones that thrive in cold water. Many characteristic Arctic species, such as certain brachiopods, starfishes and sediment-eating bivalves, belong to biological orders whose origins extend back hundreds of millions of years into the Paleozoic era. In contrast, tropical faunas such as reef communities, buffeted by periodic mass extinctions, have come and gone quite rapidly on a geologic time scale. The coral-sponge reef community decimated in the late Devonian crisis gave way to a less effective association of reef builders that included bryozoans, brachiopods, calcareous sponges and algae; after suffering heavy extinction at the end of the Permian period this association was in turn replaced by a coral community resembling that of the modern world. Corals then seem to have been outcompeted by rudists in the late Cretaceous, only to return as the dominant tropical reef builders after the rudists were annihilated by the terminal Cretaceous crisis. Often adapted to a narrow range of temperatures, and with no refuge in times of cooling, tropical species have been hurt most by climatic changes.

It has often been asserted that tropical species are in general less able to tolerate changes in their environment. If this were true, dramatic changes in a limiting factor other than temperature could also result in mass extinctions with a tropical bias. Fortunately for the climatic-cooling hypothesis, however, there is no evidence that most tropical marine species are any more specialized in their requirements, except with respect to temperature, than temperate species. Food requirements illustrate the point. Most nonmicroscopic marine species are herbivores, and at all latitudes they tend to be generalized rather than specialized feeders, consuming many types of algae, bacteria or minute plant debris.

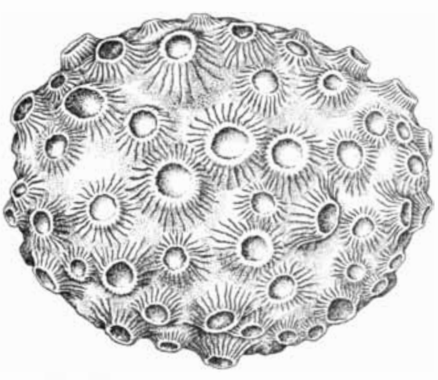
In making a case for the connection between climatic change and marine crises I have with good reason neglected an obvious question: What causes the cooling that causes the mass extinctions? Various explanations have been suggested for the periodic advance of glaciers from the poles over the past few million years, including fluctuations in the earth's orbit. The equatorial cooling accompanying earlier marine crises might reflect a reduction in the sun's output of radiation—a change in the solar constant—but other factors could be involved. Although continued examination of the fossil record should reveal further evidence of the link between cooling and marine extinctions, it may never be possible to understand fully the reasons for climatic changes millions or hundreds of millions of years ago.

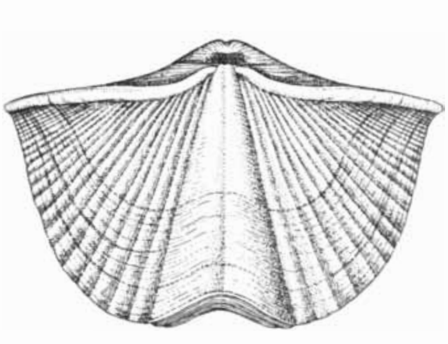


TRILOBITE FAUNAS of shallow tropical seas were repeatedly decimated by mass extinction in the Cambrian period, which began about 570 million years ago. In contrast, species adapted to deep, cooler waters survived.



GRAPTOLITES, floating colonial animals, suffered heavy extinction at the end of the Ordovician period, when glaciers advanced from a center in North Africa. Each "tooth" along a stalk contained an individual animal.





TROPICAL REEF CORALS AND BRACHIOPODS experienced major losses in the late Devonian crisis, about 370 million years ago. Devonian corals (*left*) were never again significant as reef builders. Brachiopods, commonly called lamp shells (*right*), were abundant throughout the Paleozoic era. Many of the brachiopod families that vanished in the late Devonian, however, may have been limited to warm seas; 90 percent of them are not represented in a fossil fauna from the cold waters off South America, which was then near the South Pole.

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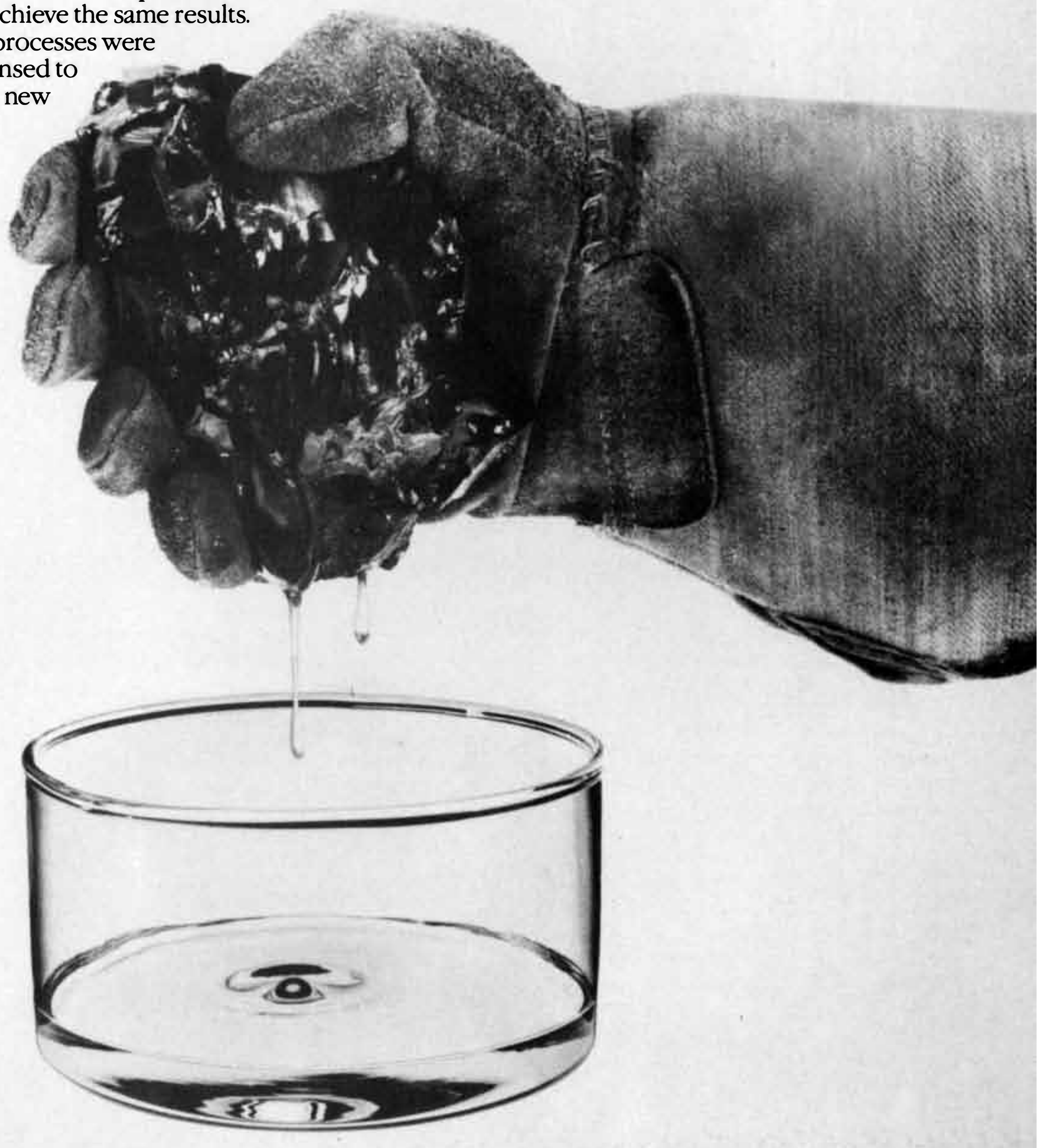

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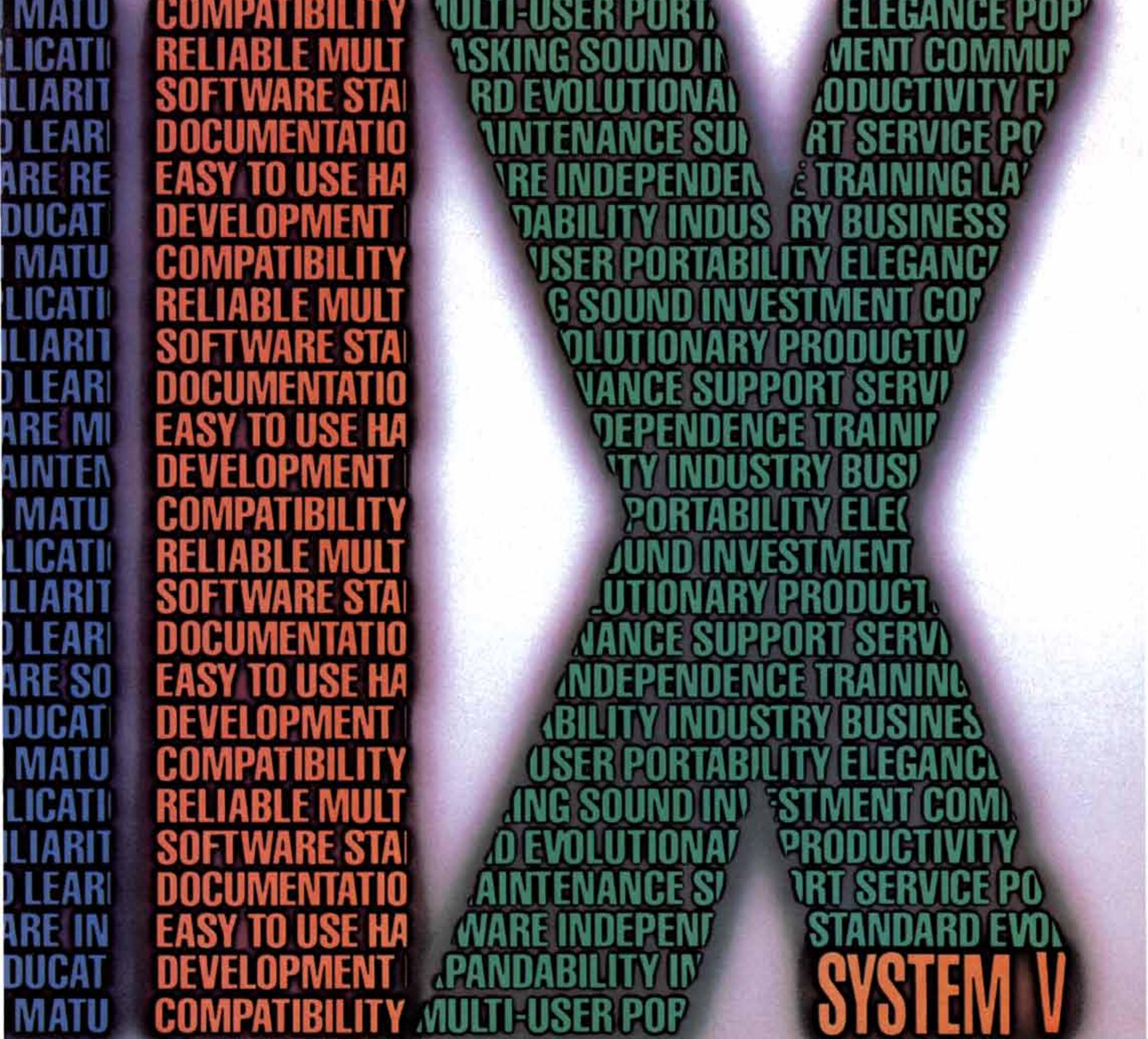

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SCIENCE AND THE CITIZEN

Knowledge Is Power

The U.S. Government ranks second only to U.S. industry in its support of research and development; it is probably the largest supporter of basic scientific research. Under the budget proposed by the Reagan Administration for fiscal year 1985, funding for R&D would again receive a substantial boost, rising 18 percent to $54 billion. It has been widely observed that the increase is almost entirely accounted for by a planned expansion of military programs, whose funding would jump by 26 percent to nearly $38 billion, whereas support for civilian R&D would just keep up with inflation. As George A. Keyworth II, the science adviser to the president, has pointed out, however, the flat civilian spending curve masks an increase of 10 percent, to $7.6 billion, in spending on basic research, which would come at the expense of civilian applied research and development projects. According to an analysis by the American Association for the Advancement of Science, the result is a budget that "should gratify most of the major scientific and technical constituencies."

The Administration's bullishness on basic research is particularly interesting in view of its attitude toward the goals of science. These it seems to see as being twofold: helping the U.S. to compete militarily with the U.S.S.R. and helping it to compete economically with Japan.

Why should a society support the work of its scientists? The answer to this question has changed over the years, but utilitarian arguments of the kind espoused by current policymakers have the longest pedigree, going back at least to the scientific revolution of the 17th century. More than a set of specific discoveries, the revolution was a transformation in the prevailing view of the nature of knowledge and its purposes. Knowledge was no longer to be gained through pure reason or the study of ancient texts but through the methodical observation of nature; understanding nature, moreover, opened up the possibility of subduing it. "Knowledge and human power are synonymous," Francis Bacon wrote, and in urging royal patronage of the new science he argued that the mastery of nature it afforded would enable man to satisfy his material needs and at the same time bring him closer to God.

Utilitarian goals remained the dominant justification for research until the mid-19th century. Until then science was still a socially marginal activity, largely excluded from the universities and often engaged in by amateurs. Eager to achieve social recognition as practitioners of a legitimate profession, scientists stressed the purported utility of their work well before practical applications were common. By the late 19th century, however, all that had changed, as the historian George Daniels and others have pointed out. The applications of science had become conspicuous: the chemicals industry, electricity, the telegraph, to name only a few. Confident of their usefulness, scientists no longer felt compelled to draw attention to the fact. At the same time, as they moved into the universities, they learned a different ideal of knowledge from the classicists they had once scorned; they came to appreciate knowledge as an end in itself, worth pursuing without regard to its potential applications.

The ideal of pure science changed the self-image of scientists. Even today most workers engaged in basic research would probably say they are motivated by intellectual or aesthetic impulses—"the pleasure of finding things out," as the physicist Richard P. Feynman put it in a recent television interview. It is safe to say that this ideal has not caught on among the government patrons of science. The result has been what René Dubos once called a "schizophrenic attitude": in private scientists may say they are interested primarily in knowledge itself, but in public they defend their work on the ground that it will inevitably have useful applications.

That the pure-science ideal carries little weight in Washington today is evident from the statements of policymakers. Passing mention is sometimes made of the intrinsic intellectual interest of science, but the emphasis is clearly on its usefulness. In announcing the spending plans of the National Science Foundation, which is to receive a 13.6 percent funding increase in 1985, NSF director Edward A. Knapp said the new $1.5 billion budget "is exciting because it enables us to strengthen and initiate programs... that will direct this country to a stronger position in international competitiveness and national security." A staff member of the Senate committee that oversees the NSF recently put it more bluntly: "Growth, jobs, national security—these are issues we feel very strongly about," she explained, "and that's why we support the NSF."

According to Keyworth, it is precisely the Administration's attention to these "broader needs of the nation" that have led it to emphasize basic research. If Congress approves the 1985 budget, funding for such work will have increased by 27 percent (after adjustment for inflation) during the Reagan Administration. Universities will have received a 13 percent real increase in R&D funds in the same four years. The utilitarian ideology, however, has directed more of this money to research that is thought to have a greater potential for practical application. Physical sciences and engineering would receive a 14 percent increase in 1985, with the engineering program at the NSF getting a 22 percent boost. Spending on all the life sciences would rise by just 5 percent unless Congress, as it has in the past, decides to expand the budget of the National Institutes of Health; on the other hand, the Administration is launching several new programs to support biotechnology, an area in which it fears U.S. industry is in danger of losing primacy to Japan.

The subordination of science policy to other national policies raises doubts about whether continued funding for basic research can be considered secure. The budget for defense R&D, which declined in the 1970's, is now at its highest real level ever, accounting for almost 70 percent of the total R&D budget. The defense share is likely to increase in future years if the Administration succeeds in pursuing its plans for a space-based missile-defense system, a project scheduled to receive about $1.8 billion in 1985. Along with the manned space station, which is to receive $150 million in planning funds in 1985, the missile-defense system could end up costing tens of billions of dollars. Some observers think these huge projects could eventually divert money and workers from research of greater scientific interest.

At a time when Federal support of science is increasing it may seem churlish for proponents of science to criticize the philosophy underlying the Administration's science policy. Ultimately, however, the issue is what place the pursuit of science should have in American society: whether it is to be regarded as an end in itself or, as the Government would have it, primarily as a means to achieving other national goals.

Some scientific workers, not utilitarians themselves, hold that only utilitarian arguments will persuade a philistine American public to support research. This strategy ignores the fact that it is precisely the negative public image of certain applications of science—nuclear weapons and nuclear power are the most conspicuous examples—that has fueled antiscience attitudes in recent decades. Such attitudes may also be strengthened by a feeling that, in spite of dramatic advances, science has not delivered on all its promises, because fundamental social and economic problems remain unsolved. Tactical utilitarians further overlook the popularity of books, magazines and television programs that deal not only with technolo-

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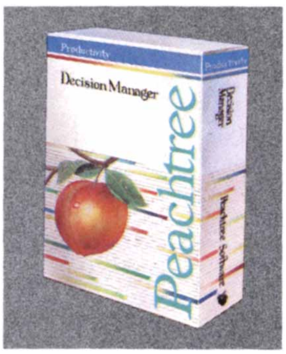

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PCjr is a trademark of International Business Machines Corporation. Peachtree and Peachtree Software are registered trademarks of Peachtree Software Incorporated, an MSA Company. © 1984 gy but also with scientific subjects such as cosmology, evolution and particle physics. A large segment of the public seems willing and even eager to hear about—and support—science as a creative enterprise, as a story of unfolding understanding, rather than simply as the search for a better mousetrap.

In a lecture to the AAAS 23 years ago Dubos argued that scientists should resist the utilitarian attitude. "It seems to me," he said, "that scientists and science writers betray a public trust when they neglect to emphasize the disinterested aspects of knowledge and are satisfied instead with claiming that all discoveries eventually prove of practical use. On the one hand, this is not necessarily true. On the other hand, this attitude ignores the fact that today, as in the past, men starve for understanding almost as much as for food. In the long run, the exclusive appeal to utilitarianism may well endanger the future of science and its very existence."

Receptor Revealed

Two kinds of cells in the mammalian immune system recognize antigens and respond to their presence. *B* lymphocytes synthesize antibodies. *T* lymphocytes regulate *B*-cell activity and also destroy foreign cells or defective "self" cells. The nature of the *B* lymphocyte's receptor, the cell-surface molecule that recognizes an antigen, has been known for some years: it is an antibody, or immunoglobulin. Each *B* cell displays on its surface copies of the unique immunoglobulin it is genetically programmed to manufacture, and the binding of an appropriate antigen to one of these receptors triggers the lymphocyte to generate a clone of antibody-secreting plasma cells. *T*-cell activity can be triggered by the same kind of antigen, and so it has long seemed likely that an antibody molecule or part of one serves also as the *T*-cell receptor. Yet efforts to establish the truth of this conjecture, by probing *T* lymphocytes with antibodies directed against immunoglobulin molecules or with DNA encoding immunoglobulins, were unsuccessful. The *T*-cell receptor remained a mystery.

In the past year and a half there have been glimpses of the elusive receptor. Several investigators made monoclonal antibodies that recognized particular *T* cells and inhibited their immunological response. The structures the antibodies bound to looked rather like antibodies: they consisted of two glycoproteins (proteins with carbohydrate groups attached) linked by disulfide bonds, and each chain appeared to have the "variable" and "constant" regions characteristic of immunoglobulins. Now two groups have independently reported in *Nature* more definitive evidence of the receptor's molecular nature. As is often the case nowadays, they came at the receptor indirectly, by first isolating DNA likely to encode receptor proteins.

Mark M. Davis, Stephen M. Hedrick and their colleagues worked primarily at the National Institute of Allergy and Infectious Diseases. They began with a set of assumptions. Receptor genes should be expressed in *T* cells but not in *B* cells. The messenger RNA for cell-surface receptor proteins should be associated with the cell's membrane system rather than being free in the cytoplasm. Genes encoding *T*-cell receptor proteins should be "rearranged" in *T* cells (and not in other cells), as antibody genes are rearranged in *B* cells, to generate the diversity required for the recognition of an enormous number of antigens. Finally, the genes should have stretches encoding both variable and constant regions.

Davis and his colleagues isolated membrane-bound RNA from mouse *T*-cell hybridomas. (Such cells, formed by fusing *T* lymphocytes with related malignant cells, respond to antigen as *T* cells do but can be maintained indefinitely in a laboratory culture medium.) They "reverse-translated" the RNA to make copy DNA (cDNA), which they labeled with a radioactive isotope and from which they removed any sequences expressed in *B* cells as well as in *T* cells. That left them with a labeled probe likely to recognize *T*-cell surface proteins specifically. With the cDNA probe they searched through a "library" of cloned *T*-cell DNA and isolated a number of homologous, or closely matching, DNA clones. One of the clones turned out to be rearranged in the course of *T*-cell development, just as immunoglobulin DNA is rearranged in *B* cells. The investigators determined the sequence of the component nucleotides in the rearranged DNA and from the sequence deduced the amino acid sequence of the encoded protein.

The protein is closely related to the light chain of mouse immunoglobulin molecules. It has the characteristic variable and constant regions and even the "joining" region between them. It has anchors for disulfide bonds at the appropriate sites, and it has a hydrophobic end that could be anchored in the cell membrane. In other words, it seems to be one chain of a two-chain *T*-cell receptor analogous to a *B* cell's immunoglobulin receptor.

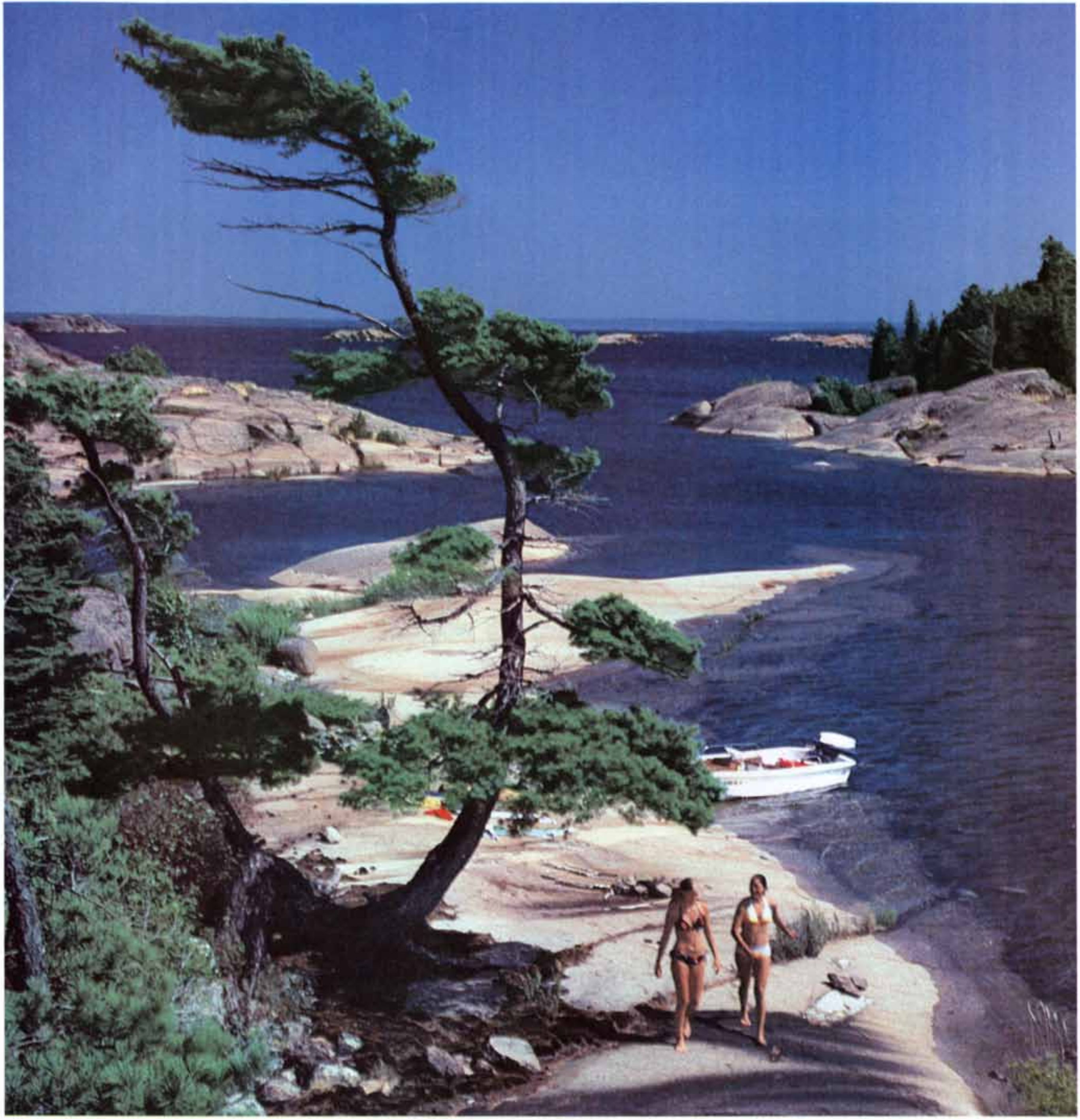
A similar result was reported by Tak W. Mak and his colleagues at the Ontario Cancer Institute and the University of Toronto. They simply cloned cDNA made from total *T*-cell messenger RNA and screened a few clones to find DNA expressed only in *T* cells; when they found a clone that looked like an immunoglobulin gene, they sequenced it. The encoded protein resembles the light chain of both human and mouse immunoglobulin; Mak and his colleagues conclude that it is part of the *T*-lymphocyte receptor.

In view of the close similarity both groups found between an immunoglobulin chain and the *T*-cell proteins predicted by sequencing cDNA clones, it is interesting that Mak's group found their cDNA would not hybridize with (bind to) immunoglobulin messenger RNA. The similarity, they report, "is much more difficult to detect at the nucleotide level than at the amino acid level." The reason is presumably that the genetic code is redundant: most amino acids can be encoded by more than one three-nucleotide codon, so that different nucleotide sequences can specify very similar proteins. This might explain the failure of earlier efforts to find *T*-cell receptor genes by exploring *T*-cell DNA with immunoglobulin-DNA probes.

Searching High and Low

When physicists gave the name "bottom" to a newly discovered particle of matter some seven years ago, it was with the expectation that a companion particle to be known as "top" would soon be found. The top particle has still not been observed, but continuing experiments with composite systems that incorporate a bottom particle may now explain why. It seems the top of the elementary-particle chart may be even higher than had been expected.

Both the bottom, or *b*, and the conjectured top, or *t*, are quarks, the constituent elements of the large class of composite particles that includes the proton and the neutron. All the known quarks, together with the leptons, the other main family of elementary particles, are organized in three generations. Each generation is thought to include two quarks and two leptons, as well as the corresponding antiquarks and antileptons. In the first generation the two quarks are labeled up and down and the leptons are the electron and the electron-type neutrino. The particles of the first generation account for all the ordinary matter in the universe. In the second generation the quarks are called strange and charmed and the leptons are the muon and the muon-type neutrino. The existence of the charmed quark was predicted 10 years before its discovery in 1974 because it could account for the failure of the strange quark to decay through the emission of a particle called the Z^0. The bottom and the much-sought top are the quarks of the third generation; the corresponding leptons are called the tau and the tau-type neutrino. The bottom quark plays a role analogous to the role of the strange quark in the second generation, and the bottom quark too has never been observed to decay through the emission of a Z^0. Both experiment and theory therefore point



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testing, assembly, and inspection phases of all types of manufacturing. From showcase applications like the design and production of microminiaturized printed circuits of staggering complexity, to equally precise—if more accustomed—uses in cameras, copiers, and microfilm processing equipment.

As more and more industries come under the influence of high technology, Zeiss—a hi-tech company long before the phrase came into vogue—emerges ever more logically as a creative supplier to those industries. And a surprising number of them there are! Automotive, aeronautics, computer, defense, energy are just a few.

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strongly to a third-generation counterpart of the charmed quark.

If the top quark exists, however, it may well be too heavy to be created by the particle accelerators currently in operation. Rumors surfaced last year that evidence for the top quark had been found at the European Laboratory for Particle Physics (CERN), but no announcement was forthcoming. The greatest lower bound on the mass of the top quark that has been determined so far by direct experimental search is given by a series of experiments done at the Deutsches Elektronen-Synchrotron (DESY) in Hamburg. Electrons and positrons are made to collide at high energy, and the by-products of the collisions are examined for particles characteristic of the decay of the short-lived top quark. The energy of the collisions has now been increased by small increments to 45 GeV (billion electron volts), and no signal for the decay of the top quark has been found. Because the top quark should first appear bound to its own antiquark in a composite system, the energy gives a lower limit for the mass of the composite system. The effective mass of the top quark alone must be greater than half of 45 GeV, or 22.5 GeV.

At the Stanford Linear Accelerator Center (SLAC) indirect experimental evidence pushes the limit even higher. The lifetime of the *B* meson, which is a composite particle made up of the bottom quark and one of the light quarks of the first generation, is thought to depend on the mass of the top quark: the more massive the top, the longer the lifetime of the *B* meson. Investigators at SLAC have inferred the *B* lifetime from the measured distance between the center of the collision that gives rise to a *B* meson and the source of a shower of leptons given off when the *B* meson decays. The distance is a few hundredths of a millimeter; because the *B* meson travels at about a tenth the speed of light, its lifetime must be approximately a picosecond (10^{-12} second). That lifetime is four or five times longer than had been expected, which implies that the mass of the top is probably greater than 30 GeV.

The bottom quark has itself been the subject of intensive study, since in the absence of the top quark it forms the heaviest systems available for the study of quark dynamics. At the Cornell Electron Storage Ring (CESR) investigators have catalogued the excited states of the upsilon particle, which is the bound system made up of a bottom quark and its antiquark. The states are designated by analogy with the states of the electronic orbits in the atom: the *S* states are those in which the orbital angular momentum is zero and the *P* states are those in which the orbital angular momentum is 1. Until recently three excited *S* states were known for the upsilon particle, in addition to its fundamental, or ground, state. The Cornell investigators have now determined the mass of two *P* states of the particle, and last month at the meeting of the American Physical Society in Washington they reported the detection of a fourth excited *S* state. The mass of the newly discovered *S* state is 10.88 GeV.

Preschool for Pathogens

Considerable attention has been given in recent years to the effects on a child's early social and psychological development of attending a day-care center. What is noted much less often is that the expansion of child care outside the home has had epidemiological consequences as well as social consequences. According to a report published in *Journal of the American Medical Association,* the changes in patterns of disease transmission that result from day care affect not only children who attend the centers but also their parents. As a result of early and sustained contact among preschool children there has been a shift in the age pattern of some childhood diseases. In addition some disease outbreaks in the adult population have been caused by pathogens that spread rapidly in day-care centers and are carried to the home.

One disease with an altered age pattern is infection by the bacterium *Hemophilus influenzae* type *B*. In spite of its name the bacterium does not cause influenza. It can, however, cause a serious form of meningitis. Before the spread of day care, infection by *Hemophilus* was commonest among infants from six months to one year old. Work done by the Colorado Department of Health and the U.S. Centers for Disease Control (CDC) shows the infection is becoming more prevalent among older children. Among children older than two years the risk of contracting the infection is 12 times greater for those who attend day-care centers than it is for those who do not. The increased risk is presumably due to exposure to younger children, who form a reservoir of infection.

Hepatitis *A* is a disease that is considerably more serious for adults than it is for children. Hepatitis *A,* the less severe of the two forms of hepatitis, often produces no symptoms in children, whereas adults have episodes of acute illness that can include high fever and enlargement of the liver. The virus that causes hepatitis *A* can be transmitted in the feces of an infected person, and the risk of an outbreak in a day-care center depends on whether or not the center admits children who are not toilet trained. Adults are readily infected by children who are infected but asymptomatic. Work done by Stephen C. Hadler of the CDC suggests that in recent years at least one-third of hepatitis *A* outbreaks in the U.S. began in day-care centers.

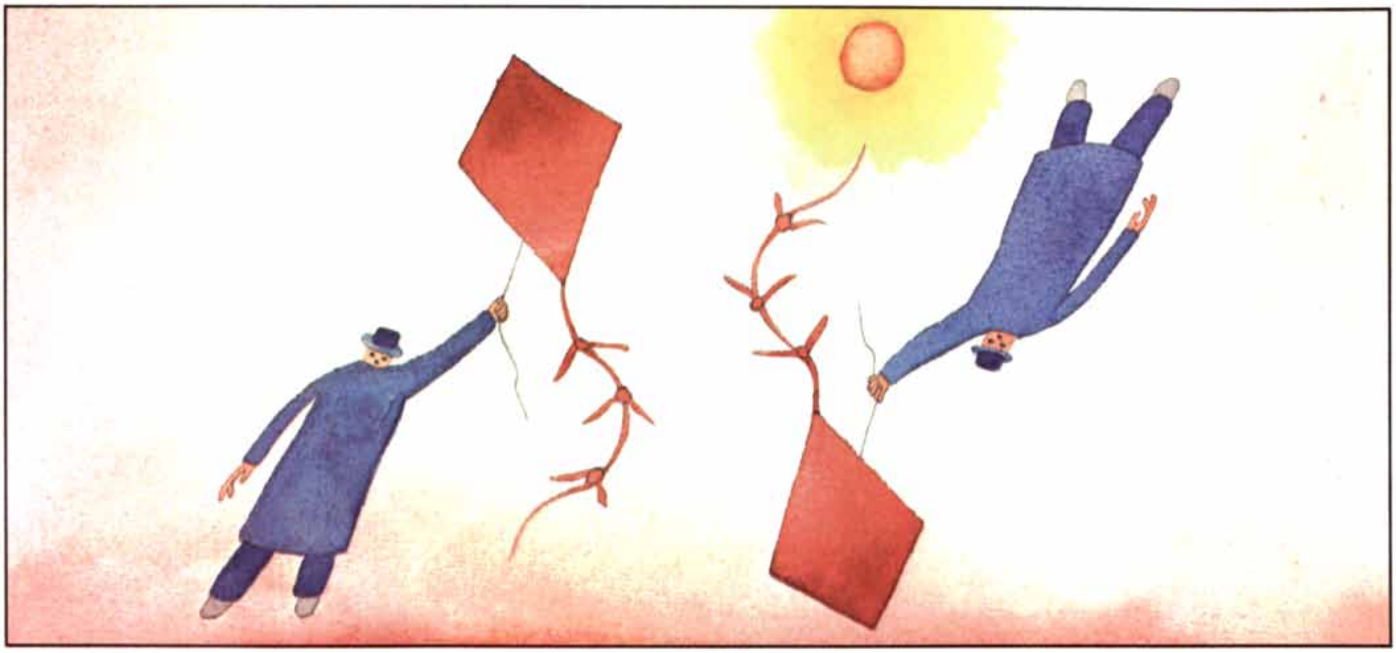
Centers for child care have also been shown to have a significant role in the transmission of cytomegalovirus infection and some forms of diarrhea caused by bacteria. The recent findings, however, do not appear to justify the elimination of day-care centers. The rate of serious *Hemophilus* infection in children under four years old is only about one per 1,000 per year, and the incidence of hepatitis *A* in the U.S. does not appear to be increasing and may well be decreasing. According to Hadler, rather than constituting a reason for closing day-care centers the findings should call the attention of physicians and parents to a problem that requires general awareness and concerted action.

Ice X

One of the most distinctive properties of water is the fact that at atmospheric pressure its solid phase is less dense than its liquid phase. The far-reaching consequences of this phenomenon, which sets water apart from almost all other substances, can be appreciated by trying to imagine how the biosphere might have evolved if water froze from the bottom up rather than from the top down. The tendency of ice to float can be traced to its remarkably open crystal structure: the H_2O molecules in ordinary ice are joined by highly directional, obtuse-angled hydrogen bonds to form a regular hexagonal arrangement that leaves a considerable amount of empty space between the molecules. When a crystal of ordinary ice melts, the breakdown of this rigid structure allows some of the molecules to fill the gaps, thereby increasing the density.

The density of frozen water can be increased in another way, although only under extraordinary conditions. By subjecting ice to pressures of more than 2,000 atmospheres the water molecules can be forced into various deformed patterns, again reducing the amount of empty space and hence increasing the density. Over the years eight additional solid forms of water have been identified in this way; designated ice II through ice IX (to distinguish them from ordinary water, or ice I), the exotic, high-pressure forms of solid water correspond to specific temperature-pressure domains in the extended phase diagram of H_2O. When the high pressure is released, each of these structures reverts to ordinary ice or to liquid water, depending on the temperature.

The existence of yet another solid form of water was proposed more than a decade ago by the German physicist Wilfried B. Holzapfel. Calculations indicate the density of this phase would be so high that the crystal structure would no longer consist of well-defined molecules linked by hydrogen bonds. Instead each oxygen atom would be sur-



ELECTRICITY FROM THE ATOM
Are we moving in the right direction?

The value of nuclear power is being questioned these days mainly because of serious financial problems with some plants under construction. What's often overlooked is that with 80 plants operating in the U.S., and over 200 more throughout the world, nuclear-generated electricity is already being used extensively, safely, and economically.

High interest rates and inflation, plus a massive updating of safety regulations, plus construction slowdowns, have made many of the nuclear plants now under construction much more expensive than they were when originally planned.

Yet these plants will still be needed, because demand for electricity is growing.

A growing economy needs more electricity

Industry is shifting to manufacturing processes that use electricity for better energy efficiency. Electronic technology is improving productivity. Our heating and cooling needs in offices, factories, malls, and homes continue to boost electrical demand.

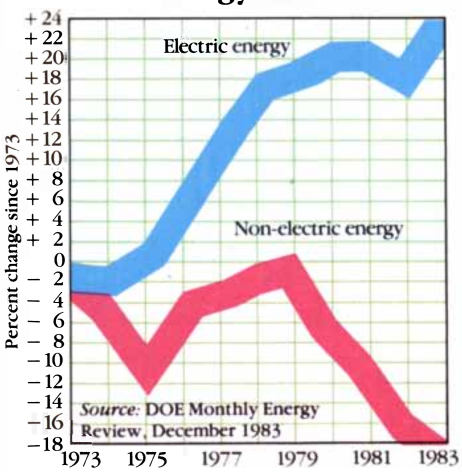
The question raised in the past few months boils down to this: Can nuclear power plants, fueled by uranium, produce reasonably priced electricity?

Uranium saves money and fuel

The average cost of electricity from the 80 U.S. nuclear plants now operating is less than half the cost of oil-generated electricity. And in many parts of the country, it's roughly the same as or somewhat less than electricity from coal.

Most of the nuclear plants now operating were built before the years of double-digit inflation and persistently high interest rates—huge factors in the higher cost of the plants now approaching completion. Even so, over their 30- to 40-year lifetimes, these new plants can provide economic benefits because of the lower cost of uranium fuel.

Electric vs. non-electric energy use



While the use of non-electric *energy has declined, U.S. consumption of* electric *energy has increased by over 25% since the Arab oil embargo.*

Renewing the nuclear promise

Utilities have learned to be more realistic about what it takes to construct and run a nuclear plant. They have been beefing up their nuclear engineering staffs and strengthening their operator training programs.

At the same time, the Federal government is moving to reform the nuclear regulation process, which causes needless delays and often adds hundreds of millions of dollars in excessive construction and operating costs.

But these steps alone are not enough. The full potential of nuclear power will be achieved only with a full public understanding of its benefits. Then, the development of America's nuclear-electric energy will continue to move in the right direction.

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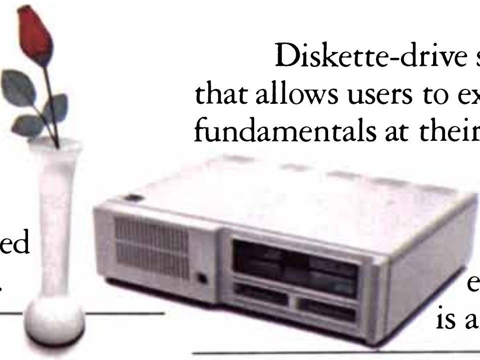

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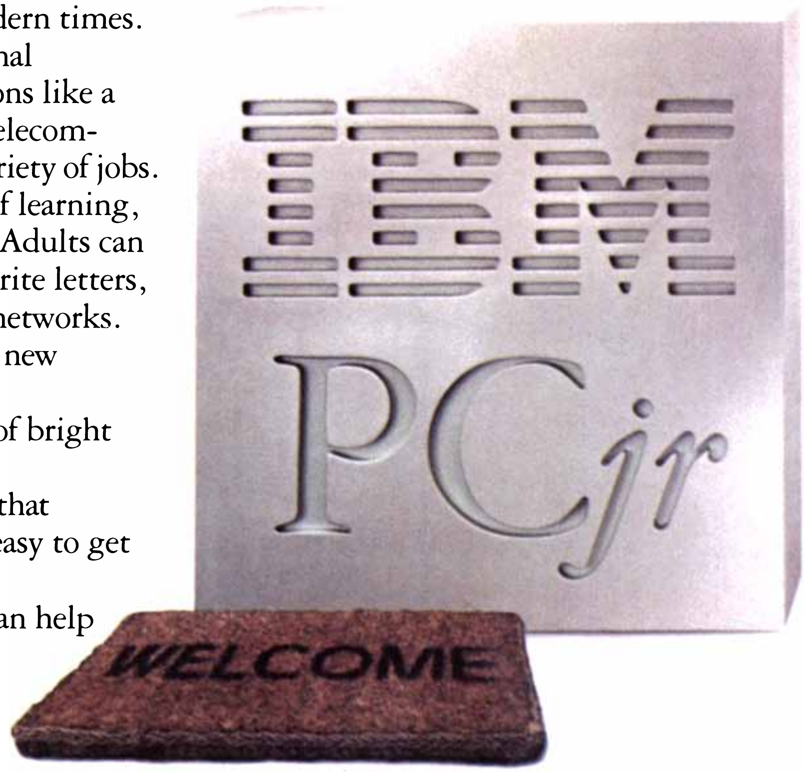

rounded by a tight cubic array of nearest-neighbor oxygen atoms; a hydrogen atom would be situated halfway between each pair of oxygen atoms and so would be associated no more with one oxygen than with the other. The structure, known as symmetric ice, or ice X, was initially predicted to form at pressures greater than 350,000 atmospheres, beyond the reach of the equipment available at the time.

It is only recently, with the advent of the ingenious high-pressure device known as the diamond-anvil cell, that the search for the new symmetric phase of ice has become feasible (see "The Diamond-Anvil High-Pressure Cell," by A. Jayaraman; SCIENTIFIC AMERICAN, April). The quest now appears to have succeeded. The first tentative identification of ice X was made in an experiment done at the Argonne National Laboratory by Alain Polian, a visiting French investigator, and Marcos H. Grimsditch of the Argonne staff. Polian and Grimsditch report their findings in *Physical Review Letters.*

In an earlier study by the same two workers a minute sample of water at room temperature was subjected to pressures ranging up to about 300,000 atmospheres in the diamond-anvil cell. Relying on the technique of Brillouin-scattering spectroscopy, in which the compressibility of a sample is determined indirectly by measuring the reflection of laser light from highly directional sound waves in the sample, the investigators reported that "no anomalous behavior was observed." When they extended their study to pressures of up to 670,000 atmospheres, however, they found "an anomaly in the behavior of the longitudinal sound velocity" at a pressure of 440,000 atmospheres, indicating that a phase transition had occurred. Although they caution that their results may be subject to at least one other interpretation, they conclude that the phase above 440,000 atmospheres "is the tenth known solid phase of H_2O and . . . is probably the predicted symmetric ice. As such it would be the first nonmolecular structure for H_2O."

A Note on Perfect Pitch

Perfect pitch, the ability to identify a tone without hearing a second tone for comparison, is an intriguing phenomenon neurologically. Introspection and guessing are generally poor guides to the workings of the brain, but in this case it is hard to resist the hypothesis that the brain of a person with perfect pitch includes (as other brains do not) a mental representation of standard tones in permanent storage. A person lacking such representations can have only relative pitch; he can listen to tones in succession and try to compare one tone with the next to establish the interval.

The available evidence supports the hypothesis. For example, people with perfect pitch are better than people with relative pitch at identifying intervals if several seconds pass between the sounding of the first tone and the second. The difference in performance is to be expected, because the "working," or short-term, memory in which a tone is stored for comparison with subsequent tones maintains the storage for a few seconds at the most. New evidence goes further. In confirming the hypothesis about perfect pitch it also tends to confirm a hypothesis about the large-scale electrical activity of the brain.

The evidence was collected by Mark Klein, Michael G. H. Coles and Emanuel Donchin of the University of Illinois at Urbana-Champaigne, who tested 14 students of music there. The results are reported in *Science.* Seven of the 14 described themselves as having perfect pitch, and they tended to be better at identifying tones. When they did make errors, they named the pitch correctly, but "they assigned it to a higher or lower octave than that of the actual stimulus."

Each subject was given "oddball tests." In a test the subject saw two visual stimuli (the letter *H* or the letter *S*) or heard two auditory stimuli (a tone of 1,000 hertz or a tone of 1,100 hertz) in random alternation. In each test one of the stimuli was rarer than the other: it was presented on only a fifth of the trials. The subject was asked to count the rarer stimuli. Meanwhile a set of scalp electrodes was recording the electrical activity of the brain. The results over many trials were averaged to minimize the "noise" in the recordings; in this way a characteristic waveform called the event-related potential emerges. It can include a positive peak, maximal in the parietal lobe at the crown of the brain, roughly 300 milliseconds after the stimulus is presented. The peak is known as a P300. It is thought to signify (in the language of cognitive science) that the brain is updating the contents of working memory.

All 14 subjects "counted all rare events with equal accuracy," but the electrical recordings revealed some remarkable differences. The seven subjects who said they did not have perfect pitch showed "standard" event-related potentials for both the visual and the auditory oddball tests. The potentials included a P300. Evidently the brain was holding the memory of a stimulus over the brief time required to compare it with a subsequent stimulus.

The seven subjects who said they did have perfect pitch tended to show standard event-related potentials only on the visual test. On the auditory test the P300 was notably smaller. Indeed, the smallest P300's were measured in the brain of the subjects who had done best on the test of their perfect pitch. Two things seem to be confirmed: a person with perfect pitch does not rely on working memory to identify a tone, and the brain's updating of working memory truly is signaled by a P300.

The Information Implosion

It would seem a safe bet that with growing population and rising level of education the number of books published annually is increasing steadily. A look at the yearly reports of the Library of Congress, however, reveals that in several fields the number of new books has declined quite sharply. In each case the decline began some 12 or 13 years ago. The fields affected most are science, technology, history and language and literature. In the fine arts, law and religion and philosophy the decline has not appeared; the number of titles issued annually has remained about the same.

The acquisitions policy of the library is essentially passive. By law a copy of each book published under a U.S. copyright is deposited in the library. In the case of foreign books the library buys those that seem likely to be of lasting value. The decline does not reflect a budgetary squeeze at the library.

What does it reflect? The question has been considered by Charles A. Goodrum, who retired from the library's Congressional Research Service a few years ago and now serves as a consultant to the library. In science and technology, he says, the electronic age may be at hand already, with an increasing number of workers doing their writing on computers and publishing only an abstract in a printed journal. An additional possibility may be that there is now thought to be less need to publish books explaining scientific topics.

Another factor at work, according to Goodrum, may be a decline in candidates for the Ph.D. degree, brought on in turn by the prospect that appointments to positions on college and university faculties will be scarce for years to come as the institutions cope with declining enrollment. The Ph.D. thesis often becomes the basis of a book. Goodrum also sees the possibility that the worldwide economic recession caused publishers to curtail their book lists. As for the fields where there has been no decline—the fine arts, law and religion and philosophy—he says a case can be made for their being somewhat remote from the economic and technological forces that have affected the other fields.

The figures on science books added to the library's holdings between 1962 and 1982 show the trend clearly. In 1962 the library acquired 5,091 science books. The total rose quite steadily to a peak of 16,923 in 1972 but then declined to 7,900 in 1982. The pattern is much the same for technology, history and language and literature.

· THE 1984 ROLEX AWA

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The Rolex Awards for Enterprise were conceived in 1976 to provide help and encouragement in breaking new ground in the fields of Applied Sciences and Inventions, Exploration and Discovery, and the Environment.

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Between 1920 and 1940 guns and poison successfully and systematically wiped out the magnificent Griffon Vulture from the Massif Central area of France.

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So far, Michel Terrasse, after much effort and patience, has succeeded in repopulating the area with a colony of 30 vultures, and in recording the births of two young vultures—the first to be born free in the area for 50 years.

Ecologists and ornithologists watch the work of Michel Terrasse with interest. His Rolex Award for Enterprise will help him with his fascinating programme of repopulation.

PLANTING ASPARAGUS TO PREVENT SOIL EROSION

Three years ago, Mr. Thean Soo Tee realised the opportunity of cultivating asparagus in the Mt. Kinabalu area of his native Malaysia, some 1,200 metres above sea level. Asparagus grows well and quickly on this irrigated land, reaching maturity nine months after sowing.

The enormous root system of the asparagus plant, set firmly by permanent cultivation, would hold back the soil and save the sloping fields from erosion.

With existing crops of cabbage, peas, carrots, etc., the earth must be turned over after each harvest for the next cropping cycle, exposing it to attack by wind and water, which turn it ultimately into stone-strewn, unproductive land.

Mr. Tee also recognised that, as asparagus fetches a higher price in the market-place, its cultivation would substantially increase the income of the local farmers.

Encouraged by early success, Mr. Tee plans to develop five model farms where the local farmers could work and learn the cultivation techniques necessary and then, hopefully, abandon their traditional system for permanent agriculture.

A careful evaluation of European and American species of asparagus is also planned with a view to providing a wider genetic base for the asparagus development programme in Malaysia.

For its originality and endeavour, Mr. Tee's project has earned a Rolex Award for Enterprise.

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AN EXPLORATION OF BRABANT ISLAND IN ANTARCTICA

A specially picked team of men is currently over-wintering on Brabant Island—an island as yet unsurveyed.

It is the intention of Kenneth W. Hankinson, an Englishman, to ensure that a thorough study of the island will be made. A study which will yield a geological history of this gateway to the Bransfield and Gerlache Straits.

Flora and fauna will be studied to assess ecological balance and likely future development on the island.

In particular, a close study will be made of a seal species which feeds on planktonic shellfish. The major peaks will be scaled. The land mass charted. And the first circumnavigation of the island effected by canoe.

Throughout the entire stay, under canvas, a close observation will be kept on the psychological effect that close confinement, intense study and almost continual darkness and danger will have on the behaviour of individual team members.

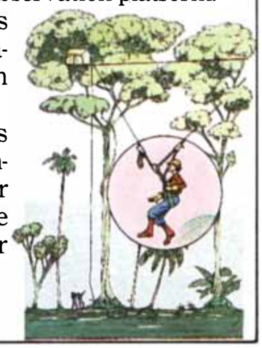
The 1984 Rolex Award for Enterprise he won will help Kenneth Hankinson and his expedition to achieve their aim: putting Brabant Island comprehensively on the map.

EXAMINING THE TROPICAL FOREST CANOPY

The upper layer of tropical rain forest is one of the last unexplored frontiers known to man. This "canopy" is the home of several million species of plants and animals, most of which are still unknown to scientists.

A no-man's land between earth and sky. Its branches are too thin, too flexible, to bear the weight of eager research biologists.

Donald Perry, an American biologist, whose project is planned for Costa Rica, however, has devised an ingenious "spider's web" which can be suspended from the taller trees in order to carry a harness from a secure observation platform.



Biologists may thus study life processes, pollination, fruit bearing, etc., in relative safety.

As tropical rain forest is being cut down at an alarming rate, a Rolex Award for Enterprise couldn't have come at a better time for Donald Perry's project.

AN INVENTORY OF ALL THE MAYAN WALL PAINTINGS

Eight years ago, Martine Fettweis-Vienot, a determined and dauntless Belgian archaeologist, decided to take on the gigantic task of compiling the first inventory of Mayan wall paintings.

The last remnants of Mayan culture, which flourished between the 3rd and 15th centuries, are to be found in ruined temples and cities soon to crumble and disappear forever.

Mme. Fettweis-Vienot is reproducing the work done between the 7th and 15th centuries. Each painting must be traced on cellophane paper directly from the wall or ceiling. Every single one must be transferred with immense precision. Each colour intensity must be accurately reproduced.

Mme. Fettweis-Vienot then intends to analyse the constituents of the Mayan colours in special laboratories.

Her Rolex Award for Enterprise will help towards the completion of this important iconographic study.

A book about the Rolex Awards for Enterprise, detailing the projects of the five Rolex Laureates and over 200 other projects, including the 26 winners in the "Honourable Mention" category, will be published in the Spring of 1984.

Further information is available from:
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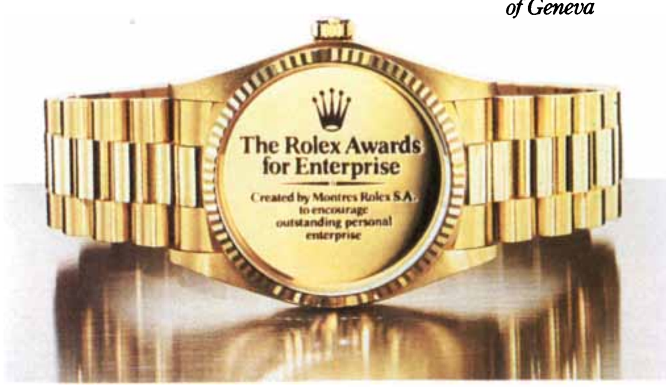


STABLE AND UNSTABLE MUTATIONS affect the pigmentation of kernels on maize ears studied by the author. A stable mutation in a gene required for the synthesis of a purple pigment accounts for the colorless kernels in the ear at the left. The other two ears illustrate patterns of variegation generated by unstable mutations caused by transposable genetic elements. Coarse or fine pigmented spots are generated in colorless kernels (*center*) when two different versions of the *Spm* element transpose, early or late in kernel development, away from a genetic locus affecting the synthesis of a purple pigment. The "bronze" kernels (*right*) result from a mutation, caused by the *Ac* element, partially interfering with pigment synthesis. When *Ac* transposes away from the gene, purple sectors are generated in the kernels.

Transposable Genetic Elements in Maize

The mobile genes Barbara McClintock discovered 40 years ago have since been identified in bacteria, other plants and animals. Several maize elements have now been characterized at the molecular level

by Nina V. Fedoroff

A transposable genetic element is a bit of DNA that can move from place to place in an organism's genome (its total complement of genetic material). It is excised from one site and inserted at another site either on the same chromosome or on a different one. In structure it can be quite simple, consisting of just a few genes that promote transposition, bracketed by special recognition sequences. The movement of a transposable element can generate mutations or chromosomal rearrangements and thus affect the expression of other genes. Chromosomes are found to be littered with these mobile elements, or "jumping genes," and it is suspected that their ability to modify the expression and structure of other genes and even the structure of an entire genome is an important mechanism mediating the long-term genetic change that is central to evolution.

Discovery and Isolation

Transposable elements were first identified in maize plants during the 1940's as a result of some remarkable genetic studies done by Barbara McClintock of the Carnegie Institution of Washington's Department of Genetics at Cold Spring Harbor, N.Y. In the past 20 years similar elements have been identified in every kind of organism that has been examined, from bacteria to worms and fruit flies. Some of the elements were isolated and analyzed in molecular detail, but until very recently the maize elements themselves remained a genetic abstraction.

For the past few years, in my laboratory at the Carnegie Institution's Department of Embryology in Baltimore, I have had the pleasure of applying the new techniques of molecular biology to isolate and study McClintock's mobile maize genes. Some of the elements first identified almost four decades ago have now been isolated, and the analysis of their structure and DNA sequences has deepened understanding of how the elements work.

A New Awareness

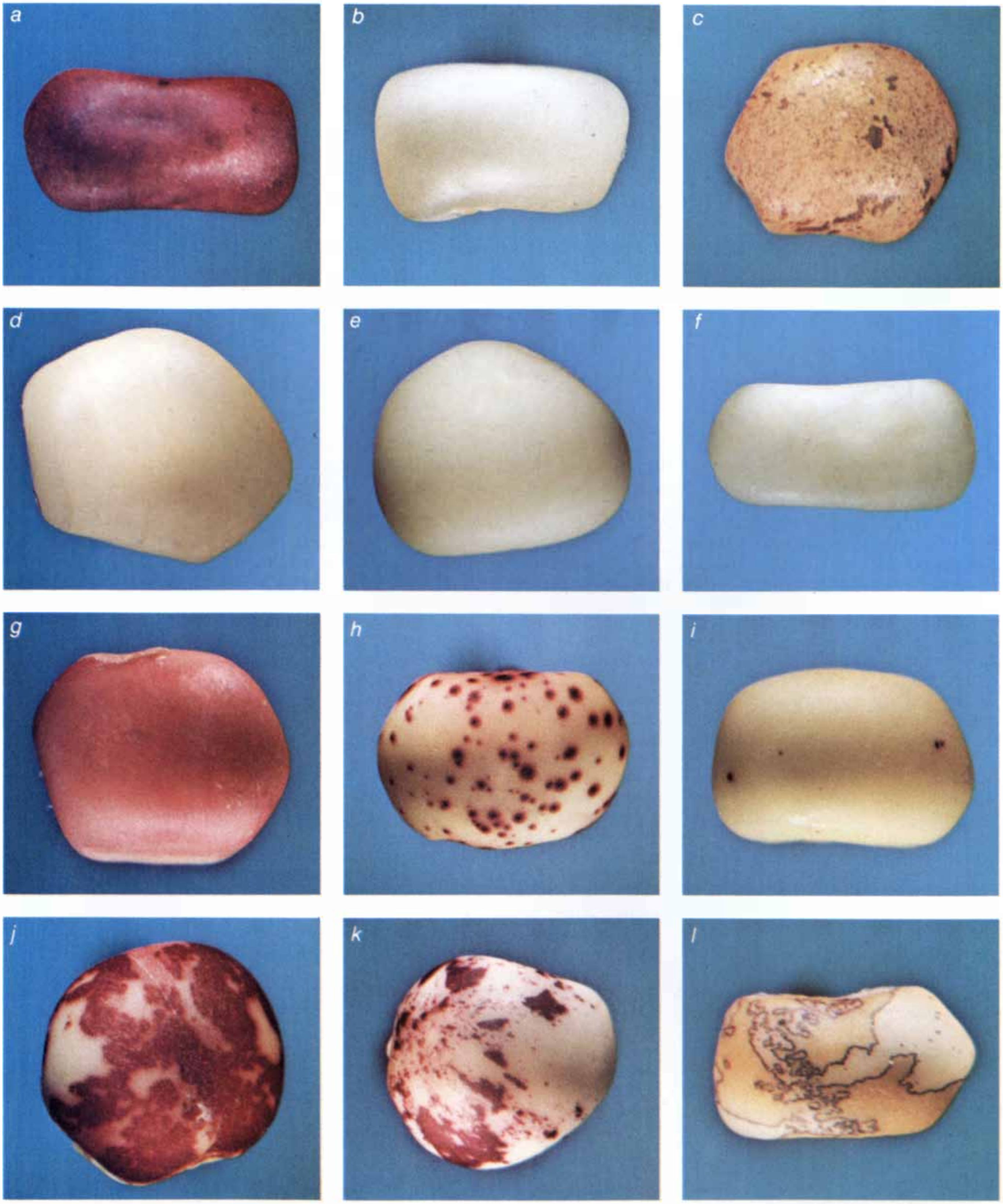
The awareness that transposable elements are both abundant and ubiquitous is recent. Until the late 1970's an organism's genome was considered to be quite stable. The genes that determine structural and biochemical traits are discrete elements arrayed along linear chromosomes. Each gene occupies a fixed position that generally does not change from one generation to the next. The stability of chromosomes and of the genes residing on them underlies the work of classical geneticists, who identified genes and figured out their chromosomal positions without ever isolating a gene or knowing its chemical nature. They defined a gene by tracing the inheritance of a trait governed by a single Mendelian hereditary "factor." They mapped the relative positions of genes through analysis of the progeny of repeated crossings, which revealed what genes are linked to one another on individual chromosomes and showed how closely they are linked. Later, biochemical geneticists and molecular biologists learned how the genetic material, identified as DNA, is faithfully reproduced from generation to generation. The emphasis continued to be on the constancy of genes and chromosomes and on the orderly rules governing inheritance.

Rules can have exceptions, however. Most genes do stay put, but a few of them move. People struggling to understand the rules can pay little attention to the exceptions, and so the first emerging indications that some genes (or genetic loci, to use a more general term) do not stay in the same place were mostly ignored. The first clues to transposition, which were not at all understood at the time, came from the analysis of unstable mutations. A mutation is a change in the DNA, and its effect is commonly to inactivate a gene. In most cases the change is all but irreversible. The damage is spontaneously undone by back mutation, or reversion, in perhaps only one in a million progeny of a mutant organism. For a few mutations, however, the frequency of reversion is so high that an organism becomes a patchwork of mutant and revertant tissue. Such unstable mutations can therefore give the organism a variegated appearance.

Variegation and Reversion

In the first decades of this century R. A. Emerson of Cornell University studied a type of variegation that is quite familiar in maize strains sold as Indian corn. It is caused by a mutation interfering with the synthesis of a red-orange pigment in the pericarp, the tough protective layer of cells surrounding the corn kernel. Unlike most mutations, this

RED-ORANGE STREAKS on a maize kernel are caused by an unstable mutation. The transposable element *Mp* interferes with pigment synthesis when it is inserted at a locus called *P*. In some cells it moves away; the mutation reverts, giving rise to pigmented sectors. The transposition of *Mp* has been studied by Irwin M. Greenblatt of the University of Connecticut, who supplied this kernel.



MAIZE KERNELS show the effect of mutations and transpositions. The *C* locus makes a factor required for the synthesis of a purple pigment (*a*). Insertion of the *Ds* element in the locus inactivates the gene, rendering the kernel colorless (*b*). In the presence of the *Ac* element, *Ds* is transposed away from the locus in some cells, giving rise to sectors of pigmented cells and thus to a spotted kernel (*c*). The *waxy* locus encodes an enzyme needed for the synthesis of the starch amylose, which makes the endosperm translucent (*d*). With *Ac* inserted into the locus the endosperm is opaque (*e*). Transposition of *Ac* leads to variegation for translucent and opaque sectors (*f*). A defective *Spm* element can be inserted into a pigment-enzyme locus in such a way that the gene is partially inactive and the kernel is palely pigmented (*g*). A nondefective *Spm* has two effects: its suppressor function completely inactivates the gene, making the kernel colorless, and its mutator function transposes the defective *Spm*, generating clones of revertant and hence fully pigmented cells (*h*). If transposition is infrequent, there are few spots (*i*); if transposition takes place early in kernel development, the revertant clones are large (*j*). The effect of a cycling version of *Spm* is to generate pigmented spots within which there are small colorless sectors (*k*). Chromosome breakage, a frequent occurrence at a site of *Ds* insertion, can generate patterns of palely pigmented sectors separated by fine, deeply pigmented boundary lines (*l*).

one is so unstable that it reverts many times in the course of each kernel's development, giving rise to alternating streaks of pigmented and unpigmented cells. Emerson understood that the streaks are generated by unstable mutations, but he did not know what causes such mutations.

In the 1930's Marcus M. Rhoades, who is now at Indiana University, added the information that genetic instability in maize can be conditional. What appears to be a stable mutation can suddenly become unstable in the presence of a particular gene. The mutation he studied is one that disrupts the synthesis of a purple pigment in the aleurone, the outermost layer of the kernel's endosperm (just under the pericarp), rendering the aleurone colorless. Rhoades showed that when a particular gene is present in the cell, the mutation reverts, giving spots of purple pigment in the otherwise colorless aleurone. Rhoades called the spot-generating locus *Dotted*. He did not know that the *Dotted* locus could move.

It was Barbara McClintock who first understood that a genetic element can transpose. Her first report, in 1947, that a genetic locus could move was a troubling oddity, and for years no one knew what to make of it. Now it is recognized as one of the most important genetic discoveries of the century, and last year McClintock was awarded a Nobel prize for her work.

McClintock discovered transposition when she was studying the properties of broken chromosomes in maize. She found such chromosomes make a genetic mess. They are quite unstable and they take part in chromosomal rearrangements that disturb the genome profoundly. She observed further that plants with broken chromosomes often gave rise to variegated progeny. The variegation affected several traits, and this suggested to McClintock that a number of new unstable mutations were being generated.

The locus McClintock first observed to transpose turned up as an odd kind of locus indeed. It manifested itself as a specific site of chromosome breakage, or dissociation, and so she called it the *Dissociation* locus, or *Ds*. Although *Ds* is the site of breakage, it is not itself responsible for breakage, which takes place only if another locus is present. McClintock called this second locus *Activator*, or *Ac*, for its ability to activate breakage at the *Ds* locus. It became apparent to her that the inheritance pattern of *Ac* and *Ds* was unusual. *Ac* acted like a conventional locus most of the time, but in some instances (in no more than a few percent of the progeny) it disappeared or moved to a new position on either the same chromosome or a different one. The *Ds* locus could transpose too, but just as it was incapable by itself of breaking the chromosome on which it resides, so too it was unable to transpose in the absence of *Ac*. McClintock came to understand that *Ac* can move by itself (autonomously), but *Ds* can move only when it is activated by *Ac*.

Reversion and Transposition

McClintock undertook a series of experiments that led to an understanding of the relation between unstable mutations and transposition. She analyzed a case in which *Ds* had transposed from its original site to a locus, designated *C*, that had been studied by several geneticists. The *C* locus makes a factor required for the synthesis of a purple aleurone pigment, and mutations at *C* were known to interfere with pigment production. McClintock meticulously collected evidence that the new mutation at *C* was caused by the insertion there of *Ds*. She showed that (if *Ac* was present) the same kind of chromosome breakage took place at *C* as had been noted at the original position of *Ds*. Now, however, *Ds* had a second effect. It caused a mutation at *C* resembling the ones studied by Emerson and Rhoades. In the absence of *Ac* the mutation was a stable one: kernels were colorless and the entire plant was green. With *Ac* in the genome, on the other hand, the mutation reverted in some cells, so that both the kernels and the plant showed sectors of purple pigment [*see kernels* a–c *in illustration on opposite page*].

McClintock was now in a position to understand the genetic basis of unstable mutations. In a small fraction of kernels the reversion had taken place early enough to have affected the germ cells, so that it could be passed on to progeny plants. McClintock grew plants from the rare completely revertant kernels and found in all cases that *Ds* was no longer at the *C* locus. The locus now functioned normally. Moreover, even in the presence of *Ac* the chromosome no longer broke at the *C* locus, as it had when *Ds* was there.

McClintock concluded that the insertion of *Ds* had indeed caused the original mutation to a colorless aleurone and that the removal of *Ds* was responsible for reversion. She inferred from these observations that the variegation in the plants and kernels resulted from the excision of *Ds* from the *C* locus in a large number of cells during the plant's development. Her inference was confirmed by the observation that the purple sectors on kernels had none of the small colorless regions that would have been present if the chromosome breakage associated with the *Ds* locus were still taking place. McClintock concluded that an unstable mutation can arise from the insertion of a transposable element at a locus. The frequent transposition of the element away from the locus during development accounts for the high rate of reversion that produces the characteristic variegated patterns.

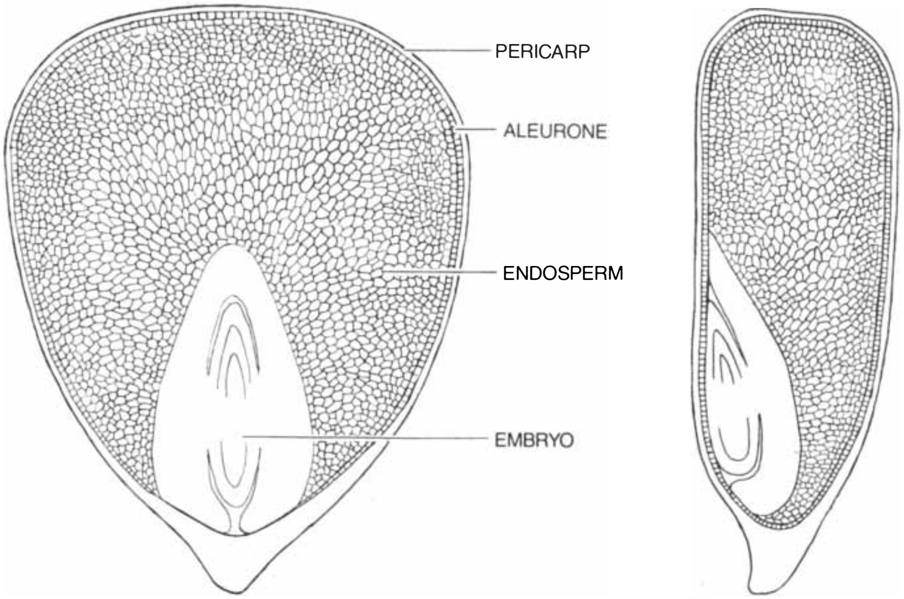
In the years that followed her first description of transposition McClintock continued her analysis of *Ac* and *Ds* and, along with a few other maize geneticists, identified and characterized additional elements. R. Alexander Brink of the University of Wisconsin at Madison learned that the unstable mutation originally studied by Emerson, affecting the red-orange pericarp pigment, is caused by the presence of a transposable element at the *P* locus. The element, which he designated *Mp*, eventually turned out to be genetically identical with *Ac*. Like *Ac*, it can cause an unstable mutation by inserting itself into the *P* locus and then transposing away from the locus at a high frequency.

Brink and his students, notably Irwin M. Greenblatt of the University of Connecticut, did some elegant experiments that led to an understanding of how *Mp* (or *Ac*) transposes. It moves during the phase of the cell cycle when the chromosomes are replicating in preparation for cell division. The moment of transposition comes after *Mp* itself has replicated but often before the chromosome on which it resides has completed its replication. Only one of the two daughter copies of the element moves, and most often it moves to a nearby site on the same chromosome. If the recipient site has not yet replicated, its subsequent replication gives rise to one daughter chromosome carrying two copies of *Mp* and one chromosome with a single copy at a new site. If the element moves to a site that has already replicated, one daughter chromosome is without an *Mp* and the other carries two copies of the element, one of which is at a new site. The departure of the element from the *P* locus results in reversion of the unstable mutation. The locus subsequently functions normally to promote the synthesis of the red-orange pigment.

The relation between the *Ac* (or *Mp*) locus and the *Ds* locus remained obscure. It was clear from McClintock's genetic analyses that the two loci are both mobile but that the mobility of *Ds* depends on the presence in the same genome of *Ac*. McClintock observed that in some cases a mutation with the properties of an *Ac* mutation changed to one with the character of a *Ds* mutation. She suspected that the *Ac* and *Ds* loci are somehow related. The physical nature of the two loci and their precise relation were not to become clear, however, until they were isolated last year.

Transposons in Bacteria

In the decades between the genetic identification of *Ac* and *Ds* and their molecular isolation, transposable elements were discovered in other organisms and the molecular basis of their transposa-



MAIZE KERNEL, seen here in two cross-sectional views, is composed of the embryo and its nutrient tissue, the endosperm. Many of the unstable mutations analyzed in greatest detail affect the synthesis of pigments in aleurone and pericarp tissues or of starch in the endosperm.

bility began to be intelligible. The first indication of transposable elements in bacteria came in the mid-1960's, when certain peculiar mutations were found to be the result not of small changes in the sequence of nucleotides (the four subunits of DNA whose sequence encodes genetic information) but of the insertion in a gene of a sizable piece of foreign DNA. Then it developed that multiple transferable drug resistance in bacteria is mediated by mobile genetic elements. The widespread use of antibiotics in animals and in human beings had resulted in the emergence of bacterial strains simultaneously resistant to several antibiotics. Microbiologists learned that the genes conferring resistance are carried from one strain to another on the small circular molecules of bacterial DNA called plasmids. By the mid-1970's it was clear that the antibiotic-resistance genes are actually passengers on small mobile elements, called transposons, picked up by the plasmids as they travel from cell to cell.

A few investigators understood immediately that the bacterial transposons and the transposable elements of maize plants are more alike than they are different [see "Transposable Genetic Elements," by Stanley N. Cohen and James A. Shapiro; SCIENTIFIC AMERICAN, February, 1980], but for most of them the work of maize geneticists on transposable loci remained obscure and seemed to be of doubtful relevance to modern molecular biology. The bacterial elements were, however, analyzed in detail and some of the mechanisms of their mobility came to be understood.

Perhaps the best-studied transposon is the one designated Tn3. It is about 5,000 nucleotides long and carries three genes. Two of the genes encode enzymes required for transposition; the third is the passenger gene encoding the enzyme beta-lactamase, which inactivates ampicillin and thus makes bacterial cells carrying Tn3 resistant to the antibiotic. The ends of the Tn3 transposon are special noncoding sequences called inverted repeats. (The four nucleotides, designated *A, G, T* and *C,* are linked in complementary pairs to form the double helix of DNA: *A* binds to *T* and *G* binds to *C.* The sequences at the terminals of a transposon are bidirectionally and rotationally symmetrical, that is, the same sequence appears at both ends of the element, but it reads in the opposite direction on opposite strands.) The inverted repeats serve as recognition signals demarcating the sequence to be transposed. There are two transposition enzymes, a "transposase" and a "resolvase." The transposase begins the transposition process and the resolvase finishes it.

Like the maize elements, bacterial transposons can cause insertion mutations. A mutation within an essential gene is lethal to a cell, however, and a very high rate of transposition would increase the risk of such mutations. The transposon therefore has a mechanism for regulating the expression of both the transposase and the resolvase genes. The resolvase itself is the regulator. In addition to acting as an enzyme, the protein acts as a repressor. It binds to a site between the transposase gene and its own gene, preventing the expression of both genes.

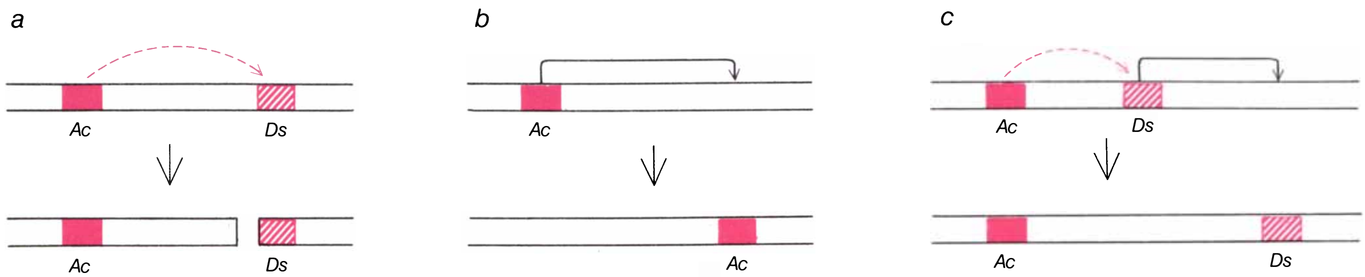
Not all bacterial transposons are as small or as simple as Tn3. Some are composite elements bounded at both ends by a copy of a small transposable element. DNA sequences resembling bacterial transposons have been isolated from a number of higher organisms, including yeast, the fruit fly *Drosophila melanogaster* and nematode worms. Because there are many copies of such sequences, however, and because they move at a low frequency, it has been difficult to show that they transpose. Allan C. Spradling and Gerald M. Rubin of the Carnegie Institution of Washington demonstrated that if a *Drosophila P* element is injected into a fruit-fly embryo on a plasmid, it can promote its own transposition onto a *Drosophila* chromosome, as well as that of a "defective" *P* element carrying a genetic marker. Their results make it clear that *P* elements have the properties of bacterial transposons and also resemble the *Ac* and *Ds* elements of maize.

The Isolation of *Ac*

In undertaking to isolate *Ac* and *Ds* my colleagues and I began with the knowledge that both elements cause insertion mutations in a variety of genes. We guessed that if we could isolate a gene with an *Ac* or a *Ds* insertion mutation, we would be able to figure out what part of the isolated DNA constituted the transposable element. We decided to isolate the *waxy* locus, which encodes an enzyme required for the synthesis of amylose, one of the two kinds of starch in a corn kernel. The endosperm of a kernel with a functional *waxy* gene contains amylose and is rather translucent. The endosperm of a mutant kernel that lacks amylose has a somewhat more opaque appearance [*see kernels* d–f *in illustration on page 86*].

Working with normal kernels, we first isolated their messenger RNA. (The DNA of a gene is not translated directly into protein. First one strand of the DNA double helix—the coding strand—is transcribed into a complementary strand of the similar nucleic acid RNA, which is then translated into protein.) We reverse-transcribed the kernel RNA molecules into complementary DNA (cDNA) copies, cloned the cDNA in a plasmid and identified the clone containing the cDNA made from the messenger RNA encoded by the *waxy* locus. That cDNA was in effect an artificial *waxy* gene, which would serve as a probe for finding the *waxy* gene itself, first in normal plants and then in plants with *Ac* and *Ds* mutations.

To find the *waxy* gene we extracted the DNA from normal plants, cut it into short segments and inserted the fragments into the DNA of a cloning vector, the bacterial virus called lambda. When such virus particles are added to a culture of bacterial cells, they infect the cells and proliferate to create a large number of viral clones, each of which is descended from a single virus particle. A clone can include millions of vi-



ACTIVATOR, **or** *Ac*, **locus was named by Barbara McClintock for its ability to activate chromosome breakage at another locus:** *Dissociation*, **or** *Ds* **(***a***). The two loci are shown here on the same chromosome, but they can be on different chromosomes.** *Ac* **is able to promote its own transposition (***b***), or that of** *Ds* **(***c***) to another site either on the same chromosome or on a different one.** *Ds* **cannot move unless** *Ac* **is present in the same cell.** *Ac* **is an autonomous transposable element and** *Ds* **is a nonautonomous element of the same family.**

rus particles and therefore millions of copies of a single inserted fragment of maize DNA. To find the *waxy* gene among those fragments we searched the cloned maize DNA fragments with our cDNA probe, labeled with a radioactive marker. The labeled probe bound to, and thus identified, maize DNA clones containing the wanted *waxy* gene.

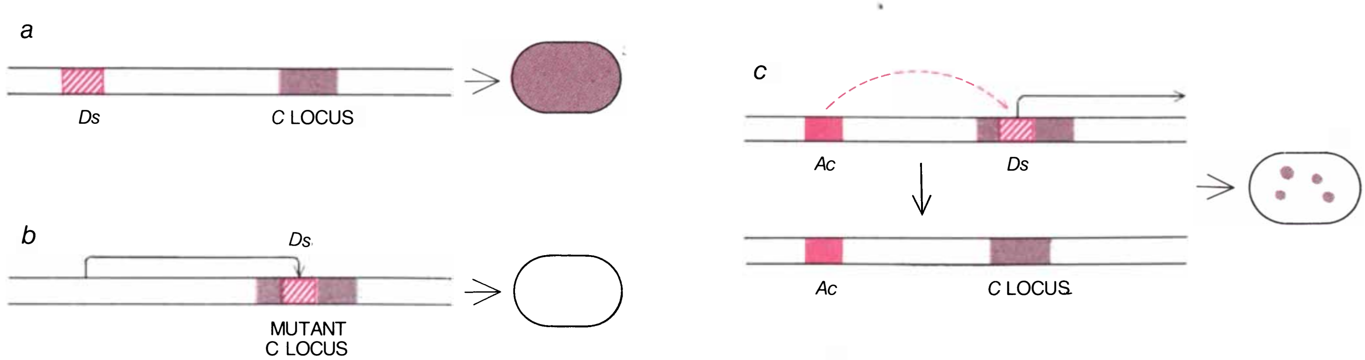
Having isolated the normal *waxy* gene, we repeated the procedure with DNA from a strain carrying an unstable *Ac* mutation at the *waxy* locus. (In such a strain the endosperm is variegated for "waxiness." It has translucent sectors and opaque ones.) When we compared the normal gene with the mutated one, we found the mutant gene is longer. It includes a small sequence not present in the normal gene: the *Ac* insertion. We were able to make the particular stretch of DNA that is the *Ac* element visible in an electron micrograph by the process known as heteroduplexing, in which maize DNA fragments carrying the normal gene were combined with fragments carrying the gene containing *Ac*. Single strands of the two fragments, still in their vector DNA, were allowed to bind to each other. For most of their length the two maize-DNA strands are complementary, and those portions matched up perfectly to form a double-stranded DNA molecule. The heteroduplex had a single-stranded loop, however. The loop was a short sequence in one of the strands that could find no complementary sequence in the other strand. Because the normal *waxy* fragment had come from a revertant strain, one that arose from the transposition of *Ac* away from the locus, there could be no doubt the loop was the *Ac* element itself.

The Structure of *Ac* and *Ds*

In time we were able to isolate the *Ac* element, analyze its structure and, in collaboration with Robert F. Pohlman and Joachim W. Messing of the University of Minnesota, determine its nucleotide sequence. *Ac* is a little more than 4,500 nucleotides long, not much longer than the shortest element known to be able to transpose autonomously. It is slightly shorter than the bacterial transposon Tn3 and is curiously similar to it in organization. To begin with, the element has the inverted terminal repeats that are the hallmark of transposable elements. In *Ac* the repetition is slightly imperfect and the repeated sequences are only 11 nucleotides long. The terminal repeats in most transposable elements are longer (38 nucleotides in Tn3), but evidence is accumulating that the important signals for transposition are provided by a rather small number of nucleotides, no more than 20, at the ends of the element.

The *Ac* element looks like Tn3 without its passenger beta-lactamase gene. *Ac* has two genes, a long one and a short one. The proteins they encode are about the size of the transposase and the resolvase of Tn3. As in the bacterial transposon, the two genes are oriented so that they are transcribed in opposite directions, away from each other. In Tn3 that orientation is known to make it possible for the two genes to be coordinately controlled by the binding, to a single site between them, of the resolvase acting as a repressor. The striking similarity in gene orientation in *Ac* suggests that its genes may also be regulated from a common site.

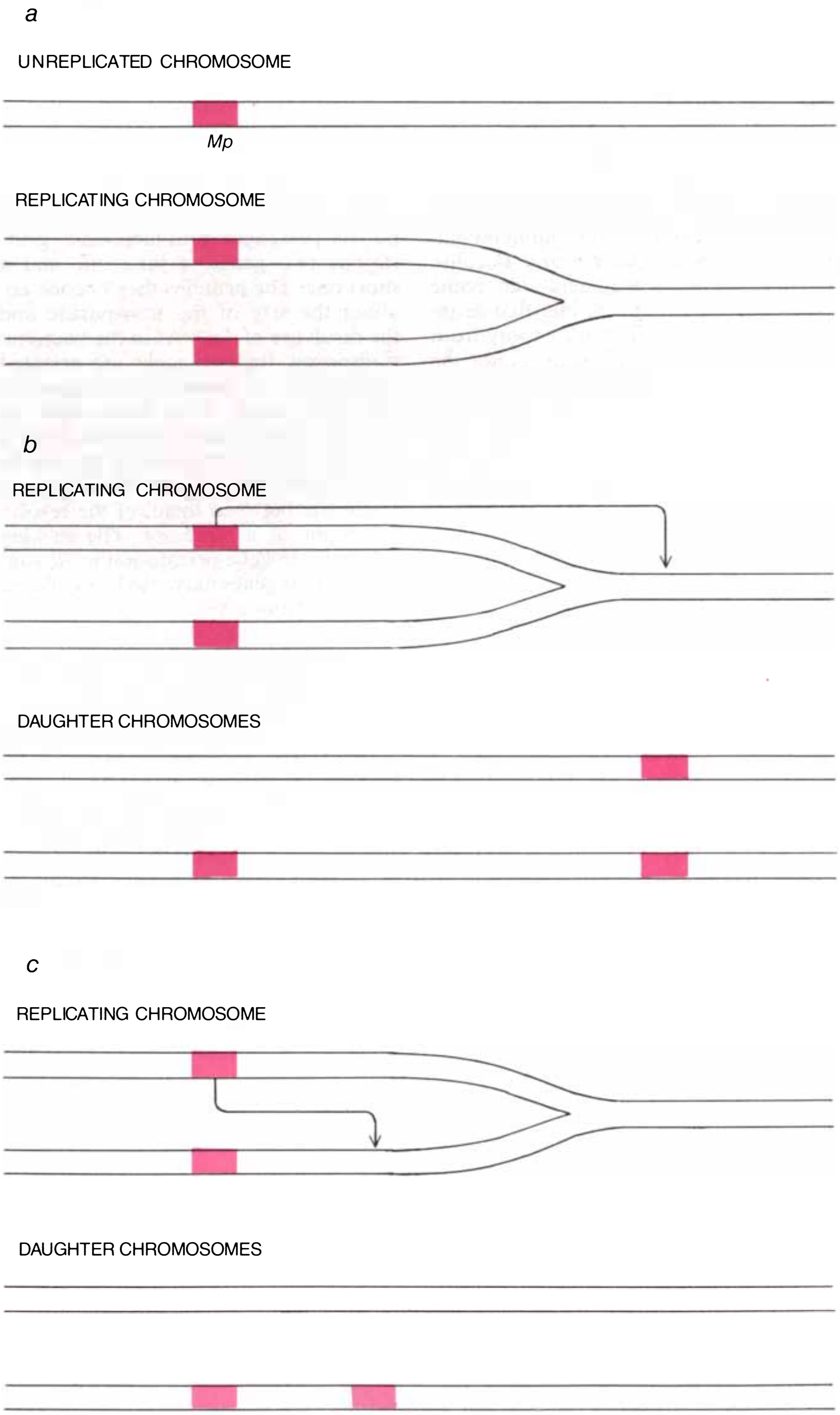
There is evidence that the larger of the two *Ac* genes encodes a protein analogous to the transposase of Tn3. The evidence comes from the analysis of a *Ds* element we isolated. As I mentioned above, genetic data suggested that *Ds* elements are closely related to *Ac* elements. Not only are *Ds* elements mobilized in the presence of *Ac* but also *Ac* insertion mutations can give rise spontaneously to mutations that act as if the *Ac* has been replaced by a *Ds* element. We isolated the *Ds* element from just such a derivative of the original *Ac* mutation of the *waxy* gene. The *Ds* insertion was precisely where the *Ac* had been in the parent strain. The insertion turned out to be almost, but not quite, identical with the



MUTATION OF *C* **LOCUS, a gene required for synthesis of a purple pigment in the aleurone (***a***), takes place when** *Ds* **moves into the locus (***b***). The mutation disables the gene, the pigment is not made and the aleurone is colorless. If** *Ac* **is present in the genome, however, it promotes the transposition of** *Ds* **away from the locus in some cells during kernel development (***c***). The mutation reverts when the element leaves, giving rise to cells in which the** *C* **locus is functional. Each such cell gives rise in turn to a pigmented sector in the aleurone.**

Ac element. It looks like a mutant *Ac:* a small part of the *Ac* sequence is missing. The length of the deleted sequence is only 194 nucleotides. The deletion is within the *Ac* gene coding for the larger of the two proteins. Because a *Ds* element can transpose only in the presence of an *Ac,* we infer that the protein whose sequence is ruined by the deletion in the *Ds* element is a protein involved in transposition: a transposase.

It is not yet clear whether all *Ds* elements are simply defective *Ac*'s. The sampling of *Ds* elements isolated so far suggests they can be very different from *Ac* in structure. The second *Ds* we isolated is about half as long as *Ac* and consists of the two ends of *Ac.* A related element was isolated in the laboratory of Peter Starlinger of the University of Cologne. It is made up of two copies of an element like our smaller *Ds,* with one copy inserted, in inverted orientation, into the middle of the other copy. A very different element has been isolated in W. J. Peacock's laboratory at the Commonwealth Scientific and Industrial Research Organization in Canberra. It is about a tenth as long as the *Ac* element and resembles the *Ac* only in having virtually the same short terminal inverted repeats. This raises the possibility that any sequence bracketed by these short terminal sequences can act as a *Ds* element. Perhaps all the information the transposition enzymes need in order to recognize, cut out and transpose a sequence is given by the inverted repeats. If this is true, then whenever an *Ac* element is present in the genome to provide the enzymes, any stretch of DNA with terminal sequences that are recognized by the enzymes would potentially be able to move.



TRANSPOSITION of *Mp*, an element genetically identical with *Ac*, takes place (*a*) after the element has replicated but while the chromosome on which it resides is still replicating. One of the two daughter copies of the element moves, usually to a site on the same chromosome. If the recipient site has not yet replicated (*b*), one daughter chromosome will have two copies of *Mp* and one will have a single copy. If the recipient site has already replicated (*c*), one daughter chromosome will be without an *Mp* element and the other will have two copies of *Mp*.

Element Families

Ac was originally thought to be a single locus. Subsequent genetic studies suggested that more than one *Ac* could be active in a genome at the same time but that the number of such elements is small. Genetic studies can, however, detect only active elements having some observable effect on the organism; the molecular probes for *Ac* made available by the isolation of the element can detect any sequence related to *Ac,* whether it is active or not. The genome appears to be strewn with such sequences. Many of them resemble the ends of the *Ac* element. Although the estimates are not very accurate, it appears there are at least 40 sequences (and there may be more than 100) resembling the ends of the *Ac* element in the genomes of all the plants we have examined.

Yet the molecular findings are not altogether inconsistent with the genetic findings. If one asks how many of the elements are structurally identical with the *Ac* element, the answer is very few. Indeed, there is reason to think the *Ac* element that is detected genetically has a unique structure. Even though there are many pieces of the element distributed throughout the genome, there are few complete *Ac* elements. Many of the pieces, although we do not know how many, can probably transpose when a functional *Ac* is present. The *Ac* and *Ds* elements, in other words, constitute a family of related elements.

The *Ds* elements can be viewed as a collection of sequences, more or less related to *Ac* but all carrying at least the

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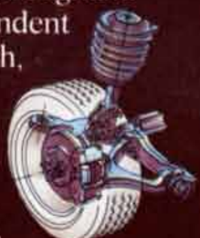

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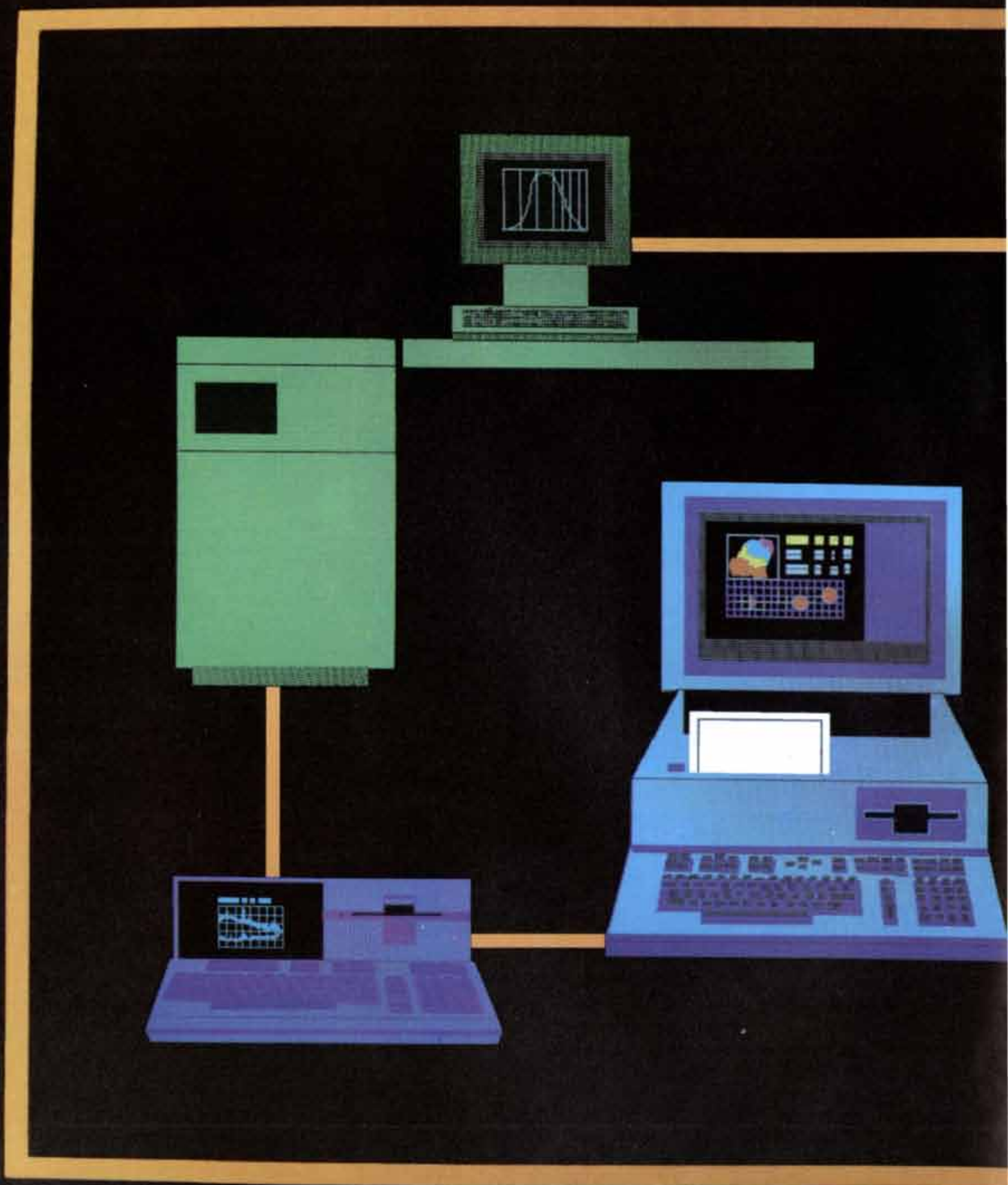

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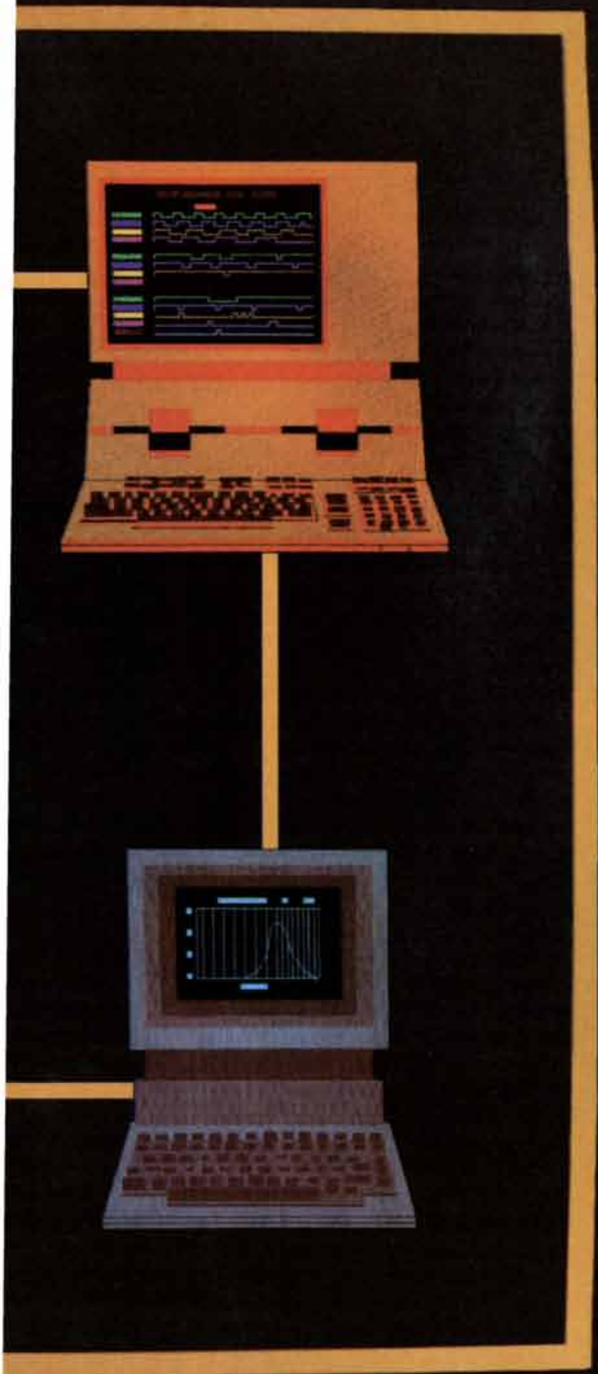

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BACTERIAL TRANSPOSON called Tn3 is about 5,000 nucleotides long and carries three genes. Two of the genes encode enzymes, a "transposase" and a "resolvase," that catalyze transposition; the third encodes an enzyme, a beta-lactamase, that inactivates the antibiotic ampicillin. The resolvase acts as a repressor as well as an enzyme. It binds to a site in a noncoding region (*gray*) between the transposase and the resolvase genes, preventing the expression of both of them. The repressor covers the initiation sites where transcription of the two genes into RNA begins; the initiation sites are adjacent because the genes are transcribed in opposite directions (*colored arrows*). At the terminals of the transposon there are 38-nucleotide "inverted repeats," stretches of DNA whose nucleotide sequences are symmetrical, reading the same in opposite directions on opposite strands. Such sequences serve as recognition signals for transposition enzymes.

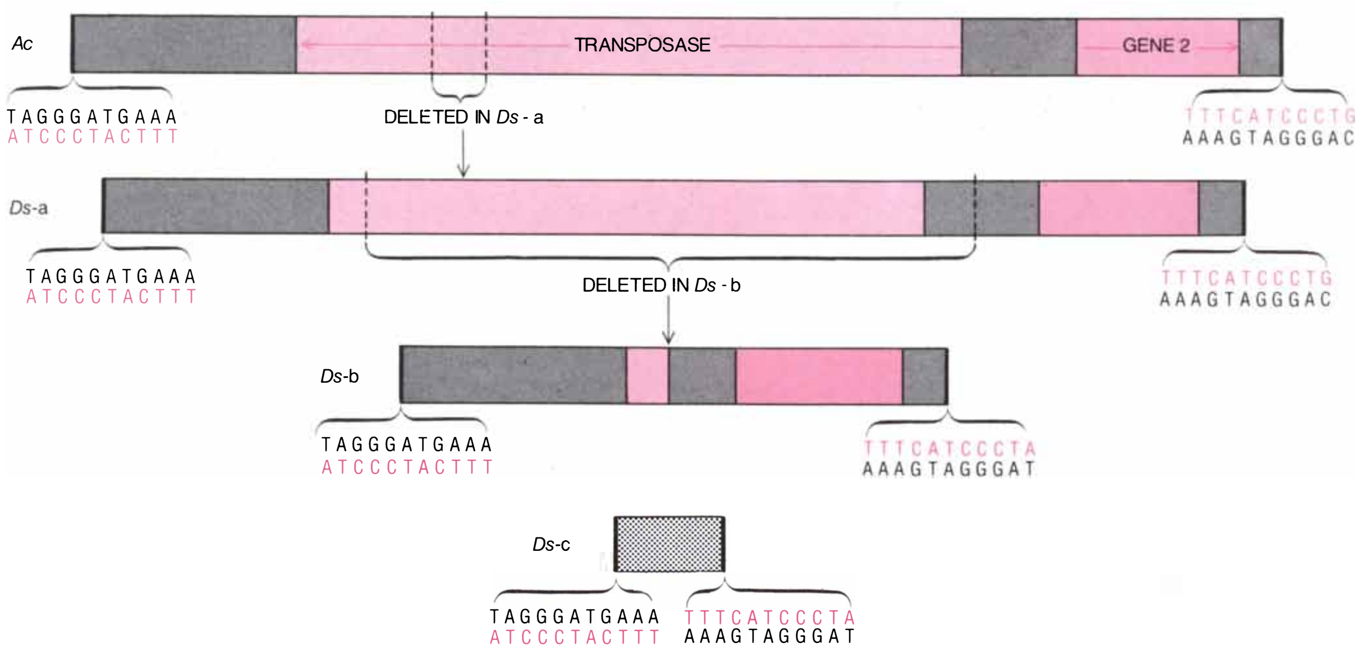
critical terminal sequences the *Ac* transposition enzymes recognize and move. *Ac* elements, on the other hand, probably cannot differ greatly in structure because they must maintain the ability to encode and express the transposition enzymes. Three *Ac* elements have now been isolated, and they appear to be nearly identical. It would not be surprising, however, to find one that has picked up a passenger gene, as the bacterial Tn3 seems to have done at some point in its evolutionary history.

There are probably many element families in maize like the *Ac-Ds* one. It is a characteristic of transposable elements that a given element's transposition enzymes recognize only its own transposition signals. This specificity makes it possible to divide elements into families on the basis of genetic experiments. For example, a newly identified transposable element can be introduced into a plant that has a mutation caused by a *Ds* insertion. If the mutation reverts, the newly identified element is similar to or identical with *Ac;* if the mutation remains stable, the element belongs to a different family. At least six families of elements have been identified in maize by this criterion, but they probably represent only a small fraction of the families actually present in maize. The Indians of Central and South America who first cultivated maize liked the pigmentation patterns generated by transposable element mutations, with the result that there are many races of maize showing variegation. Only a few of them have been collected and analyzed genetically, and so it is not known whether their mutations are generated by recognized transposable elements or by elements still to be identified.

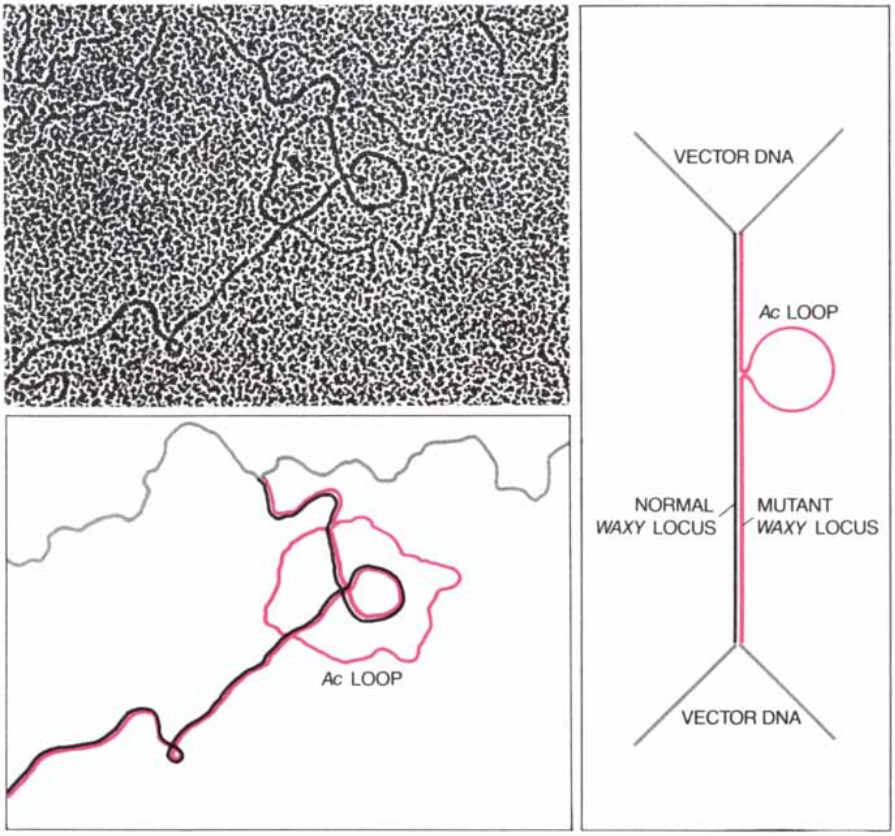
The *Spm* Elements

The only other elements that have been studied as thoroughly as *Ac* and *Ds* are those belonging to the *Spm* family. This element family was identified independently by McClintock and by Peter A. Peterson of Iowa State University in the 1950's. McClintock called the fully functional member of the family the *Suppressor-mutator* (*Spm*) element; Peterson called it the *Enhancer* element. It has not yet been isolated, but mutations caused by *Spm* elements have been studied genetically in great detail. The mutations illustrate vividly the complex effects of transposable elements in higher organisms, and they provide the molecular biologist with a rich source of material whose analysis may one day illuminate the mechanisms that determine how genes are expressed at different times in development and in specific tissues.

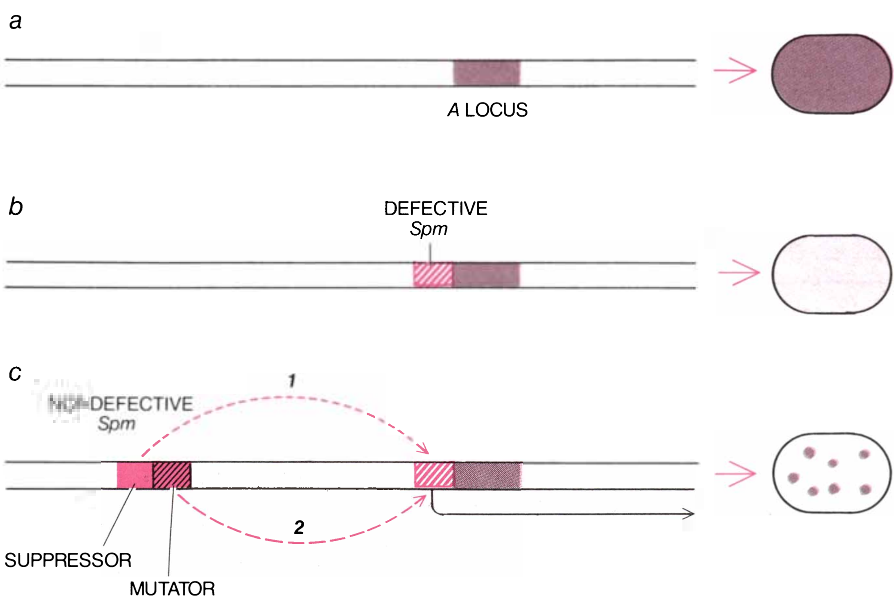
The basic behavior of *Spm* elements resembles that of *Ac* and *Ds.* An autonomous *Spm* element, like an *Ac,* can cause an unstable mutation by inserting itself into or near a gene. The gene is inactivated by the insertion; the subsequent



***Ac* ELEMENT OF MAIZE and several *Ds* elements have been isolated. The *Ac* element is about 4,500 nucleotides long; it has two coding sequences, or genes (*color*), three noncoding sequences (*gray*) and imperfect inverted terminal repeats (*black*). The first *Ds* element isolated, *Ds*-a, is almost identical with *Ac,* except that a 194-nucleotide segment (*broken lines*) of *Ac*'s larger gene has been deleted. That is enough to disable the transposase gene, and it accounts for the inability of *Ds* to transpose itself. In *Ds*-b a much longer central segment of *Ac* has been deleted. *Ds*-c is very short and retains only the inverted terminal repeats of *Ac,* suggesting that any piece of DNA bracketed by these terminal sequences can be recognized and transposed by the transposition enzymes and can therefore act as a *Ds* element.**



HETERODUPLEX ANALYSIS locates an *Ac* element inserted into the *waxy* locus of maize. Single strands of cloned DNA comprising either the normal *waxy* locus or a locus mutated by an *Ac* insertion are incubated together. Complementary sequences find and bind to each other, forming a DNA duplex, which is seen as the heavier line in the electron micrograph. The micrograph is interpreted in the map below it and in the schematic diagram at the right. For most of their length the normal locus (*black*) and the mutated one (*color*) match up to form a duplex, but the *Ac* insertion finds no complementary sequence and forms a single-stranded loop.



***SUPPRESSOR-MUTATOR* (*Spm*) family of transposable elements includes defective *Spm* elements analogous to *Ds* and nondefective *Spm*'s analogous to *Ac*. Here a defective *Spm* has inserted at the *A* locus (*a*), which is required for the synthesis of a purple aleurone pigment, in such a way that the gene is partially inactivated (*b*); as a result the kernel is palely pigmented. If a nondefective *Spm* is present, it has two effects (*c*). First, its suppressor function inactivates the gene completely (*1*). The result would be a colorless kernel if it were not for the mutator effect (*2*): a transposase made by the nondefective *Spm* causes the defective *Spm* to move out of the *A* locus in some cells during development, giving rise to sectors of deeply pigmented cells.**

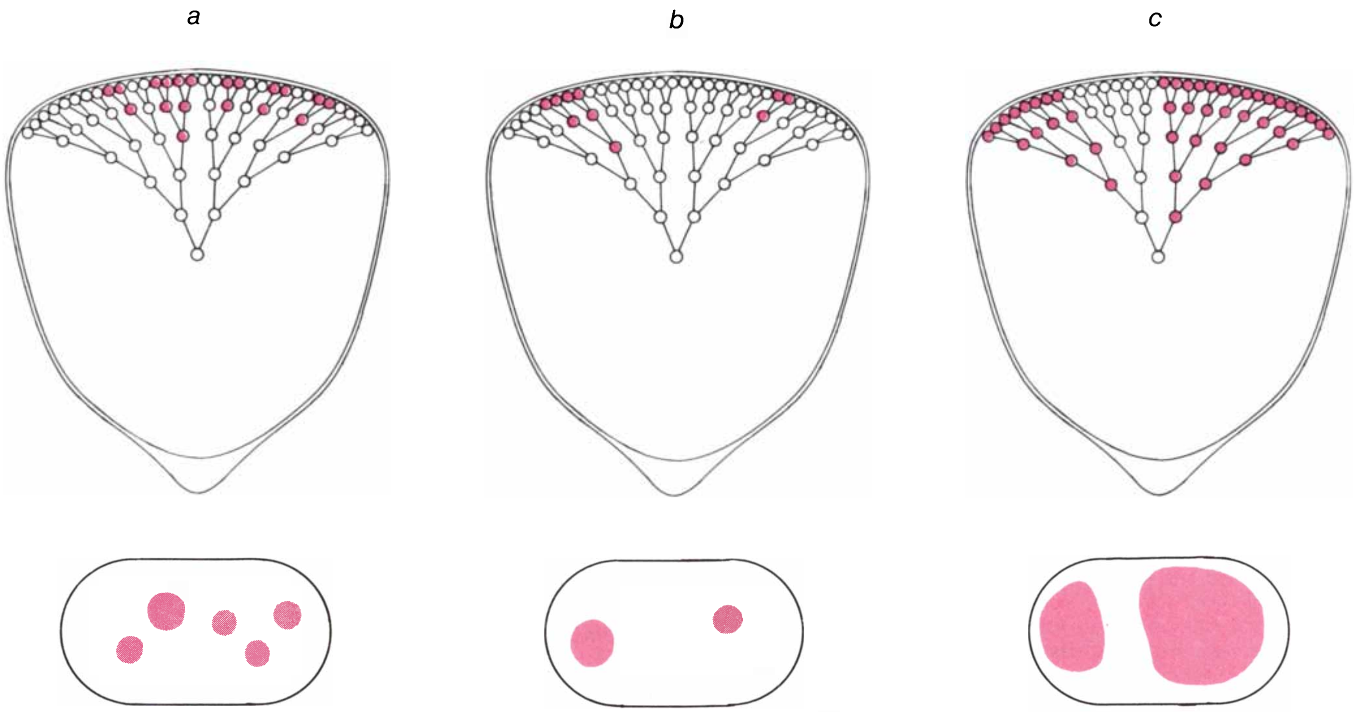
excision of the element in some cells during development restores gene function, giving kernels a variegated appearance. The *Spm* family also includes nonautonomous elements analogous to *Ds* elements. These "defective" *Spm*'s (McClintock did not give them a name of their own) can transpose only when an autonomous, "nondefective" *Spm* is present. In spite of this basic similarity between *Spm* and *Ac,* they are clearly different elements by the criterion described above. An *Spm* element cannot cause a *Ds* element to move, and a defective *Spm* does not move in the presence of an *Ac*.

There is also an interesting functional difference between the *Spm* and *Ac* families. Defective *Spm* elements often insert into a gene in such a way that the gene is only partially rather than wholly inactivated. As long as the genome does not include a nondefective *Spm,* the gene continues to be expressed at a reduced level; in the case of a mutation affecting a gene required for pigment synthesis, the kernel is palely pigmented rather than colorless [*see kernel* g *in illustration on page 86*].

When a nondefective *Spm* is present, the situation is quite different. The pigment gene is "suppressed," or fully inactivated, and the kernel is colorless. The nondefective *Spm* provides a transposase, however. As a result the defective element is excised in some cells in the course of development, giving rise to deeply pigmented spots consisting of revertant cells in which the gene functions normally [*see kernel* h *in illustration on page 86*]. McClintock called the element *Suppressor-mutator* for its two distinguishable effects on a gene carrying a defective element: suppression and back mutation, or reversion.

Mutations of *Spm*

McClintock studied two categories of heritable changes in the *Spm* elements themselves: mutations that affect the transposition of defective elements and mutations affecting the functions of the nondefective *Spm*. Mutations of the first category all give rise to a pattern of pigmented spots, but the patterns of variegation can be very different. Each spot represents a clone of cells derived from a single cell in which the defective *Spm* transposed out of the gene. If the transposition events take place late in kernel development when only a few cell divisions are still to come, the clones of revertant cells (the spots) will be small. There may be many such spots or few, depending on the frequency with which the defective *Spm* is transposed; each mutation has its characteristic frequency. If the transposition events restoring gene function take place early in kernel development, the clones of revertant



DEVELOPMENTAL TIME AND FREQUENCY of transposition differ in mutations caused by the insertion of different defective *Spm* elements. If transposition takes place late in development, the clones of revertant cells are small and therefore so are the pigmented spots (*a*). If transposition takes place at about the same time but at a lower frequency, there are fewer such clones and fewer spots (*b*). If the transposition that restores gene function takes place earlier, the revertant clones and the spots of pigmented tissue are larger (*c*).

cells are large [*see kernels* h–j *in illustration on page 86*]. Thus mutations at the same locus, caused by what seems at the genetic level to be the same defective *Spm,* can differ both in the frequency and in the developmental time at which the element transposes away from the locus.

What makes such mutations so different? How does the element "know" when and how frequently it is to transpose? Does each element include within its nucleotide sequence a genetic signal that acts as a kind of developmental clock? Or is the element in some sense a captive of the developmental program of the gene into which it is inserted? Might it be that when the element is inserted at different sites in or near the same gene, it becomes accessible to the transposition enzymes at different times in the development of the kernel? These questions cannot be answered yet, but they are worth asking. As the mutant genes are isolated and the structure and location of the defective *Spm* elements within them are studied, it should be possible to gain insight into the genetic signals that determine developmental timing.

Some mutations that affect the functions of the nondefective *Spm* element itself are quite similar to the defective-element mutations I have just described. They influence the frequency and timing of transposition, in some cases making the element incapable of promoting either its own transposition or that of a defective element and yet leaving its suppressor function intact. Perhaps the most intriguing mutations, however, affect the expression of the nondefective element as a whole. In one case the element seems to be turned on and off repeatedly during development, that is, to cycle between an active and an inactive state.

The behavior of this cycling *Spm* is best illustrated by its effect on a mutation caused by a particularly defective *Spm,* one that is unable to transpose even in the presence of a nondefective element but that does respond to the element's suppressor function. In the absence of a nondefective *Spm,* kernels carrying this mutation are quite deeply pigmented. When a normal nondefective *Spm* is present, the kernels are completely colorless as a consequence of the element's suppressor function. They are not spotted, because the defective element is stuck and cannot be excised to restore normal gene function.

When the usual nondefective *Spm* is replaced by the cycling version of the element, kernels show a distinctive pattern of variegation. There are rather large pigmented sectors in the colorless aleurone, and within those large spots there are in turn small colorless sectors [*see kernel* k *in illustration on page 86*].

This variegation pattern does not arise from the transposition of the defective *Spm,* which cannot move. The pattern results instead from the cycling of the nondefective *Spm*. When the element is turned on, it expresses its suppressor function, and the corresponding portion of the aleurone is colorless. When the element is turned off, the suppressor substance is not synthesized and the gene functions to give rise to pigmented sectors. The element is silenced only transiently, however; several cell divisions later it can become active again, giving rise to the small colorless sectors within the pigmented spots.

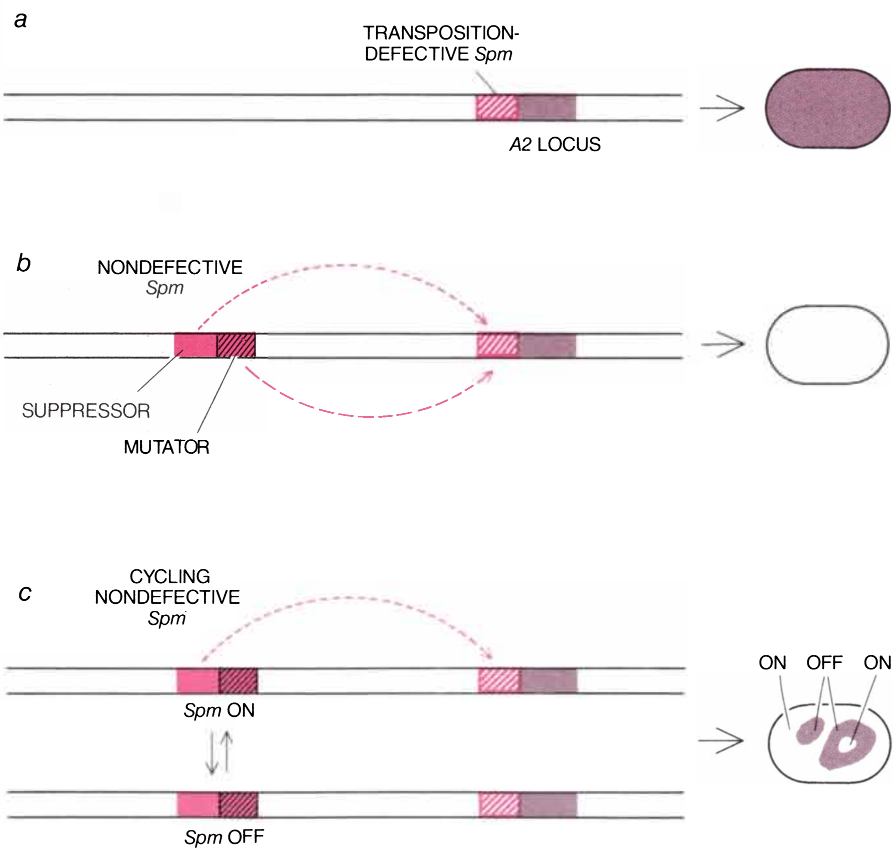
Instead of cycling on and off throughout the plant, other nondefective *Spm*'s are turned on at one time in development or in one part of the plant and turned off at other times and in other places. An element can be on only at the top of the kernel, for example, or only in the base of the kernel. Or it may be on in ears produced by the main stalk of the plant and off in ears produced by the tillers, or side stalks.

Development and Evolution

The ubiquity of transposable elements and the growing awareness that they are major agents of genetic instability force one to consider their importance in the genetic choreography underlying development and their role in the long-term process of genetic change called evolution. McClintock called the maize elements she studied "controlling elements" because she understood that in some sense they reversibly inhibit gene expression and that the genetically determined pattern of excision in somatic cells (the nongerm cells) is responsible for a highly characteristic "pattern" of gene expression in the organism as a whole. Moreover, the properties of the elements and their interactions with genes give rise to many varied patterns of gene expression. This suggested to McClintock that perhaps the controlling elements are examples of normal control mechanisms gone awry.

The idea that transposable elements are important devices controlling gene expression in development has not received direct experimental support. Yet it is now clear that a variety of genes, such as those specifying the synthesis of antibodies in higher animals, are indeed restructured in the course of their normal developmental program. Moreover, patterned gene expression much like what is observed in maize is widespread in other plants and in animals. It is not unreasonable to suspect that the underlying genetic mechanisms responsible for such patterns resemble those described in maize.

Transposable elements may be of even greater significance in evolution. One can only speculate about such a role, but their properties appear to make them suitable agents for modifying not only the expression of genes but also the structure of genes and genomes. In maize and in other organisms it is known that transposable elements are activated when the genome is stressed and chromosome breakage is taking place. Just how this happens remains a mystery, but once the elements are activated they can promote many kinds of mutations and chromosomal rearrangements. It is as if transposable elements can amplify a small disturbance, turning it into a genetic earthquake. Perhaps such genetic turbulence is an important source of genetic variability, the raw material from which natural selection can sift what is useful for the species. Moreover, evidence is accumulating that in addition to turning genes off transposable elements can turn them on or amplify their expression. There is reason to suspect they can reprogram genes in more subtle ways as well, changing when and where in the organism a gene is active. This is indeed the stuff of remodeling and rebuilding, of organismic evolution.



CYCLING *Spm* is alternately on and off. Its effect is evident when the defective *Spm* at a pigment-enzyme locus is one that cannot be transposed. In the absence of a fully functional *Spm*, the transposition-defective *Spm* has little effect on pigmentation (*a*). When an ordinary *Spm* is present (*b*), its suppressor function inactivates the gene but its mutator function has no effect because the transposition-defective element cannot move; the kernel is completely colorless. If the *Spm* is a cycling one (*c*), the suppressor function is alternately on and off, so that there are pigmented sectors (*Spm* off) that have small colorless sectors within them (*Spm* on).

An Atomic Preference between Left and Right

The left- and right-handed versions of an atomic experiment do not always give rise to mirror-symmetric effects. The asymmetry is caused by the weak force between the electrons and the nucleus

by Marie-Anne Bouchiat and Lionel Pottier

The idea of symmetry is fundamental to the understanding of nature, and one physical system that exhibits a high degree of symmetry is the atom. In the simplest atoms the electrons that orbit the atomic nucleus are distributed in spherical shells, which are obviously symmetrical in every possible orientation. In more complex atoms the distribution of the electrons is not spherical, but even here some plane or axis of symmetry can be identified. For the physicist there is a symmetry within the atom that is still more profound: until recently the atom was regarded as a system governed only by the electromagnetic force, and that force is entirely indifferent to the distinction between left and right. More precisely, suppose any physical configuration and a second configuration exactly like the mirror image of the first configuration are both acted on by the electromagnetic force. It then turns out that the effect of the force on the second configuration is identical with the mirror image of the effect of the force on the first configuration. This important property of the electromagnetic force is called the conservation of parity.

In the past decade substantial experimental effort has been expended to test the conservation of parity in the atom. Such tests are not motivated by any suspicion that the electromagnetic force violates, or in other words does not conserve, parity. On the contrary, the influence of the electromagnetic force on atomic interactions is so overwhelming that any observed deviations from the exact conservation of parity are expected to be exceedingly small. Nevertheless, the atom is not a purely electromagnetic system. Three fundamental forces in addition to the electromagnetic force are thought to contribute to the motions of the elementary constituents of the atom. The three forces are gravity, the strong, or nuclear, force and the weak force. Of the three gravity is negligible on the atomic scale and the strong force does not affect electrons, whose motions determine the properties of all atomic interactions. According to theoretical calculations, however, the weak force between each electron and the atomic nucleus should cause small perturbations in the orbits of the electrons, provided the electrons wander close enough to the nucleus to "feel" the effects of the weak force.

The perturbations caused by the weak force should give rise to a small violation of parity in the atom. The effects of the weak force in the atom can therefore be tested experimentally in a way that is conceptually straightforward, although by no means practically so: the configuration of the atoms in a gas is given a preferential handedness, say left, and some suitable property of the atoms is measured. The configuration is then replaced by one that coincides with the mirror image of the first configuration; the second configuration must therefore have a preferential handedness opposite to that of the first. The same atomic property is then measured for the second configuration. If the measured property in the second experiment is not the exact mirror image of the first result, parity is violated.

By the end of the 1970's several experiments had failed to detect such parity violations, and their failure was beginning to be viewed as a weak link in an otherwise successful chain of theoretical reasoning. That important link has now been forged. Several groups of investigators, including our group at the École Normale Supérieure in Paris, have confirmed the existence of parity violations in a few atomic systems. These results complement the spectacular successes of the new theory of weak interactions in predicting phenomena at extremely high energies, such as the discovery of the W^+, W^- and Z^0 particles at the European Laboratory for Particle Physics (CERN) in Geneva last year. Experiments in atomic physics are carried out at much lower energies than those generated in accelerators, and so they test the action of the weak force over a much greater distance than accelerators do. Moreover, they provide information about the strength of the weak force between such fundamental constituents of matter as quarks and electrons that has not yet been derived from high-energy experiments.

The weak force is most commonly associated with beta decay, an important step in one mechanism for the thermonuclear conversion of hydrogen into helium in the sun. A neutron decays into a proton within an atomic nucleus, and the reaction is accompanied by the emission of an electron (the "beta ray") and a particle called the antineutrino. It has been recognized for more than 25 years that parity is not conserved in this reaction. The electron always emerges from the nucleus spinning in the same sense as the fingers of the left hand would curl if the left thumb were pointed in the direction of the electron's motion. The antineutrino is always emitted spinning in the right-handed sense. The mirror image of the process would be a reaction in which the beta electron spins in the right-handed sense and the antineutrino spins in the left-handed sense; the reaction is never observed in the real world.

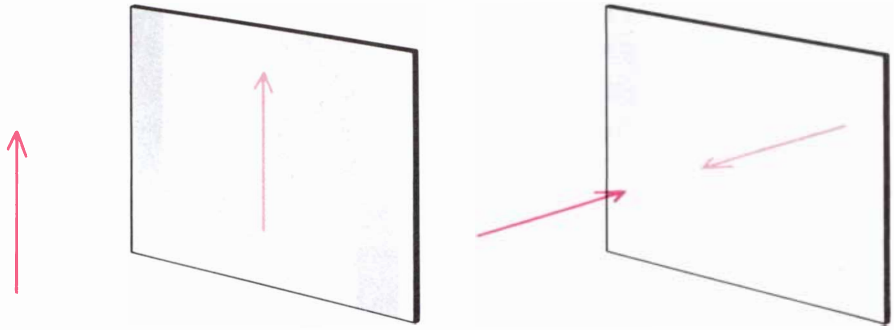
The violation of parity in beta decay is accompanied by a change in the electric charge of the decaying neutron. As other weak reactions were catalogued, it began to appear they were always accompanied by a change in the charge, and hence in the identity, of the reacting particle. For example, a neutrino can be converted (by the addition of energy) into an electron, but in the process it must take on a unit of negative electric charge. These transformations are brought about by the particles that mediate the weak force, which belong to a family of particles called gauge bosons.

The gauge bosons that mediate the weak force are analogous to the photon, which is the gauge boson that mediates the electromagnetic force. Unlike the photon, however, which is electrically neutral, the weak gauge bosons that mediate beta decay (and all other weak interactions known before 1970) carry a unit of electric charge. The W^+ gauge boson bears a unit of positive charge, and the W^- gauge boson bears a unit of negative charge. It was therefore taken for granted that the weak force and its associated violation of parity were not relevant to the physics of the stable atom. If the weak force always brought about a transformation of charge, it could not affect the motions of atomic electrons without altering their charge and thereby undermining the stability of the atom.

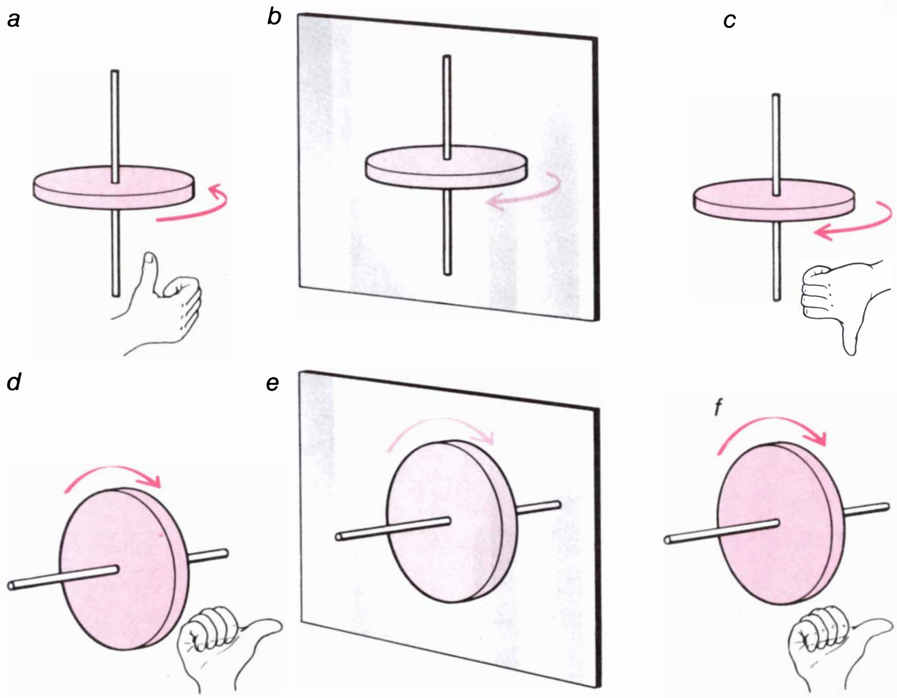
The theoretical understanding of weak interactions was mathematically unsatisfactory until the late 1960's, when a new theory was proposed. Sheldon Lee Glashow and Steven Weinberg, both then at Harvard University, and Abdus Salam of the International Center for Theoretical Physics in Trieste suggested independently that the weak force and the electromagnetic force can be understood theoretically as different manifestations of a single, underlying force: the electroweak force. The unified electroweak theory was subsequently put on a firm mathematical footing by Gerard 't Hooft of the University of Utrecht.

According to the theory, there is a third, neutral gauge boson called the Z^0 that mediates a new kind of weak force. Interactions that involve the Z^0 gauge boson can also violate parity, but because the Z^0 particle carries no electric charge, the interactions do not lead to a change in the identity of the interacting particles. Thus the exchange of the Z^0 is closely analogous to the exchange of a photon in an electromagnetic interaction. Weak interactions involving the exchange of Z^0 particles were first observed in experiments with neutrinos at CERN in 1973. In principle, therefore, the electroweak theory had proposed a mechanism, whose existence was partially confirmed by experiment, whereby the atomic electrons in a stable atom could be perturbed by the weak force.

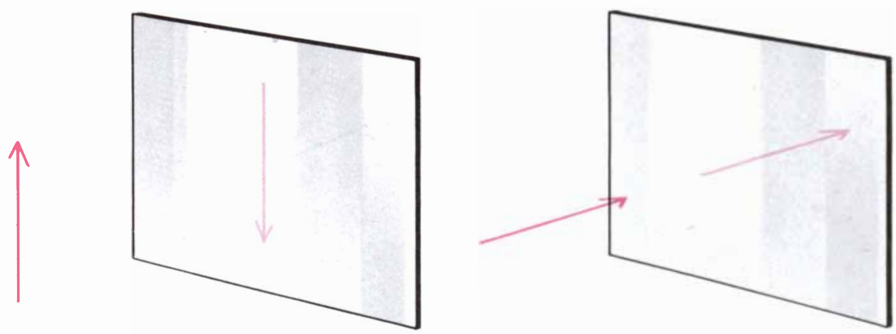
In the real atom, however, simple theoretical considerations appeared to suggest that the effects of the weak force on orbiting electrons would be much too small to be detected. The electroweak theory predicts an enormous mass for the three weak gauge bosons: the W^+ and W^- bosons must each have a mass equivalent to an energy of approximately 80 GeV (billion electron volts) and the Z^0 boson must be slightly heavier, about 90 GeV. All these predictions were confirmed last year by the experimental findings at CERN. It has been



SYMMETRY AND ASYMMETRY in a physical system such as the atom can be defined by considering the effects of mirror reflection on objects such as the ordinary vector, or arrow. A mirror maintains the apparent direction of the arrow when the mirror and the arrow are parallel (*left*) and reverses the direction when the mirror is perpendicular to the arrow (*right*).



RIGHT-HAND RULE is a conventional system for consistently labeling the sense of rotation of a spinning object. The rule states that the sense of the rotation is given by an arrow aligned along the axis of rotation and pointing in the direction the right thumb would point in if the fingers of the right hand curled in the direction of the spin (*a, d*). When the plane of a rotating disk is perpendicular to a mirror, the image of the disk in the mirror appears to rotate in the sense opposite to that of the real disk (*b*). When the plane of the disk is parallel to the mirror, both the disk and its image appear to rotate in the same sense (*e*). The right hand is not shown reflected in the mirrors, because to do so would be to give the mirror images of the rotating disks a sense that is inconsistent with the right-hand rule. When a real disk rotates in the same sense as the disk in the mirror image, the right-hand rule gives the sense of the rotation unambiguously (*c, f*).



AXIAL VECTORS, which are the arrows that represent the rotational sense of a spinning disk, are transformed by a mirror reflection into an image that is the opposite of the image of an ordinary vector. If the axial vector is parallel to the mirror, its direction is reversed by the mirror (*left*); if the axial vector is perpendicular to the mirror, its direction remains the same (*right*).

known since the work of Hideki Yukawa of Kyoto University in Japan in 1934 that the greater the mass of a particle, the shorter the range of the force it mediates. For example, the photons that mediate the electromagnetic force have zero mass, and so the range of the force is infinite. The large masses of the weak gauge bosons imply that the range of the weak force is extremely short, about 2×10^{-18} meter. This range has been confirmed by experiments that measure the scattering of the neutrino by other particles, a process governed only by the weak force. The range is more than 10 million times smaller than the typical radius of an atom.

How can one hope to detect the effects of the weak force in the atom? In most orbits the atomic electron is virtually beyond reach of the weak force, but if the orbit is highly eccentric or elongated, the electron can come close enough to the nucleus for the weak force to exert a more powerful influence. Since the spectroscopic and chemical properties of the atom are determined almost entirely by the outermost electrons, one of these electrons must penetrate deep below the cloud of inner electrons for a violation of parity to be observed.

In the inner region of such an orbit the motion of the penetrating electron is not affected by the other atomic electrons, which ordinarily screen the positive charge of the nucleus. Instead the penetrating electron is subject to the full effect of all the protons in the nucleus; the part of the electronic orbit that lies under the cloud of other electrons in the atom resembles the orbit of the single electron in the hydrogen atom. The nucleus of a heavy atom, however, is made up of many positive charges, whereas the hydrogen nucleus has only one unit of charge. (In any atom the total nuclear charge is equal to Z, the atomic number.) Accordingly the distance between the electron and the nucleus in the inner region of the electronic orbit is smaller than the distance between the electron and the nucleus in the hydrogen atom by a factor of Z. Moreover, the weak force is proportional to the velocity of the electron near the nucleus, which increases by another factor of Z. In 1973 Claude C. Bouchiat, also of the École Normale Supérieure, and one of us (Marie-Anne Bouchiat) showed that the left-right asymmetry, or amount of parity violation, expected under such circumstances increases slightly faster than the cube of Z.

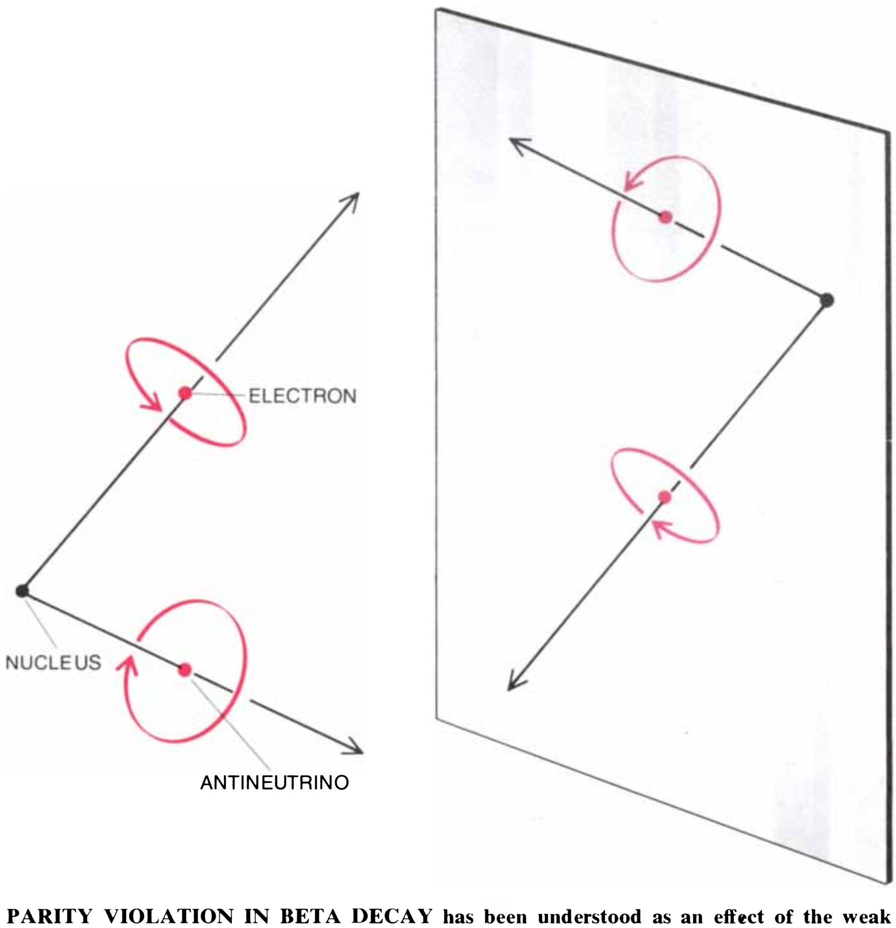
The roughly cubic enhancement of parity violation implies that the effect of the weak force should be 10^6 to 10^7 times as strong in the heaviest atoms, in which Z is between 50 and 100, as it is in hydrogen. Nevertheless, there is a difficulty in heavy atoms that must be balanced against their advantage. In order to apply the results of an experiment to the determination of numerical constants in the electroweak theory, a difficult mathematical description of the atom must be given. The difficulty of the calculation increases with the number of electrons in the outermost electronic shell. The other shells can be treated, to the first approximation, as a fairly inert, spherical structure.

Experimental physicists have struck various compromises between computational simplicity and the strength of the effect in attempting to measure parity violation in atomic systems. Experiments are carried out with bismuth (atomic number 83), lead (82), thallium (81), cesium (55) and even hydrogen (1). There are now about a dozen experiments in progress or recently completed, and they can be assigned to three major categories.

In the first category are the experiments that measure the optical rotation of polarized light by a gas of atoms. The technique was proposed independently by Patrick G. H. Sandars of the University of Oxford, by I. B. Khriplovich of the Institute of Nuclear Physics in Novosibirsk and by David C. Soreide and Edward N. Fortson of the University of Washington. In order to understand optical rotation it is useful to consider the ways in which a beam of light can be polarized.

Associated with every point along a beam of light there is an electric field. The electric field at each point is a vector, or arrow, that lies in the plane perpendicular to the direction of the propagation of the beam and rapidly oscillates in that plane. When the tip of the arrow oscillates along a straight line in the plane, the polarization of the light is linear; as the beam propagates, the oscillating arrow traces a sinusoidal curve in space. When the tip of the arrow rotates along a circle in the polarization plane, the polarization of the beam is circular; the trace of the arrow in space is a helix that twists through space like a left- or right-handed screw, depending on the sense of the rotation of the arrow.

The most general kind of polarization is elliptical polarization: the tip of the arrow traces an ellipse in the polarization plane. Both linear and circular polarization are special cases of elliptical



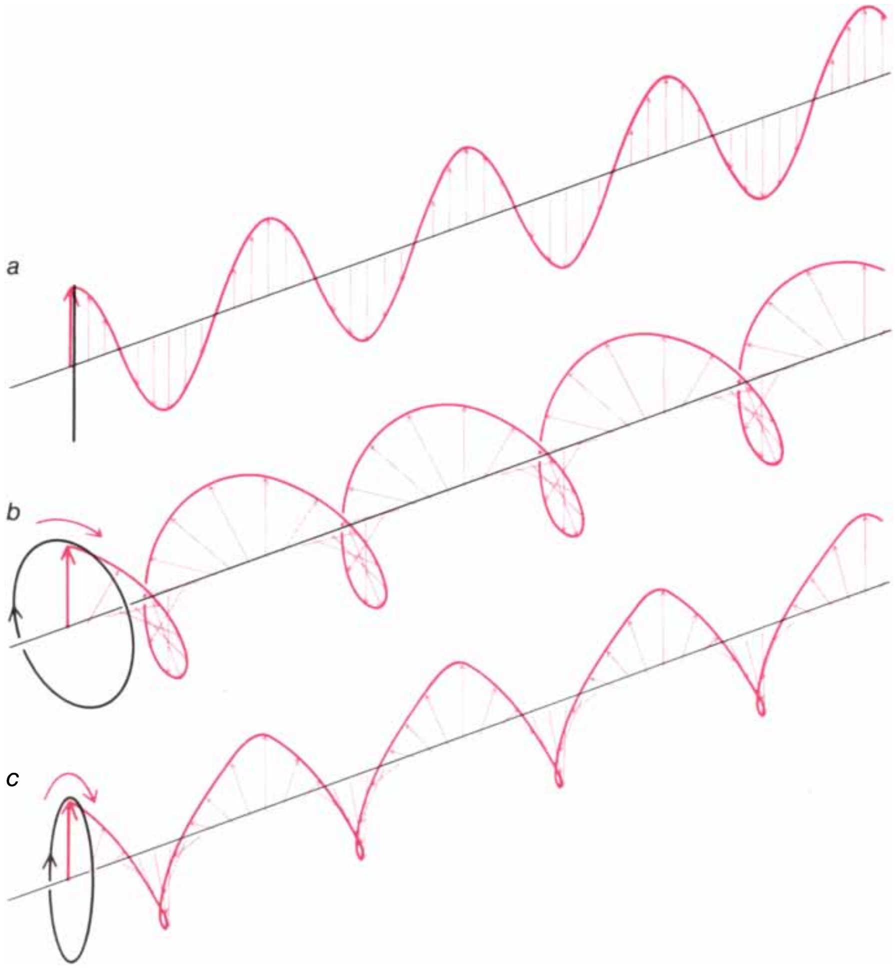
PARITY VIOLATION IN BETA DECAY has been understood as an effect of the weak force for more than 25 years. A neutron decays to yield a proton within the atomic nucleus, and an electron and an antineutrino are emitted. The electron always spins in the same sense as the fingers of the left hand would curl if the left thumb were pointed in the direction of the electron's motion. The antineutrino always spins in a right-handed sense with respect to its direction of motion. The mirror image of the process is forbidden by laws governing the weak force.

polarization. Linear polarization is a degenerate case in which the minor axis of the ellipse is zero, and circular polarization is the extreme case in which both axes of the ellipse are equal in length. Elliptically polarized light has a definite handedness just as circularly polarized light does, because the motion of the electric field along the ellipse can be either left- or right-handed with respect to the direction of the propagation of the beam. Linearly polarized light, however, has no handedness; it corresponds to the intermediate case in which the motion of the arrow is neither left- nor right-handed.

Optical rotation is an effect of an optically active medium on linearly polarized light. When a linearly polarized light beam passes through such a medium, the linear polarization of the beam is rotated through some angle and the beam emerges from the medium linearly polarized in a different direction. Such rotation has been detected in many molecular compounds, including many biological substances. Until recently, however, it had not been observed in an atomic gas. The reason is that molecular optical rotation is caused by the handedness of the particles that make up the medium.

It is common for the atoms in a molecule to be arranged in such a way that no rotation or motion in space can transform the molecule into a replica of its mirror image. The DNA molecule, for example, twists along its central axis in a preferred way, and the molecule can no more be transformed into its own mirror image than a right hand can. The molecule is said to exhibit handedness. If a right-handed molecule exhibits an optical rotation A, in the mirror one would see the corresponding left-handed molecule exhibit the opposite optical rotation $-A$. It turns out the optical rotation caused by a real left-handed molecule is precisely equal to $-A$; in other words, it matches the mirror image of the optical rotation of the right-handed molecule. Hence in optical rotation by molecules parity is conserved.

For the atom, however, there is no geometric handedness. Any handedness in a gas of atoms must be imposed from outside, perhaps by applying an external magnetic field to the atoms or by giving them some preferred orientation of their spin. In the absence of such externally imposed handedness the atoms look the same in a mirror as they do in reality. Suppose a small optical rotation of a beam of linearly polarized light were detected in such a medium. In a mirror one would see atoms identical with the real atoms, which nonetheless give rise to an optical rotation contrary to the one observed in reality. The conservation of parity would be violated. Optical rotation in an atomic gas is not caused by handedness in the geometry of the atoms, as it is in a molecular gas, but by the handedness embodied in the laws of physics that govern the weak force.



POLARIZATION OF LIGHT can be understood by tracing the path taken by the vector that represents the electric field of the light measured at any fixed point in space. The vector oscillates in a plane perpendicular to the direction of the propagation of the beam at the frequency of the light wave. If the tip of the vector traces a straight-line segment in the polarization plane, the light is linearly polarized; if the tip of the vector traces a circle, the light is circularly polarized. In the most general case the tip of the vector traces an ellipse, and the light is elliptically polarized. When the propagation of the light beam is combined with the motion of the electric-field vector, the vector traces a path in space. If the light is linearly polarized, the path is a sine wave, which has no handedness (*a*). If the light is circularly polarized, the path is a helix whose handedness depends on the relation between the rotation of the vector and the direction of the propagation (*b*). In elliptical polarization the path of the vector is also left- or right-handed (*c*).

The angle of optical rotation predicted by the electroweak theory is extremely small, about 10^{-5} degree under the most favorable experimental circumstances. The angle is roughly equal to the angle subtended by the width of a sewing needle viewed at a distance of five miles. Nevertheless, several groups of experimenters have carried out sensitive tests that should detect such small rotations in a heated gas of bismuth atoms. The first results were published in 1976 and 1977 by investigators at Oxford and Washington, and the results were null: no effect was observed at the predicted magnitude. For a short time there was speculation that the electroweak theory of Weinberg and Salam would have to be revised.

In 1978, however, L. M. Barkov and M. F. Zolotorev, also of the Institute of Nuclear Physics in Novosibirsk, reported observing optical rotations of the proper size and sense in bismuth. Soon after this result investigators at the Stanford Linear Accelerator Center (SLAC) observed a clear case of parity violation in the scattering of high-energy electrons by neutrons and protons. Although the finding agreed quantitatively with the Weinberg-Salam theory, it was not strictly pertinent to the question of parity conservation in the atom. After repeated measurements with improved techniques the investigators at Oxford and Washington finally reported optical rotations in bismuth of the expected magnitude. Last year a similar rotation was detected at Washington in lead. A fourth group in Moscow, which in 1980 had reported no rotation in bismuth, has just observed a rotation whose magnitude agrees with the Oxford result.

In spite of these findings, in experiments with optical rotation one must confront important systematic effects that tend to simulate the effects of real violations of parity. Indeed, the quantitative results of the experiments at Oxford and at Moscow do not entirely agree with the results at Novosibirsk, even though all three experiments measure the same properties of the bismuth atom. (At Washington a different measurement of the bismuth atom was made, and so the results are not directly comparable.) There can be no doubt about the existence of optical rotation in bismuth, but a quantitative theoretical conclusion from the experiments is still somewhat premature.

Three experiments in a second major category have attempted to measure the violation of parity in the hydrogen atom. Since the atomic number Z of the hydrogen atom is equal to 1, Z^3 is also equal to 1 and there is no cubic enhancement of the effects of parity violation. The effect of the weak force on the electron in its lowest energy state in the hydrogen atom is so small that the atom should exhibit almost exact parity conservation, within one part in 10^{14}. On the other hand, in the hydrogen atom it is possible to exploit another mechanism that can enhance the effects of parity violation. Two excited energy states of the atom have nearly the same energy, and by working with one of the two states, which is almost stable, the parity violation can be increased by several orders of magnitude. The experiments with hydrogen are nonetheless much more difficult than the corresponding experiments with heavier atoms.

There is considerable incentive to measure the violation of parity in hydrogen; the measurement would give information about relatively long-range effects of the weak force, which cannot be determined from the experiments with heavier atoms. It would also give more complete information about the structure of the weak force. Finally, one can carry out theoretical calculations for the hydrogen atom much more accurately and reliably than one can for heavy atoms. The calculations reflect the simplicity of the atom, in which only one electron orbits the single proton of the nucleus. Experimenters at the University of Michigan, the University of Washington and Yale University have undertaken the measurements, but so far the techniques are not sensitive enough to test the electroweak theory.

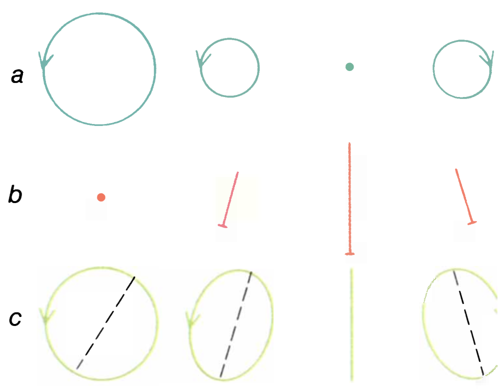
The third category of experiments includes two experiments done on atomic cesium by us and our collaborators Jocelyne Guéna and Larry Hunter at the École Normale Supérieure, an experiment with thallium done by Eugene D. Commins and his colleagues at the University of California at Berkeley and experiments with cesium now under way at Michigan and the Federal Institute of Technology in Zurich. In all these experiments a fraction of the atoms in a gas are excited to a higher energy state by a laser beam, and a preferred handedness is chosen for the initial experimental configuration. The atoms give off the light of fluorescence as they fall back to an intermediate energy state, and the polarization properties of the fluorescence light are recorded. The experimental configuration is then changed to a new one, which is identical with the image of the first configuration reflected in some mirror. For example, the change can be made by reversing an electric field or by changing the handedness of the circular polarization of the incident laser light. A second measurement of the atomic fluorescence is then made; if the second measurement does not match the mirror image of the first measurement, there is evidence for parity violation in the atoms.

It might seem needlessly complicated to work with transitions between two energy levels instead of with some property of a single level. The weak effect we can detect arises in the brief period during which the atom oscillates between the lower and the higher energy states, before it comes to rest for a relatively long time in the higher state. The excited atom bears the mark of the weak interaction acquired during the oscillations.

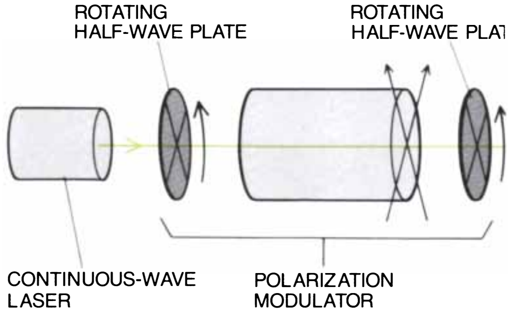
In searching for effects of the weak force it is advantageous to reduce the effective strength of the electromagnetic force, because that force can systematically mimic the parity-violating effect of the weak force. A practical way to minimize the effect of the electromagnetic force is to work with a "forbidden" atomic transition; the transition is forbidden because it is very unlikely to take place as a result of electromagnetic effects. In highly forbidden transitions the ratio of the strength of the weak force to the strength of the electromagnetic force is substantially increased; even in such transitions, however, the electromagnetic force is much the stronger.

In 1981 Commins and his group at Berkeley were the first to observe parity violations by working with a highly forbidden transition in the thallium atom. The uncertainty in the experimental result was about 30 percent. Because of the somewhat complex structure of thallium, however, the expected theoretical value of the parity violation could also be calculated to a probable accuracy of about 30 percent. Within the experimental and theoretical uncertainties the measured and computed values of the parity violation are in accord.

The choice of cesium for our experiment was made because the necessary calculations of the atomic structure are more reliable. Cesium, like all the other atoms in its column of the periodic table, has only one electron in its outer shell. The remaining 54 electrons are relatively tightly bound in an electronic core that acts much as the atom of a nonreacting noble gas does. For computation-



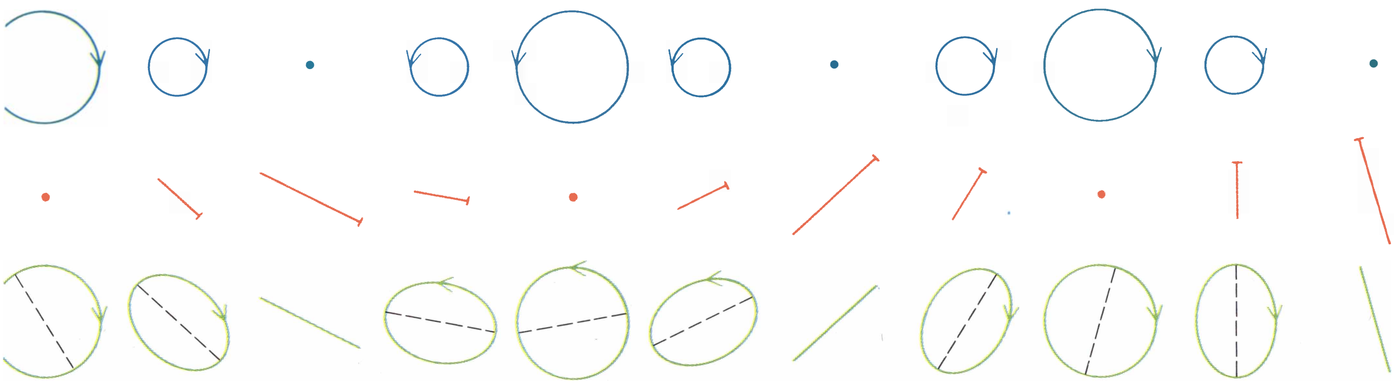
POLARIZATION MODULATOR changes monochromatic, linearly polarized light emitted by a laser into a beam whose polarization



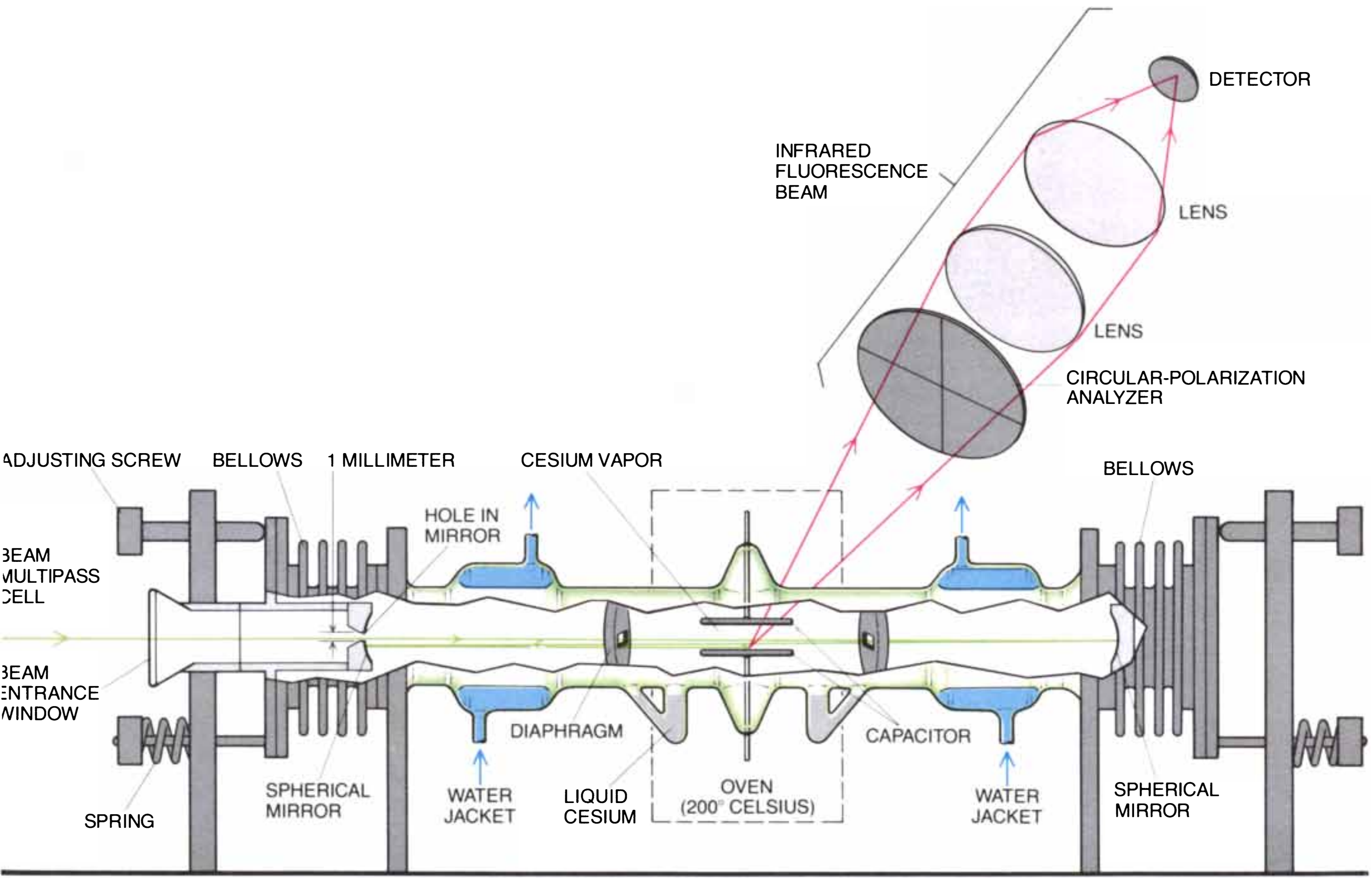
APPARATUS employed by the authors and their colleagues for measuring the violation of parity in the cesium atom is made up of three major parts: the light source, the beam multipass cell that contains the sample and the detection assembly. The laser and the po-

al purposes, therefore, the perturbations of the core electrons can be nearly disregarded in considering the orbit of the outer electron. Moreover, cesium has a moderately high atomic number, and so the experiment can benefit from the enhancement of the parity-violation effects associated with the cube of the atomic number. The actual enhancement is nonetheless about 10 times smaller in cesium than it is in bismuth, lead and thallium. Cesium is the simplest of heavy atoms and the heaviest of simple atoms.

The cesium atoms in our experiment enter the gas phase by evaporating from a liquid reservoir inside a closed glass tube. They are heated to approximately 200 degrees Celsius and subjected to an electric field between the two charged, parallel plates of a capacitor. The electric field distorts each cesium atom into a small antenna: positive charge is concentrated along one direction in the atom and negative charge is concentrated along the other. The small atomic antenna can resonate with the electro-



varies periodically with time. The output polarization (*c*) can be resolved into a circular component (*a*) and a linear one (*b*) that oscillate at the same frequency but out of phase by a quarter of a period. Hence when one component vanishes, the other one is at a maximum. The linear component rotates while it oscillates, but the frequency of the rotation differs from that of the amplitude oscillation.



larization modulator that constitute the light source deliver monochromatic green light of smoothly varying polarization to the beam multipass cell. In the cell the light bounces between two mirrors and passes roughly 100 times through the cesium vapor in a region bounded by the two charged, parallel plates of a capacitor. The light excites a small fraction of the atoms to a higher energy level, and the excited atoms are spin-polarized. When they return to a lower energy state, they emit infrared fluorescence that is registered and analyzed by the detection assembly. The mirrors are placed inside the cell to avoid the loss of intensity that would result with each passage of the beam through a cell window; the mirrors are protected from the corrosive effects of the cesium vapor by a water-cooled buffer of helium gas.

What?

What is the latest R&D activity in Japan in the field of industrial robots?

Is?

Is the name "datascan" trademarked?

Which?

Which drugs have been successfully used to treat osteoporosis?

What?

What is the current and projected market for frozen orange juice?

Are?

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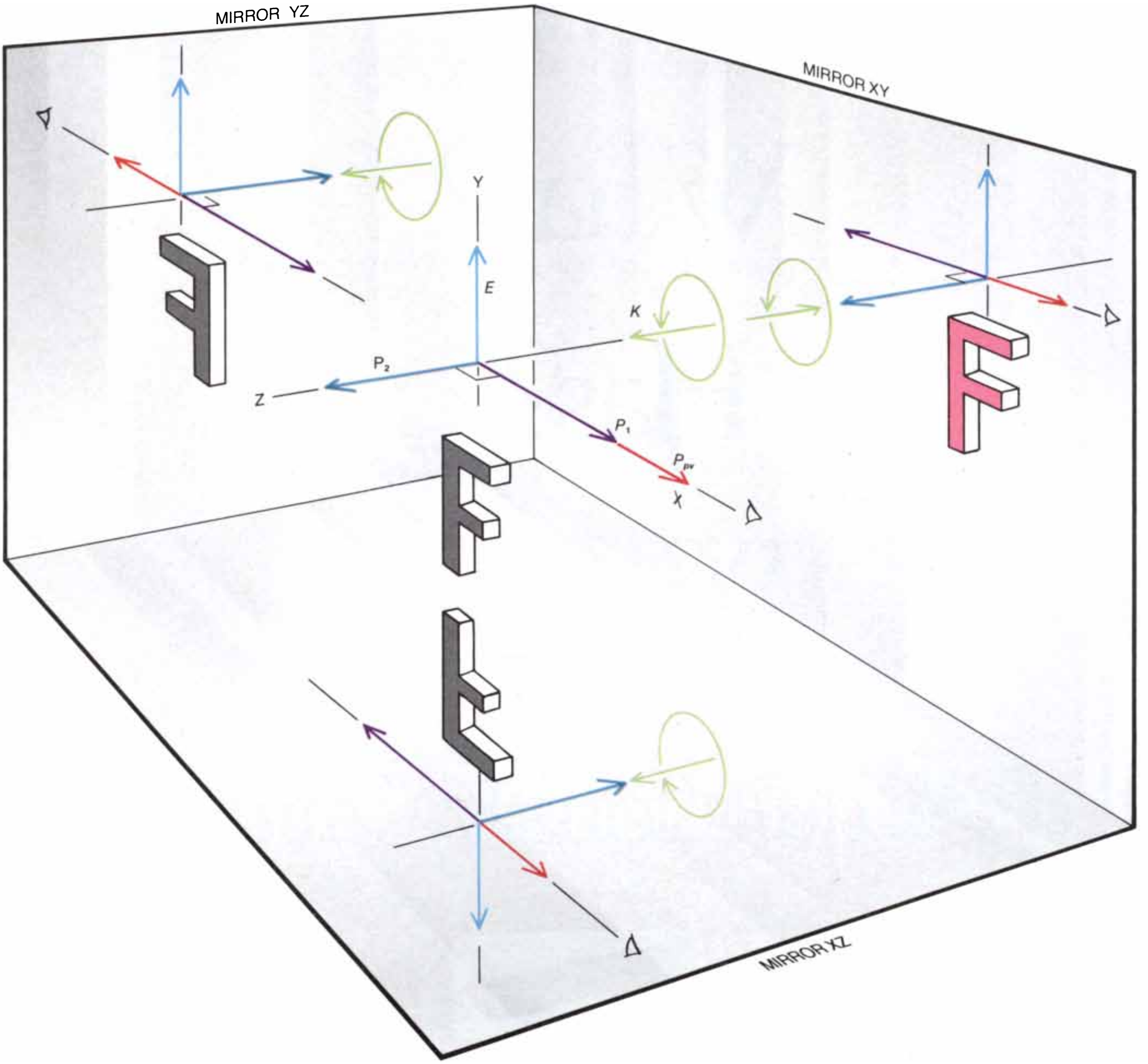
magnetic oscillations of the laser light.

The oscillation of the cesium atom, however, is not caused by electromagnetic effects alone. In addition to the induced electromagnetic antenna, the atom has a second, much less sensitive antenna associated with the weak force. When the two antennas are driven by the resonant vibrations of the incident laser light, they can both absorb power from the laser. The power absorbed is not equal to the simple sum of the power that would be absorbed by the two antennas if they were driven independently. Instead the total power absorbed also depends on the magnitude of the interference between the two antennas. The signal of parity violation that we observe in our experiment depends on the magnitude of the interference.

Every electron has a spin similar to the spin of a top. In physics the spin is usually represented by an arrow called an axial vector directed along the axis of the spinning object, or in other words perpendicular to the plane of the rotational motion. The direction of the axial vector is fixed by a convention known as the right-hand rule: the axial vector points in the same direction the right



SPIN OF EXCITED ATOMS in the gas can be resolved into three components: P_1 (*purple*), P_2 (*dark blue*) and P_{pv} (*red*). P_1 and P_2 arise entirely from the effects of the electromagnetic force, and so when the experimental configuration is replaced by its mirror image, both components point in the same direction as their mirror images. P_{pv}, which is actually much smaller in magnitude than the other two components, arises from the interference between the weak force and the electromagnetic force. It is the parity-violating component of the spin, and when the experimental configuration is replaced by its mirror image, P_{pv} is replaced by an arrow that points in a direction opposite to that of the mirror image of an axial vector. In other words, P_{pv} acts as a true vector would act if parity were conserved. The degree of circular polarization of the fluorescent light emitted along the x axis depends on the total magnitude of the spin component there; this magnitude is not the same for the initial experimental configuration (*center*) as it is for configurations in the mirrors. The handedness of the initial configuration is set up by the direction of the electric field E (*light blue*), the direction of the laser beam k (*green*) and the sense of the circular polarization of the incident beam. A suitable reversal of one or two of these values is equivalent to a mirror reflection in one of the three planes shown. The capital letter F indicates how each reflection transforms the initial experimental conditions.

thumb would point if the fingers of the right hand curled in the direction of the spin. Note that according to the right-hand rule, the spin of the electron emitted in beta decay points in the direction opposite to that of its forward motion.

A characteristic feature of the weak force is that it distorts the electronic orbit in a way that tends to align the spin of the electron with its velocity. It then turns out the atomic antenna associated with the weak force is directed along the electronic spin. In a gas of atoms the axial vectors representing the electronic spins point in all directions at random; the average spin is zero. The same property initially holds for the electrons in the cesium atoms subjected to the electric field in our experiment. The direction of the atomic antenna associated with the electromagnetic force, however, depends on the direction of the electric field imposed by the capacitor. The interference between the two kinds of antenna depends on the angle between them, and that angle depends in turn on the direction of the electric field, on the direction and polarization of the laser light that drives the oscillations of the antennas and on the direction of the electronic spins. Since the spins are random but the other two properties are not, atoms whose electronic spins are oriented in certain directions are preferentially excited by the laser beam to a higher energy state. As a result the atoms that become excited are spin-polarized. In other words, the average electronic spin of the excited atoms is not zero but instead points in some preferential direction.

The axial vector that represents the total electronic spin of the atoms in the excited state can be resolved into three components [*see illustration on opposite page*]. Two of the components, labeled P_1 and P_2, are perpendicular to each other and also to the direction of the electric field; they both originate from the electromagnetic force alone. The third component arises from the interference between the electromagnetic force and the weak force. It is labeled P_{pv} because it is the parity-violating component of the spin. P_{pv} points along the same axis as the component P_1.

Once the atom is excited its transition back to the initial energy state is still forbidden, but the transition to an intermediate energy state is allowed. In the process the atom emits a photon of infrared radiation whose energy is equal to the difference in energy between the excited state and the intermediate state. Because the angular momentum of the system must be conserved, the emitted photon carries away part of the angular momentum of the spinning atom. In other words, part of the spin polarization of the excited atoms is converted into polarization of the fluorescence light, and so the spin polarization can be inferred. More precisely, the degree of circular polarization of the fluorescence light emitted in a given direction is proportional to the size of the atomic spin component in that direction. We measure the degree of circular polarization in the fluorescence light emitted along the axis defined by the two spin components P_1 and P_{pv}. Hence we obtain the sum of the two components P_1 and P_{pv}.

We are primarily interested only in the magnitude of P_{pv}, how is it to be distinguished from P_1, which is directed along the same axis? For that matter, what is the distinction between the components P_1, P_2 and P_{pv}? To answer these questions it is instructive to consider what happens when an axial vector is reflected in a mirror.

When a spinning disk is viewed in a mirror parallel to the spin axis of the disk the disk and its mirror image appear to spin in opposite directions. When the mirror is perpendicular to the axis of the disk, both the disk and its image appear to spin in the same direction. Since the axial vector is directed along the spin axis, reflection in a mirror parallel to the axial vector reverses its direction, whereas reflection in a mirror perpendicular to the axial vector leaves its direction unchanged. The transformations are exactly opposite to the transformations imposed by mirror reflections on a true vector [*see illustrations on page 101*].

The difference between P_1 and P_{pv} can now be stated succinctly. When the experimental configuration that gives rise to P_1 is replaced by a second configuration that coincides with the mirror image of the first one, the direction of the counterpart to P_1 in the mirror corresponds to the mirror image of an axial vector. In other words, the axial vector to which the original configuration gives rise is reflected just as it should be when parity is conserved. On the other hand, the direction of the counterpart to P_{pv} in the second configuration is exactly opposite to that of the mirror image of an axial vector. Because P_{pv} is generated by a force that does not conserve parity, it acts as a true vector would act if parity in the experiment were conserved.

In practice there are additional ways to distinguish the spin components P_1, P_2 and P_{pv}. Both their magnitude and their direction are governed by the polarization of the energizing laser beam, and so it is useful to examine how the polarization of the beam is established. Before the beam reaches the cesium vapor, it is passed through a device called the polarization modulator. The polarization of the light that emerges from the modulator oscillates with time from full right circular polarization to full linear polarization to full left circular polarization and back again. Moreover, the direction of the linear polarization smoothly rotates with time, although with a period different from that of the oscillation between left and right circular polarization [*see upper illustration on pages 104 and 105*]. It is important to note that the circular polarization of the incident laser beam imparts a handedness to the experimental configuration. Remember that as the electric-field vector of the laser moves in a circle, the beam of light moves forward, and so the tip of the vector traces a left- or right-handed helix. The oscillation of the light between left and right circular polarization is one of the ways the handedness of the experimental configuration is periodically reversed.

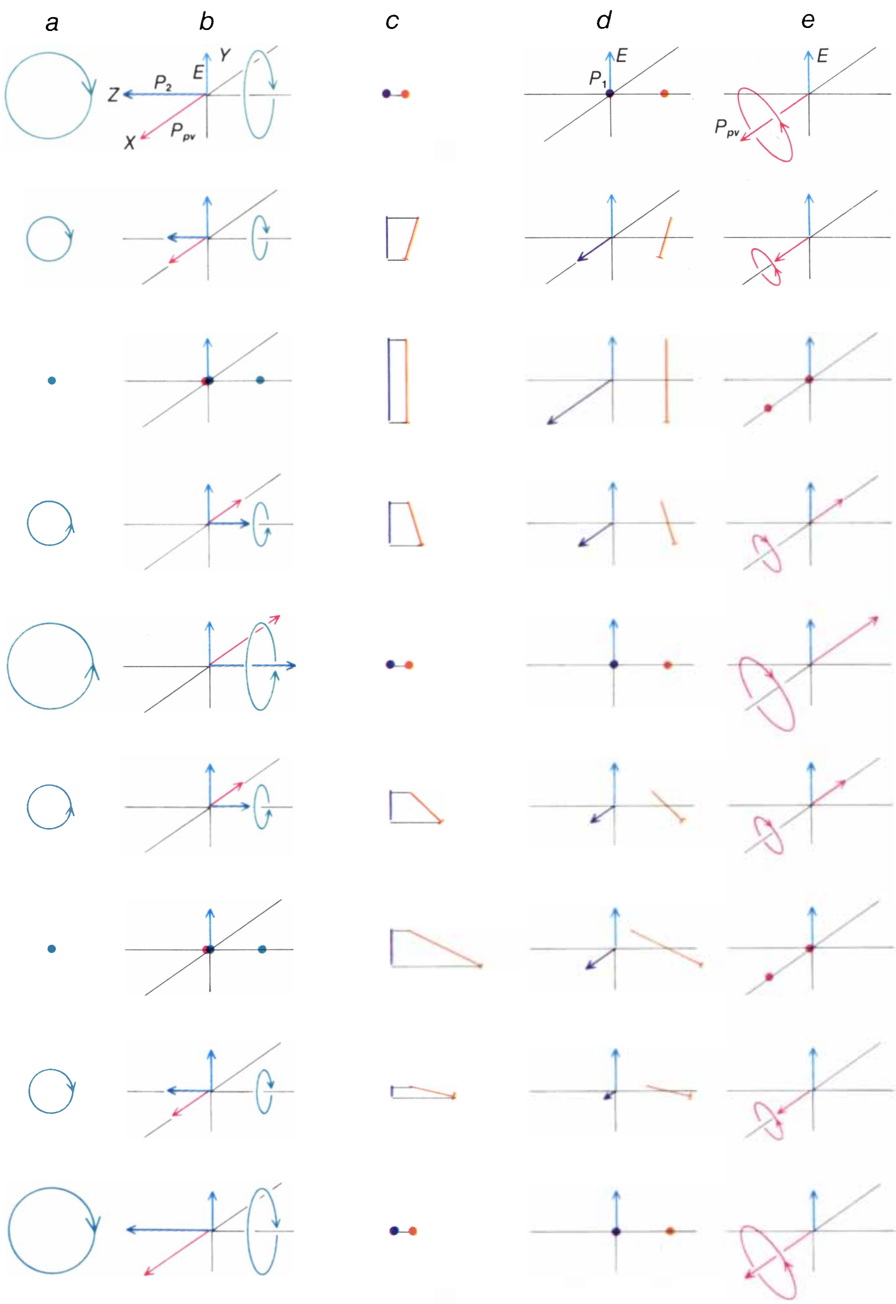
These modulations of the laser beam modify the spin components of the atomic gas in specific ways that serve to label the components. The components P_2 and P_{pv} are both proportional to the amount of circular polarization in the incident beam; they are modulated by the periodic change in that polarization. The component P_1 is proportional to the projection of the linear polarization of the beam along the axis parallel to the direction of the electric field. Because of the rotation of the linear polarization, P_1 is modulated with a rhythm that does not match the oscillations of P_2 and P_{pv} [*see illustration on next page*].

There are three simple ways to replace our experimental configuration by its mirror image, corresponding to three mutually perpendicular planes of spatial mirror reflection. First, as we have discussed, the polarization modulator can reverse the circular polarization of the incident beam while leaving the directions of the beam and the electric field unchanged. The reversal corresponds to a reflection in a mirror perpendicular to P_1 and P_{pv}. Second, both the circular polarization and the electric field set up by the capacitor can be reversed, which corresponds to a reflection in a mirror perpendicular to the electric field. Third, the direction of the laser beam can be reversed, while maintaining the electric field of the capacitor and the absolute rotational direction of the vector that represents the electric field of the laser. The reversal of direction changes the handedness of the laser beam and therefore corresponds to a reflection in a mirror perpendicular to the beam.

In practice we continually reverse the direction of the laser beam with two spherical mirrors. Each mirror is mounted on one side of the glass vessel that encloses the cesium vapor. The laser beam passes back and forth some 50 to 60 times between the mirrors before it escapes through its entrance hole in one of them. One advantage of the arrangement is that the parity-violating signal is amplified almost in proportion to the number of beam passes. The unwanted spin component P_1, on the other hand, changes direction with each pass, and so the multiple passages tend to cancel it. Even so, P_1 cannot be completely eliminated; it remains about 30 times larger than the component P_{pv}.

We devoted considerable effort to the analysis, reduction and control of systematic effects. In general any imperfections in geometry or in the reversals of the handedness of the experiment can result in systematic errors. For example, in reversing the circular polarization of the laser beam with the modulator, the other properties of the beam, such as its intensity and its degree of linear polarization, must remain unchanged. A spurious change of only 1 percent is enough to simulate the expected violation of parity. The trouble is that in existing polarization modulators imperfections of this kind are typically as large as several percent. In order to overcome the problem we had to design a new type of modulator that is able to guarantee a pure reversal of the polarization to within one part in 10^4.

Another systematic difficulty was the imperfections of the mirrors, which can slightly change the polarization of the light as it is reflected; this effect can also simulate the parity violation. Because we know of no mirror maker who regularly manufactures mirrors to the tolerance we needed, the mirrors were obtained by sorting. Among a stock of 20 mirrors two were found to be adequate. After the mirrors were installed we rotated the return mirror from time to time through an angle of 90 degrees in its plane. The periodic adjustment reverses any systematic effect and, on the average, cancels it.



MAGNITUDE OF THE SPIN COMPONENTS P_2 (*dark blue*) and P_{pv} (*red*) (*b*) is proportional to the part of the incident laser beam that is circularly polarized (*green*) (*a*). The magnitude of the spin component P_1 (*purple*) (*d*) is proportional to the projection along the electric-field axis of the linear polarization of the laser beam (*orange*) (*c*). The signal is obtained from the circular polarization of the fluorescence light (*red*) observed along the *x* axis. It is that part of the circular polarization proportional to the circular polarization of the laser (*e*).

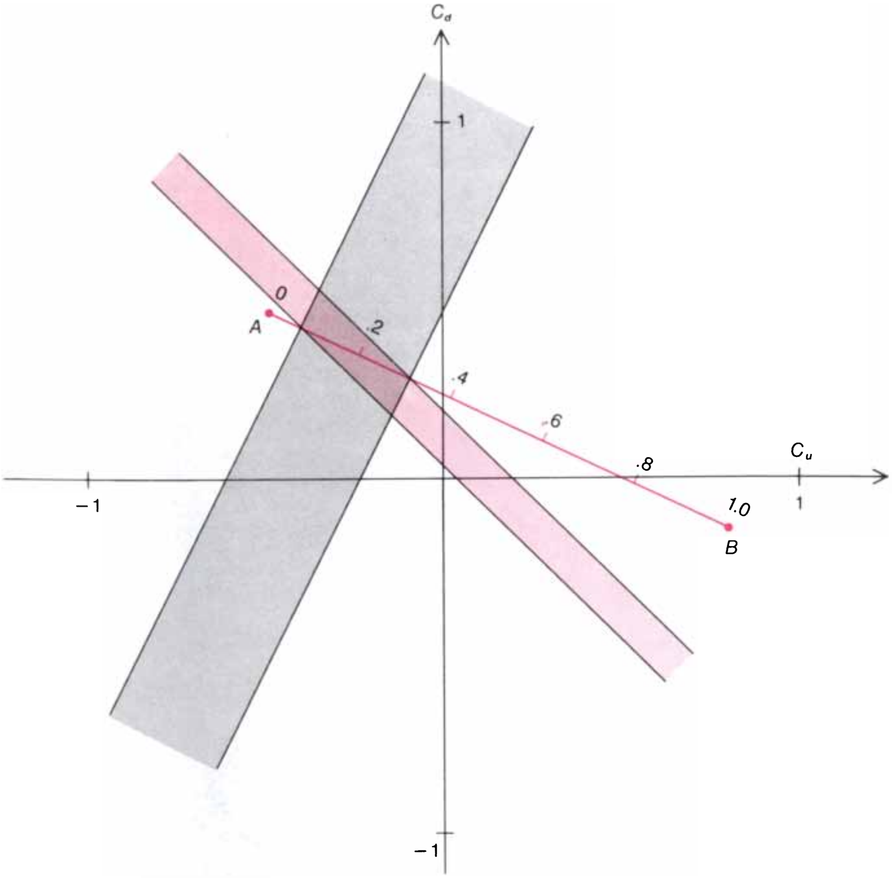
There were many other potential imperfections, such as stray electric fields or the inaccurate reversal of the beam in the glass vessel, that had to be considered. We measured these imperfections using the atoms themselves as a probe, and we have included all of them in a theoretical model that gives a quantitative estimate of the possible systematic effects. The estimate plays a crucial role in determining the confidence one can have in the measurement. Our attempts to understand and control systematic effects took more than three years. Our goal was to keep all known systematic effects smaller than a few percent of the measured value. Because the goal was reached, we were not obliged to make any significant correction to the raw, measured value of the parity violation.

Against possible unexpected systematic effects not included in the model, the only realistic policy is to verify that the data delivered by the experiment satisfy any conditions that common sense would demand. For example, it happens in our experiment that the parity-violation signal is obtained simultaneously through two independent channels, corresponding to two modulation frequencies. We have checked that the signals carried by the two channels agree. While parity was being measured, two null measurements were also carried out: the two results are found to be null as expected. Statistical tests were done to verify the absence of certain undesired correlations. Finally, in the middle of our data acquisition, we suddenly realized that the two rotating plates in the polarization modulator might—who knows?—introduce some spurious preference between left and right. Their rotations were reversed for all subsequent data collection, and the results before and after the reversal agree.

In order to calibrate our measurements of the electronic polarization, the large component P_2 is measured with the same apparatus that measures P_{pv}. A magnetic field is applied for a short time along the axis parallel to the electric field. The magnetic field rotates P_2 in such a way that it can be detected from the same direction as P_{pv} can. What we actually measure in our experiment is the ratio of P_{pv} to P_2, which is found to be on the order of 10^{-5}. The ratio directly gives the observed amount of left-right asymmetry; it is the analogue of the small angle of optical rotation observed in the experiments with bismuth. Because the value of P_2 is known independently from spectroscopic studies, the value of P_{pv} can be calculated from the measured ratio of P_{pv} to P_2.

Given the uncertainties of experiment and theoretical calculation, the first result of our experiment is in excellent agreement with the Weinberg-Salam theory. The statistical uncertainty is 16 percent and the systematic uncertainty is 8 percent. Claude Bouchiat and his colleagues have calculated the parity violation predicted by the theory, and the uncertainty in their prediction is less than 15 percent.

Last year we checked the result against a modified version of our experiment in cesium. The two versions of the experiment differ in the relative orientations of the electronic and nuclear spins of the atoms excited by the laser beam. This subtle practical difference gives rise to a large difference in principle. In the two versions the parity violation is detected through different physical quantities, and most of the estimates of potential systematic errors are based on different measurements as well. Nevertheless, the two experimental results are about equally accurate; they also agree with each other as well as with the theoretically predicted value, which lies between them. When the two results are combined, the statistical uncertainty is reduced from 16 to 11 percent; the systematic uncertainty remains 8 percent.



RESULTS OF TWO EXPERIMENTS designed to measure parity violation are plotted on the same axes. The C_u axis represents the weak charge of the up, or *u*, quark, and the C_d axis represents the weak charge of the down, or *d*, quark. High-energy experiments done at the Stanford Linear Accelerator Center (SLAC) confine the possible values of the two charges to a linear strip (*gray*). The low-energy atomic experiments done by the authors and their colleagues confine the possible values to another linear strip, almost perpendicular to the first one (*color*). Taken together, the two experiments put tight bounds on the values of C_u and C_d. The values predicted by the standard electroweak theory correspond to a point on the line segment in color. That point, however, is underdetermined by the theory because it depends on the value assigned to a free, or arbitrary, variable in the theory. As the graph shows, the standard theory is consistent with the points on the intersection of the two strips for values of the free variable near .2. Results of all experiments that determine the variable converge to .23.

It is instructive, in spite of our experiment's agreement with what has now become the standard theory of the electroweak force, to interpret our result independently of that theory. In heavy atoms the relevant component of the weak force between the electron and the nucleus is proportional to the nuclear weak charge, which is the sum of all the weak charges that make up the nucleus. The nucleus consists of protons and neutrons, which in turn consist of *u*, or up, and *d*, or down, quarks. An experiment such as ours determines the value of the nuclear weak charge, but that value is not sufficient to determine the weak charges of the *u* and *d* quarks separately. Instead it only imposes a relation between the possible values of the weak charges of the quarks. If the quark charges are plotted on independent axes in a system of rectangular coordinates, the point that corresponds to their true value must lie somewhere along a straight line. Only the line and not the position of the point along it is determined by an experimental measurement of the weak nuclear charge.

The results of the high-energy experiment at SLAC can be plotted on the same set of coordinate axes, and they lead to a quite different linear relation. If the results of the high-energy experiment are combined with the results of our work in atomic physics, the values of the weak charges of the quarks are confined to the intersection of two lines. In principle, therefore, the values are determined. In practice, because of uncertainty in both the experimental and the theoretical interpretation, each line is a strip of finite width. Nevertheless, the intersection of the two strips still represents only a small set of possible values. It turns out that these restricted values, although they are derived virtually without theoretical assumptions, are also consistent with the theory of Weinberg and Salam.

The mutual support of two quite different kinds of experiment in reaching a definite conclusion, unattainable by either one alone, illustrates the cooperative and complementary nature of this enterprise. Each of the difficult experiments we have discussed is a challenge to many technical problems, an undertaking whose detailed evolution no one can perceive in advance or master while in progress. The fact that different paths are explored and that several groups are competing is a strong mutual incentive, and it is also a valuable warranty against spurious results. In view of the interest in these studies and in spite of their difficulty, may the experiments still in progress achieve even better accuracy and continue to provide new information about the weak force.

EGG GALLERY of the Douglas-fir beetle is a tunnel excavated in the bark by the female. The gallery is the vertical line at the center. The lines extending horizontally from it are larval mines: tunnels carved by feeding larvae. In the spring the female beetle chooses a tree and begins boring through the bark phloem at the boundary between the bark and the sapwood. A male joins her and they mate repeatedly as she lays the eggs in alternating niches at the sides of the tunnel. Over the winter the eggs hatch into larvae that tunnel away from the gallery. The larvae metamorphose into pupae and then into adult beetles, which spend the winter in the tree and emerge in April. In the photograph, which was made by Malcolm M. Furniss of the University of Idaho, the outer layer of the bark has been peeled away.

Acoustic and Chemical Signals in the Life Cycle of a Beetle

The subtle interplay of such signals enables the Douglas-fir beetle to attract a mate, to repel intruders and to regulate the density of its population in the great tree of the western forest on which it preys

by Lee C. Ryker

Every spring in the coniferous forests of western North America the annual conflict between a tree that can grow to be more than 300 feet tall and one of its chief enemies, a beetle about a quarter of an inch long, begins again. In the first warm days of April, Douglas-fir beetles leave the firs where they have spent the winter and fly in search of new host trees. The beetles generally choose trees that have been battered by the wind or stricken by drought or disease. On finding such a damaged tree the insects begin a well-coordinated attack. In a single day thousands of beetles can bore into the bark and overwhelm the tree's chemical defenses.

Each female Douglas-fir beetle bores a tunnel through the nutritious inner bark near the surface of the sapwood. The tunnel forms the gallery where the female's eggs will be laid. While the gallery is under construction the female is joined by a male. The pair mate repeatedly, and the fertilized eggs are deposited in niches at the sides of the tunnel. The eggs hatch into cream-colored larvae, which metamorphose into pupae in the tree's bark. The pupae metamorphose into adults, which leave the tree by means of neatly drilled exit holes.

The Douglas fir is a valuable tree. Much lumber comes from it, and the Douglas-fir beetle has long been a costly pest because it kills trees in relatively inaccessible areas where the dead trees cannot be quickly harvested before they decay. For this reason, and also for reasons of basic biological interest, considerable attention has been given to the beetle's cycle of life. The work has shown that the attack on the host tree, the aggressive interaction, courtship and mating of the beetles and the density of the beetle population are regulated by the combined effect of pheromones, or chemical signals, and chirps, or acoustic signals. Both types of signal given in the correct sequence are required for the events of the beetle's life cycle to mesh smoothly.

As the knowledge of how Douglas-fir beetles communicate has been gathered, one finding has been particularly striking: that one substance can evoke several quite different responses. The substance is the pheromone methylcyclohexenone (MCH). In response to MCH in a mixture of substances beetles can aggregate on the bark of the Douglas fir or fail to be attracted; they can attack another beetle or begin the courtship that eventually leads to mating. Which response is elicited depends on the concentration of the pheromone and the context in which it is released. Knowledge of these signaling mechanisms could be of great benefit in helping to reduce the economic losses caused by the beetle. The findings are also interesting for their own sake because they show how much an organism's response to a signal can vary when the context in which the signal is given changes.

The Douglas-fir beetle (*Dendroctonus pseudotsugae* Hopkins) is one of the best-understood of the more than 300,000 species of beetles that have been described by entomologists. It has taken more than 20 years for the details of the methods by which the beetle communicates to be elucidated, and much of the work was done by the late Julius Rudinsky of Oregon State University. When Rudinsky began his studies of the Douglas-fir beetle, it was already known that in killing the tree the beetle is aided by an organism called the blue-stain fungus, which is carried on the body of the female insect.

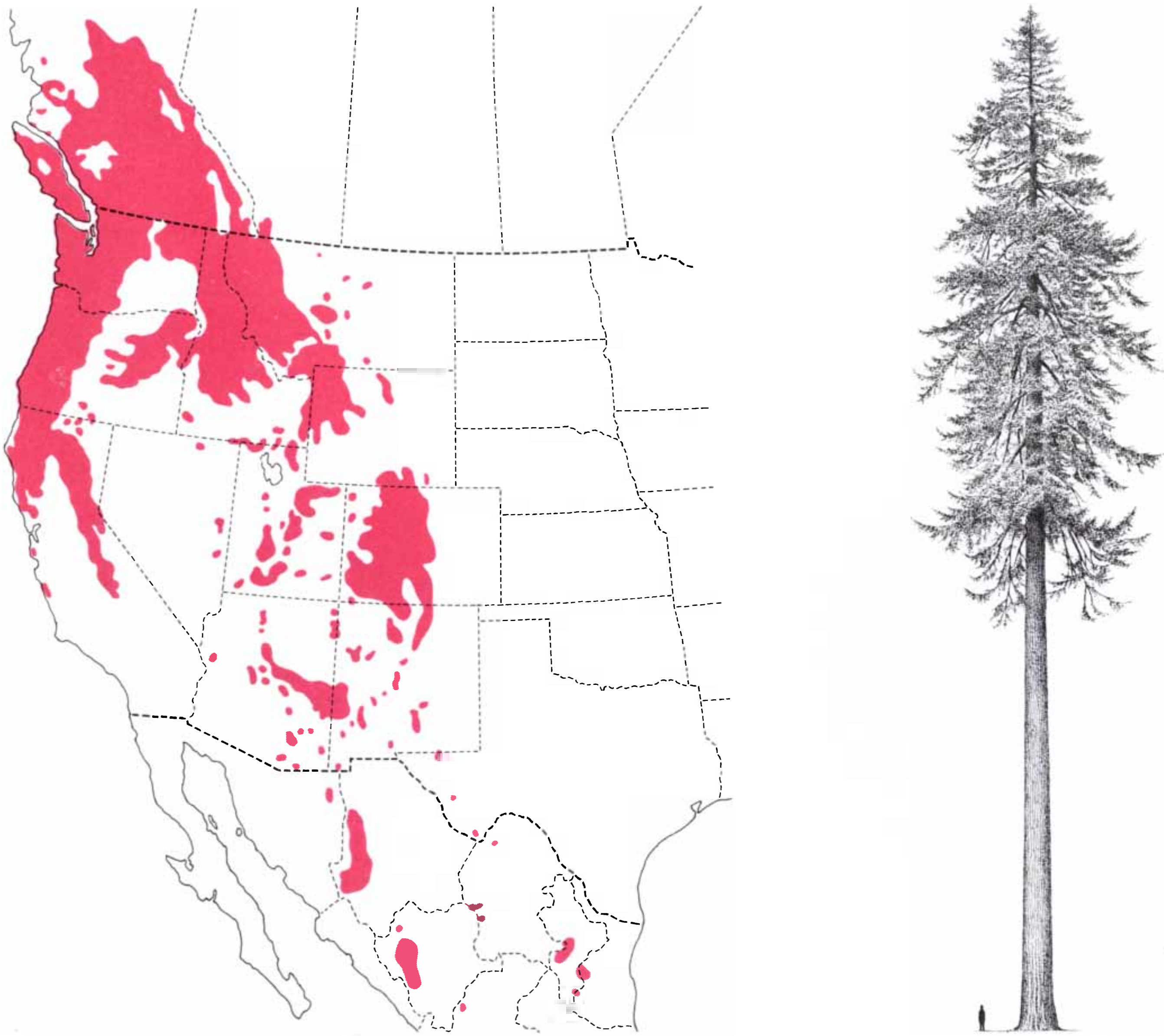
As the female bores the egg gallery she inoculates the sapwood with the blue-stain fungus. In a short time the fungus grows into the tracheids, or water-conducting channels, of the tree and blocks them. The tracheids run vertically through the sapwood and normally generate the pressure needed to pump resin through the resin channels that radiate horizontally from the center of the tree.

The resin is the main chemical defense of the Douglas fir. If resin fills the gallery bored by the beetles, the beetles die in the sticky mass. With the pressure in the tracheids interrupted, however, resin cannot flow into the gallery. Hence the beetle is protected by the fungus from the tree's defense mechanisms. The death of the tree results from the blockage of the water-conducting system by the fungus and the consumption of the phloem, or nutrient-conducting system, by the beetles.

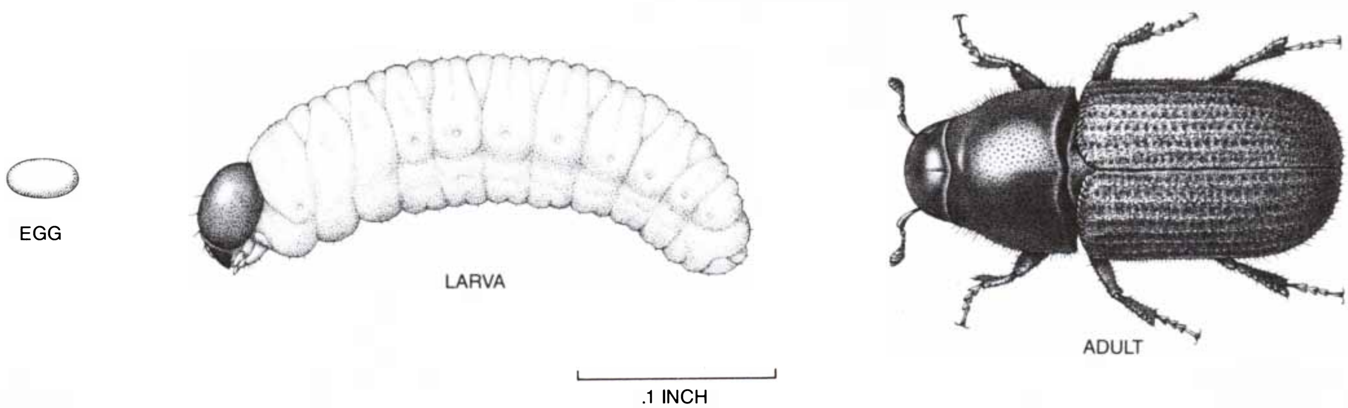
The killing of a Douglas fir is hastened by the fact that the insects tend to choose a damaged tree as the site for a new gallery. In 1963 Rudinsky showed that Douglas-fir beetles can detect damaged or cut trees in the forest. Sections of freshly cut logs attracted adult beetles of both sexes but attracted twice as many females as males. Furthermore, it was shown that fresh pitch from Douglas-fir logs had as much power to attract the beetles as the logs themselves. Accordingly work was begun on identifying the substances in the pitch that drew the flying insects.

Tests of the components of the pitch demonstrated that several of the volatile substances called terpenes could attract male and female beetles. Three of the terpenes were particularly potent: alpha-pinene, camphene and limonene. Such substances from the host tree that have the power to draw the flying insects are known as primary attractants.

Later David L. Wood and his colleagues at the University of California at Berkeley found that some substances synthesized by a bark beetle that infests pine trees can act as powerful attractants when they are combined with terpenes. Rudinsky, who was working along similar lines, introduced female Douglas-fir beetles into logs and allowed the insects to feed under the bark.



DOUGLAS FIR (*Pseudotsuga taxifolia*) can grow to be 325 feet tall and 17 feet around. In many trees the shaft is clear of branches for more than a third of its length. The bark of mature trees can be a foot thick. The range of the species is from British Columbia to Mexico.



DOUGLAS-FIR BEETLE (*Dendroctonus pseudotsugae* Hopkins) is a quarter of an inch long and is generally dark brown with reddish elytra, or wing covers (*right*). The whitish larva is slightly larger than the adult (*middle*). The egg is about a twentieth of an inch long (*left*).

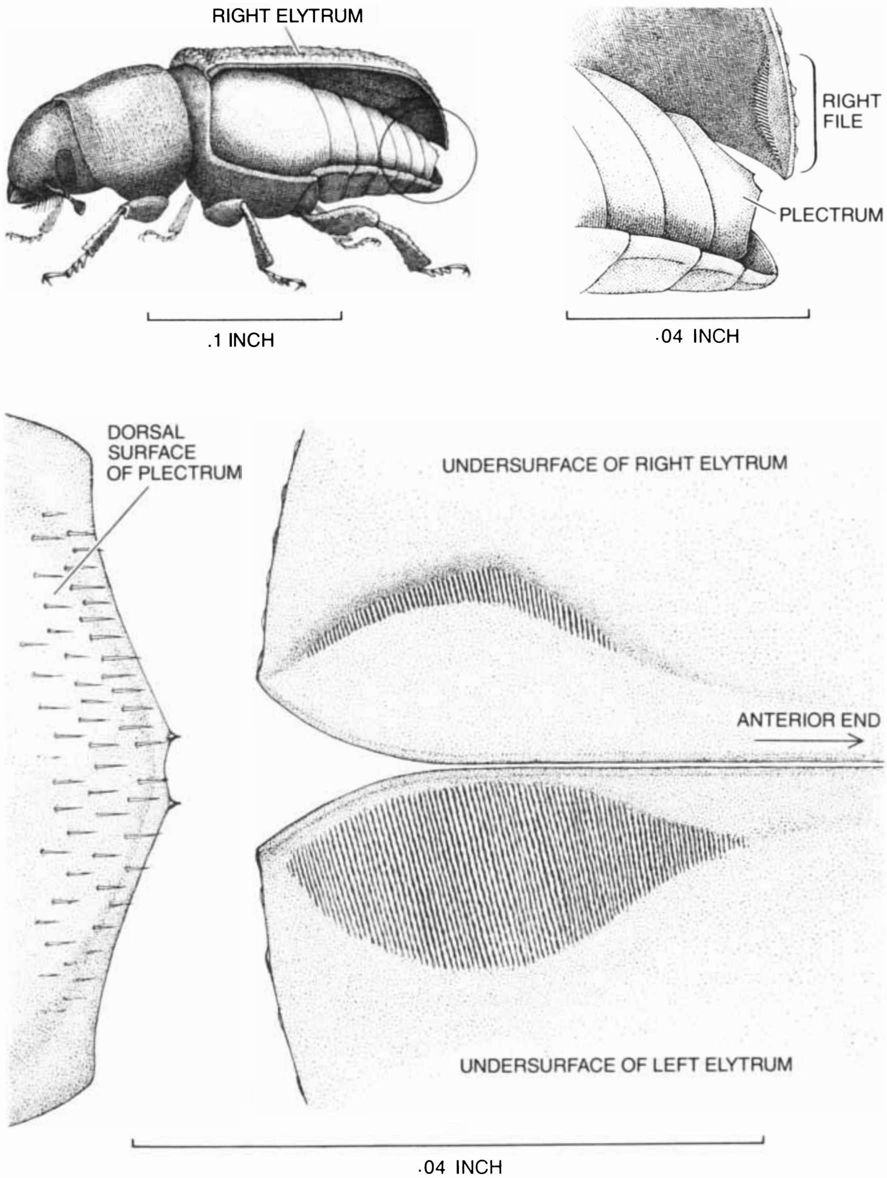
When this was done, the attraction of the logs for flying beetles was increased by a factor of 15.

The source of the heightened attraction was traced to the frass, or bark shavings, that the female cuts from the head of the egg gallery while the tunnel is under construction. The frass accumulates in piles at the entrance to the gallery; the pheromone that increases the attraction was shown to be in the fecal pellets of the female, which are mixed in with the frass. In the mid-1960's the concept of a pheromone was not new: sex attractants had been described in moths and several other kinds of animals. Because the bark-beetle substance attracted both sexes, however, it could not be considered a sex pheromone. It was therefore designated an aggregation pheromone.

In 1968 Rudinsky discovered that the effect of the Douglas-fir beetle aggregation pheromone could be reversed. If males were paired with the tunneling females, flying beetles were no longer attracted to the logs. Logs with 30 females feeding alone attracted from 700 to 900 flying beetles per hour, but when a male was put on a screen over the entrance to each gallery, the logs became unattractive in minutes. If the males were removed, the logs rapidly became attractive to flying insects again.

The reversal of the effect of the aggregation pheromone was found to be caused by a second pheromone, which was released when male and female beetles were together. The existence of the second substance, named the masking pheromone, was demonstrated by putting a log with male-female pairs next to a log with only female beetles. Both logs soon lost their power to draw the flying insects: the aggregative effect of the pheromone in the frass of the unmated females was canceled by the odors coming from the paired beetles in the other log. The rapid masking effect of the second pheromone was surprising to workers in the field of insect communication because chemical signals were generally thought to fade slowly, and the frass at the gallery entrance was permeated with the aggregation pheromone.

A second surprise came after the discovery of the masking pheromone. It was found that the male did not have to touch the female to trigger the release of the masking substance: the signal from the male was a chirp. The rubbing of two specialized body parts together to generate an acoustic signal is called stridulation; it is the commonest method of acoustic signaling among insects. The male Douglas-fir beetle stridulates by rapidly scraping the plectrum, a pair of small prongs near the end of the abdomen, across the ridges of the file, a small hardened patch on the underside of the wing covers that has many small ridges.



BEETLE MAKES SOUND by rubbing specialized body parts together in the process called stridulation. On the inner surface of the wing covers is a hard patch called the file, which has many small ridges on its surface. Near the end of the abdomen is the plectrum, a pair of tiny prongs. The beetle stridulates by rubbing the plectrum across the file. Both male and female beetles stridulate, and the sounds made in this way are a significant channel of communication.

Rudinsky observed that the male beetle always stridulates on coming in contact with the frass outside the female's gallery. He went on to show that stridulation leads to the release of the masking pheromone. He silenced male Douglas-fir beetles by clipping off their wing-cover tips and allowing the wound to heal. Such silenced males did not trigger the release of the masking pheromone no matter how long they remained on the screen at the gallery entrance. At the same time flying beetles continued to be attracted to the logs holding the female beetles.

Males that had not been silenced would stop at the entrance, dig in the frass and chirp even if the female had been removed from the gallery. If the female was gone, a normal male chirping at the gallery entrance did not cancel the attractive effect of the frass. Beetles continued to land on the screen cages around the test logs. Such evidence led Rudinsky to conclude that the female beetle alone synthesizes and releases the masking pheromone. As we shall see, this is not the case, but it was a reasonable hypothesis and it led to a fruitful investigation of how the Douglas-fir beetles communicate.

Identifying the beetle pheromones proved to be much harder than identifying the attractants that come from the host tree. It was found that the substances with the power to attract the beetles come from the hindgut of the female. Unfortunately for the purposes of investigation the hindgut holds many

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EPSON

STATE-OF-THE-ART...SIMPLICITY.

compounds, some from the tree and some synthesized by the insects, and identifying the specific attractants that are synthesized by the beetle was a difficult job. Several groups of workers in the U.S. and Canada had been cooperating in the study of *Dendroctonus* bark beetles; the groups now competed to identify the substances in the aggregation pheromone.

The first compound made by the beetle that was shown to function as an attractant was frontalin, which is a compound of the type known as a bicyclic ketal. Frontalin had been found in other species of bark beetle by G. W. Kinzer and his colleagues at the Battelle Memorial Institute before it was identified in the Douglas-fir beetle. Soon four other compounds with the attractant effect were identified: trans-verbenol, verbenone, methylcyclohexenol and MCH. All five have a similar chemical structure. Each molecule has the form of a small ring consisting of at most 10 carbon atoms, and each ring includes one or two atoms of oxygen.

Each of the five pheromones made a slightly different contribution to the aggregation mixture, but it was noted that the response of the beetles to any of the five was weak unless a host-tree terpene was also present. For example, frontalin by itself attracted few flying beetles, but with alpha-pinene or camphene present it had a potent attraction for beetles of both sexes. The inclusion of methylcyclohexenol, which is an alcohol, in a mixture of compounds led to the attraction of beetles of which the majority were males. Methylcyclohexenol is a sex attractant that operates much like the pheromones that had been identified in other insect species.

The effect of the ketone MCH, however, varied dramatically with changes in its concentration. Whereas very dilute MCH strongly enhanced the attractive power of the other pheromones in the aggregation mixture, undiluted MCH eliminated the attraction almost entirely. The inhibiting effect of pure MCH suggested it was this compound that was the masking pheromone. The overall aggregation response, however, was elicited not by a single substance but by a bouquet of them: a subtle blend of pheromones synthesized by the insect and terpenes from the host tree.

When the main pheromones had been identified, work was begun on the relation between the chemical signals and the acoustic ones. In examining such relations a helpful apparatus was one called the olfactory walkway. The olfactory walkway consists of a horizontal layer of fine screening on which a beetle walks between parallel guiding walls toward a light source. If a male beetle was put in the walkway with a vial of the attractive frass under the screen, the insect responded to the aroma of the frass. In most trials it first went past the vial and then turned back, so that it seemed to be pirouetting over the vial. At the same time it tipped its head down, chirped and made digging motions. A male responding in this way was said to be arrested by the attractant bouquet.

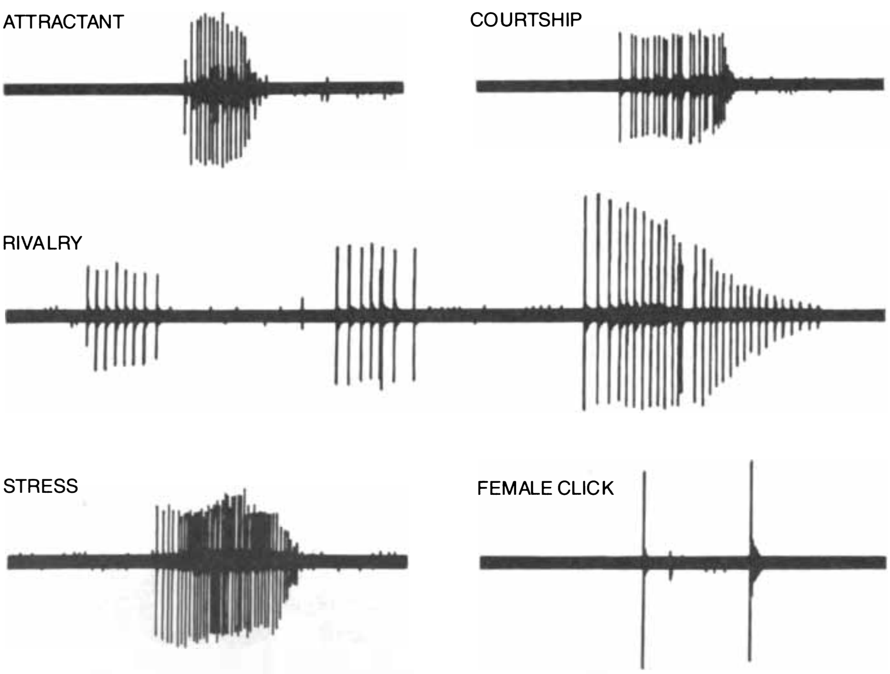
With Robert R. Michael, an electronics engineer, Rudinsky began to look more closely into the chirp given by the male on detecting the aroma of the frass. When the sound was analyzed with an oscilloscope, it was found that the chirp of a male stimulated by frass is shorter and has fewer acoustic pulses than a stress chirp, which is the sound made by an insect when it is handled by a human being. The chirp made in the presence of the frass was termed the attractant chirp.

After a male arrested by the attractant bouquet had stridulated for 10 minutes at the entrance to a female's gallery, 90 percent of the walking males that encountered the frass in the next 10 minutes passed without being arrested. Even a recording of the attractant chirp played next to the entry hole could lead to the elimination of the attractant effect if the female was present in the gallery. Surgically silenced males could not cancel the attraction, however, even if they stopped for more than 10 minutes outside the gallery entrance.

It appeared to Rudinsky and his colleagues that the attractant chirp triggers the release of the masking pheromone; when the mask is released, the frass immediately loses its attractive power. The female is quite discriminating in her response, as is shown by the fact that recorded stress chirps had no effect on the attractive power of the frass. Only the correct acoustic pattern can serve as the stimulus for the release of the mask.

Since it had been shown that MCH has the capacity to cancel the drawing power of the attractant bouquet, Rudinsky and Michael decided to find out whether MCH is released by the female in response to the attractant chirp of the male. For this purpose they designed a collection apparatus where beetles were put in short glass tubes with a screen at each end. The tubes were mounted in a chamber through which purified air was pumped. A collection device gathered the volatile products released by the insects. The products were analyzed by the techniques of gas chromatography and mass spectrometry.

When female beetles were put in the tubes alone, no MCH was released; male beetles alone also released none. When a male was put in the tube with each female, however, large amounts of MCH were given off. The male nudged the female and chirped continually as the substance was being released. To show that the MCH came from the females Rudinsky eliminated the males from the tubes and played to the females a tape recording of the male's at-



ACOUSTIC SIGNALS of the Douglas-fir beetle are shown in the form of oscillograms of the stridulations emitted by the insect. The attractant chirp (*upper left*) is sounded by the male on approaching the entrance to a gallery containing a female. The courtship chirp (*upper right*) is sounded by the male just before copulation. The rivalry chirp (*middle*) is distinguished by the pauses that make it sound as if the male were stuttering. The rivalry chirp is sounded when two males meet and also in the aggressive initial stage of courtship. The stress chirp (*lower left*) is sounded when the beetle is handled by a human being. The only acoustic signal emitted by the female is the click sounded when she is constructing and guarding the egg gallery (*lower right*).


Dance has a new partner.

tractant chirps. The females responded to the acoustic stimulus and released MCH just as they had when the male beetle was actually in the tube. It was evident that MCH is the natural masking pheromone.

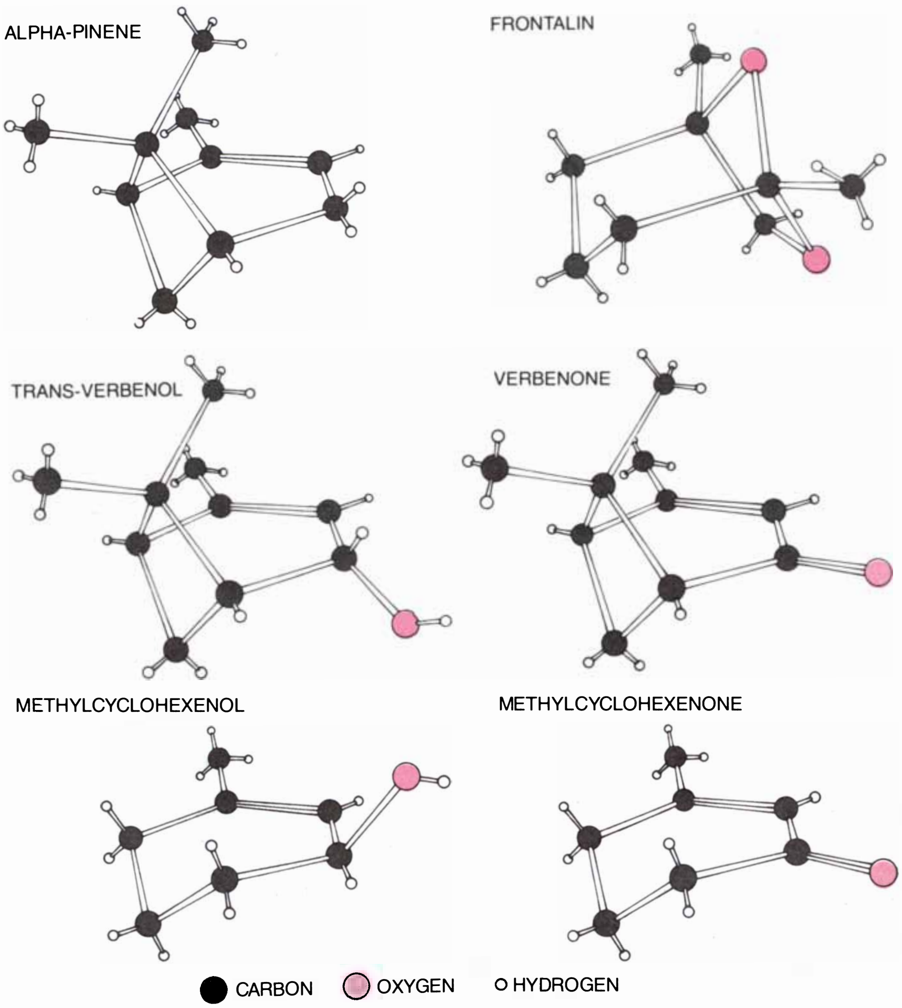
Bark-beetle experts had long assumed that only the male Douglas-fir beetle stridulated; the female was generally thought to be silent. Rudinsky discarded that assumption when he heard a female of the mountain pine beetle, which is a close relative of the Douglas-fir beetle, chirp when it was disturbed by females boring galleries nearby. With the aid of a microphone and an oscilloscope Rudinsky observed that the female Douglas-fir beetle also emits a brief acoustic signal. The signal is a single or double click more intense than the chirp of the male but so brief that it is inaudible to human beings.

The female's click serves to regulate the spacing of the egg galleries. All females click intermittently when they are tunneling, even if no other beetle is nearby. Females in the bark click with greater frequency, however, when other females are put in nearby holes. If a neighbor is within five centimeters, the sound is almost continuous. Females exploring the bark turn away when they come within 10 centimeters of the entry hole of a clicking female. As a result of such territorial signaling the gallery entrances are uniformly spaced.

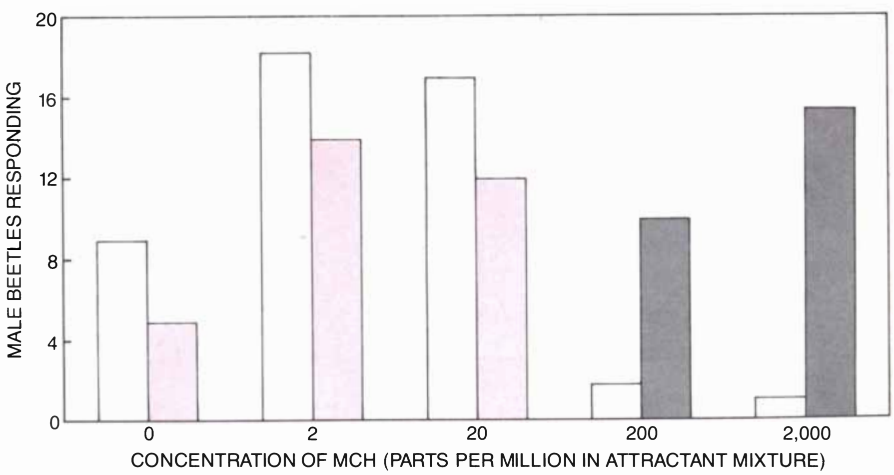
Acoustic signals also play a part in the interaction of two male beetles, although the males are much more overtly aggressive than the females. Indeed, the relations between male beetles at the entrance to a gallery are reminiscent of an encounter between two tanks. If two males arrive simultaneously at the entrance hole, a fight is certain and there are loud chirps as the rivals crash into each other and spar with their hard mandibles.

The chirp of the fighting male Douglas-fir beetle is so distinctive that it could never be confused with the attractant chirp. The chirp made when fighting is longer than the attractant one, has a slower pulse rate and includes more pulses. Even more notable are the brief interruptions in the chirp. There can be one, two or three pauses in the signal, which makes it sound as if the beetle were stuttering. Following European terminology, Rudinsky named the interrupted signal a rivalry chirp.

When two male beetles were put in the pheromone-collection apparatus together, they sounded vigorous rivalry chirps, fought violently and released a considerable quantity of MCH. When a tape recording of the rivalry chirp was played to male beetles, however, no MCH was released. It appeared the male acoustic signal alone could not stimulate the release of the pheromone;



PHEROMONES are substances synthesized by an insect or another animal that elicit specific responses from other individuals of the same species and thereby help to regulate the life cycle. The molecular structures of five Douglas-fir beetle pheromones are shown together with the structure of one compound synthesized by the Douglas fir: alpha-pinene. All the molecules have the form of a single or double ring with at most 10 carbon atoms. All are found in the mixture released by the female that attracts other beetles to the tree. Methylcyclohexenone (MCH) alone can also interrupt the attractant effect, stimulate aggression and stimulate courtship.



CONCENTRATION OF MCH has a dramatic effect on the male Douglas-fir beetle. The open bars show the number of beetles attracted to a vial containing a mixture of synthetic attractants and MCH. The colored bars show the number of beetles emitting the attractant chirp; the gray bars show the number emitting the rivalry chirp, associated with aggression. At a concentration of up to 20 parts per million MCH draws many beetles and stimulates attractant chirps. At concentrations greater than 20 parts per million MCH cancels attraction. Moreover, high concentrations cause male beetles to emit the rivalry chirp instead of the attractant chirp.

contact was required for MCH to be given off.

Although the rivalry chirp alone could not elicit the release of MCH, a sufficient quantity of MCH could elicit the rivalry chirp. Rudinsky put male beetles in the olfactory walkway and observed them as the concentration of MCH in the attractant solution was increased. A very low concentration of the pheromone, about two parts per million, served as part of the attractant bouquet and enhanced the effect of the other components. When the concentration was 20 parts per million, the males also responded by being arrested on the walkway over the vial. When the concentration reached 200 parts per million, however, the males were no longer arrested. Not only did they pass over the vial without turning back but also their acoustic response changed from the attractant chirp to the rivalry chirp.

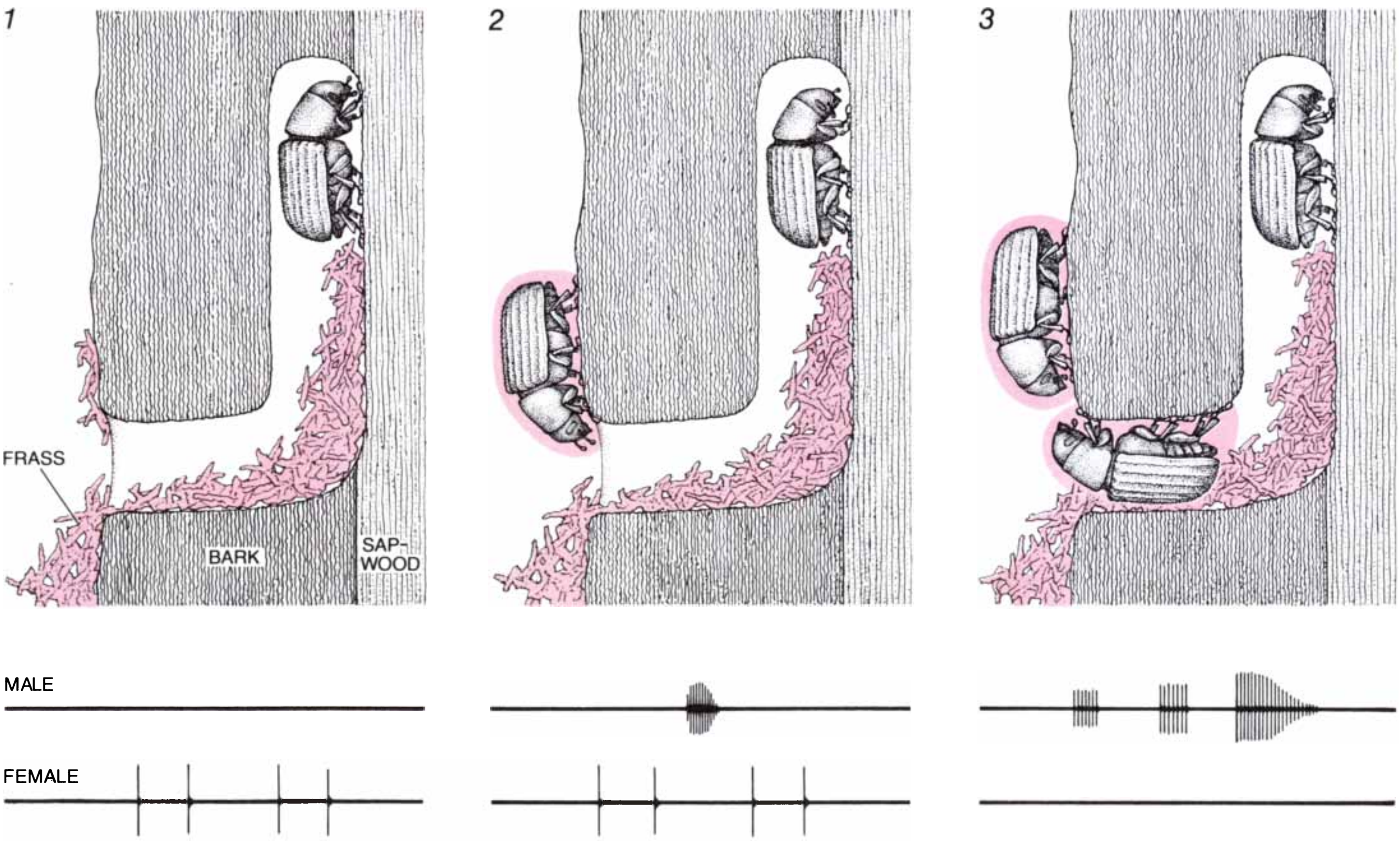
The change from the attractant chirp to the rivalry chirp that accompanies an increase in the concentration of MCH suggested that the rivalry chirp sounded by fighting males is a response to the MCH they release on making contact. The hypothesis appeared to be a reasonable one, but it immediately raised a question. Since both the male beetle and the female release MCH, how does a male intruder distinguish between another male, which he attacks, and a female, which he courts? When Rudinsky and his colleagues (of whom I was now one) observed the relations between beetles in the gallery, an answer began to emerge. In the course of the observations it became apparent that in the Douglas-fir beetle there is an interesting connection between aggression and courtship.

Tape recordings of the sounds emitted by male and female beetles were made beginning at the moment the male started to dig in the frass at the gallery entrance. For the first few minutes the male gave the attractant chirp. Soon after he found the entrance to the gallery and burrowed inside, however, the attractant chirp stopped. At the time acoustic signaling in bark beetles was not well understood. It was hypothesized, however, that when the male entered the gallery, he would give a distinctive chirp to accompany the courtship. Surprisingly, the male beetle emitted the rivalry chirp instead.

To observe the interaction in greater detail a bark sandwich was constructed consisting of a square of fresh Douglas-fir bark clamped firmly between two sheets of heavy Plexiglas. A female beetle was introduced into the sandwich through a hole in the Plexiglas and the apparatus was covered with black cloth to satisfy the female's preference for darkness.

Most of the females adjusted readily to such conditions. They turned their back to the inner Plexiglas surface as they would to the sapwood and began to tunnel through the phloem. In 12 hours the female was ready to entertain a male, and the two beetles interacted in an apparently normal way under low illumination. By means of a microphone we were able to hear and record the sounds as we watched the insects.

As had been observed earlier, the male first sounded the attractant chirp and then switched to the rivalry chirp. The change in the acoustic signal came not precisely when the male made contact with the female but soon afterward. Immediately after the rivalry chirp began the male started to jostle the female. (Such jostling as part of courtship had been noted in other beetle species.) The female responded to the jostling with



ACOUSTIC AND CHEMICAL SIGNALS jointly regulate the interactions between beetles. The pheromone MCH (*color*) has a role in several of the most significant interactions, and the release of the pheromone is closely related to the acoustic signals shown in the lower panels. When the female bores the egg gallery, she releases small amounts of MCH with other attractants in her fecal pellets, which are mixed with the frass, or bark shavings (*1*). She emits clicks as she tunnels. The bouquet of attractants draws a flying male (*2*). In response to the clicks of the female and the low concentration of MCH the male emits the attractant chirp and releases large quantities of MCH. A second male arrives and struggles with the first for possession of the gallery (*3*). On contact both males release more of the pher-

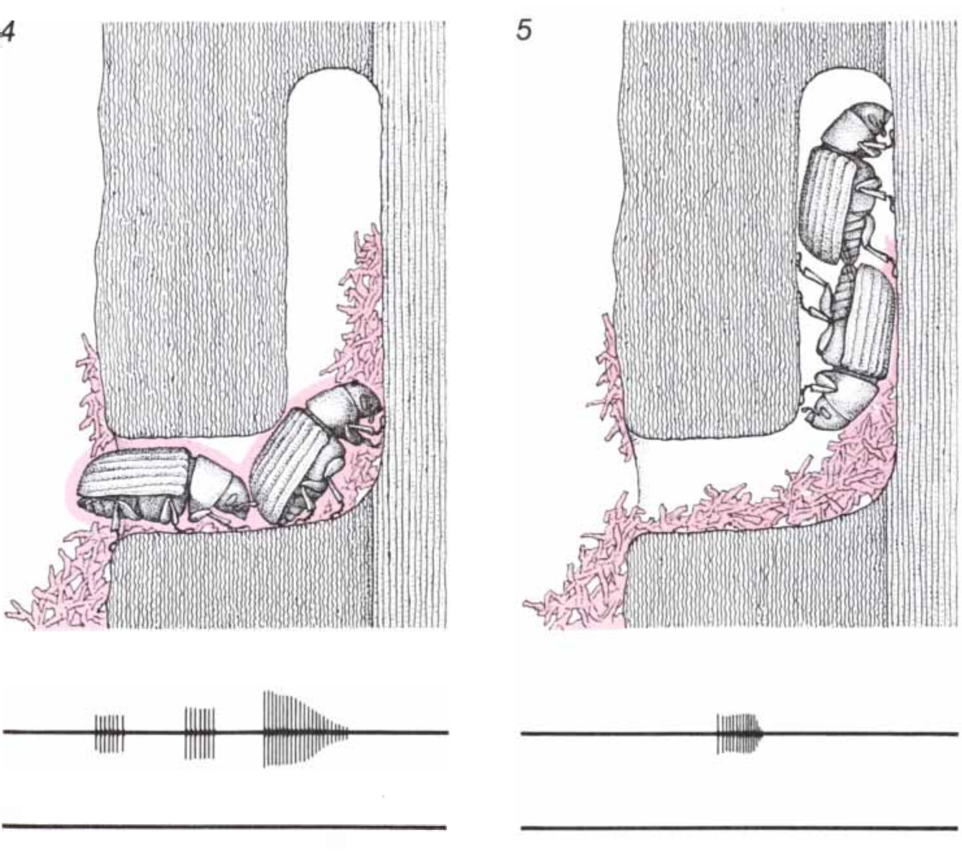
frequent clicks and also wedged herself into the tunnel near the entrance, where she pushed against the male.

After much observation of the beetles in the bark-sandwich apparatus it became clear that relations between the courting beetles are not initially friendly. When a male beetle was accidentally paired with an injured female, he dismembered her and pushed the remains out through the entrance hole; soon afterward he abandoned the gallery altogether. If the female was uninjured, however, the male appeared to become accustomed to her after about an hour of jostling and biting. He began to gather up the frass the female had cut from the head of the gallery and to push it to the entrance of the tunnel, where it was cast out onto the surface of the bark. The task required the male to breathe the fresh air outside the gallery. On returning to the atmosphere of the tunnel, which was saturated with pheromones, he renewed his attack.

Gradually the attacks became briefer, and ultimately they stopped. The male initiated a gentler courtship by stroking the wing covers of the female with his forelegs. His chirps also changed, becoming shorter and simpler and beginning to resemble the attractant chirps sounded at the gallery entrance. The female responded quickly to this gentle courting, and the pair generally copulated within a few minutes.

It soon became evident that in the aggressive courtship as well as in the all-out fighting between males a role was being played by MCH. A tape recording was made of a female clicking in response to a surgically silenced male. The tape was played to male beetles in the collection chamber, and large quantities of MCH were extracted from the air passing over the tubes where the males were kept.

The fact that the males in the tubes released MCH in response to the recorded clicks suggested that when the male outside the gallery entrance hears the clicking of the female within, he releases a large quantity of MCH. This conclusion made it possible to reinterpret the aggression shown by the male in courtship. In both fighting and courtship the interrupted chirp of the male is emitted in response to the release of MCH. In both instances the interrupted chirp is associated with aggressive behavior. Therefore it could be that MCH is the chief stimulus for aggression as well



omone and emit the rivalry chirp. When they fight, the early arrival usually wins. Having driven off his rival, the male begins to court the female (*4*). The first stage of courtship is aggressive: the male releases MCH and emits the rivalry chirp. He jostles and bites the female, who defends herself by blocking the entrance to the tunnel with her heavily armored posterior. After about an hour of jostling the male begins a gentler courtship. His acoustic signal changes to the courtship chirp. Copulation generally takes place a few minutes after the gentle courtship begins (*5*).

as serving to attract flying insects to the tree or to prevent them from being attracted.

Apparently male beetles always release MCH when they come in contact with another beetle, whether it is a male or a female. Indeed, if the other beetle is a female, the pheromone is released even before there is physical contact as a result of the female's clicks. In the case of contact between males the release of the pheromone leads to sustained hostilities, but in the case of contact with a female the male ultimately becomes accustomed to her and other patterns of behavior take over.

It may seem strange that the male beetle's approach to the female is at first so violent, but the aggression could confer a considerable genetic advantage on the male in his attempt to reproduce. The male Douglas-fir beetle is monogamous. In removing frass from the gallery entrance and defending the entrance against intruders he makes a considerable investment of time and energy. It is not in his interest to make such an investment in an unhealthy female.

The vigorous courtship appears to serve as a test of the female's maternal qualities: to survive the courtship she must be robust and therefore is likely to be fecund. A healthy female is well equipped to defend herself by blocking the male with her heavily armored posterior. The pushing and shoving of the initial courtship is actually an excellent test of the genetic fitness of both partners. Small, weak males were sometimes observed to retreat from the gallery during courtship, lose their hold and fall off the tree.

Furthermore, the release of MCH in the mating process is of benefit even to the males that are driven from the occupied gallery. The odds of ousting an entrenched male are small, and so it is advantageous to a male flying by to be deterred from expending effort in an attempt to drive out the current male occupant. The release of MCH by the mating pair serves this purpose admirably. It is also in the interest of the courting male not to waste time fighting with latecomers, and the release of MCH is beneficial to the male that arrives first.

By helping to regulate the density of a population of beetles on the Douglas fir MCH is also beneficial to individual female beetles. In order to overwhelm the chemical defenses of a standing tree the mass attack is necessary. Overcrowding, however, can result in the loss of much of the female's brood; the phloem is rapidly consumed and many larvae starve.

Such overcrowding is prevented by a combination of acoustic and chemical signals. The clicking of the female results in the regular spacing of the galleries. If new females were continually attracted to the tree, however, the galleries would become too crowded for optimum reproduction even though they are evenly spaced. The release of MCH by increasing numbers of mating pairs causes incoming beetles to turn aside to the more sparsely colonized parts of the tree or to adjacent trees, which is beneficial to both the sender of the signal and the receiver.

The functions of the pheromone MCH in the life of the Douglas-fir beetle provide an excellent example of the concept of pheromonal parsimony, which has been advanced by M. S. Blum of the University of Georgia. Pheromonal parsimony implies that the events in the life of an organism that communicates by chemical substances will be regulated by as few substances as possible. In the case of the Douglas-fir beetle the parsimony is quite intense: a single chemical substance appears to play a role in almost every significant interaction between adult beetles.

The understanding that has been gained of the roles of MCH could form the basis of attempts to limit the beetle population in the timber-growing regions of the West. Douglas-fir seedlings need direct sunlight, and the trees are typically harvested in solid blocks called clear cuts. If the aggregation pheromone were distributed on a stand of trees that was scheduled to be harvested in the near future, flying beetles would be attracted in large numbers. If the trees were cut within a year, the beetle broods would be destroyed, lowering the density of beetles in the nearby stands of timber.

MCH could also serve in a strategy based on masking the attraction. Douglas-fir beetle populations can increase to epidemic size by breeding in trees blown down in winter storms. The survival rate of the beetles in the wind-thrown trees is high because the damaged timber has no chemical defenses. Treating such trees with MCH at a high concentration would make them unattractive to the flying population and thereby prevent the buildup of beetles.

Knowledge of the communications among Douglas-fir beetles could clearly be of considerable economic significance, particularly in the Western states. The insect would be worth studying, however, for its own sake. The beetles show in a simple form many types of behavior that are present in vertebrate animals, including territoriality, the formation of groups, fighting between males, extended courtship and cooperation between the male and the female. After two decades the acoustic and chemical signals by which such events are coordinated are beginning to be understood. In refining the knowledge of this system of communication additional light will be shed on these fundamental biological processes.

The Structure and Evolution of Interstellar Grains

The particles of cosmic dust turn out to have an elaborate core-and-mantle construction. In the organic mantle there is evidence of complex, and even violent, chemical processes

by J. Mayo Greenberg

The space between the stars is filled with matter. Most of it is hydrogen and helium, which under interstellar conditions cannot form solid bodies; even at three degrees Kelvin the universe is simply too hot for them to condense. Yet there are solids nonetheless: the tiny frozen particles called interstellar grains. The grains form out of heavier chemical elements synthesized by thermonuclear fusion in stars and supernovas. The most abundant of these elements are oxygen, carbon and nitrogen, known collectively as the organics; next in abundance are magnesium, silicon and iron. The interstellar grains consist of these six condensable elements, along with the hydrogen they capture.

As in other branches of astronomy, the study of interstellar grains is hampered by the inaccessibility of the material under study. No specimens have been gathered for laboratory examination. The one direct source of information is the electromagnetic radiation reaching the earth from stars after it has passed through regions of the sky containing interstellar grains. By noting the wavelengths scattered and absorbed by the grains it is possible to make inferences about their physical properties and chemical composition. Of late another method of study has provided valuable insight: laboratory experiments have simulated the interactions of gases, solids and radiation in interstellar space. The aim is to create substances that could plausibly account for the astronomical observations.

From both the astronomical and the experimental work it has emerged that interstellar grains have a remarkable complexity. They are certainly not mere inert and amorphous lumps of cosmic dust. It appears that a typical grain has a distinctive internal structure, with a core made up chiefly of silicates (rocklike material) and a mantle of more volatile organics. The mantle of the grain, where the organic material accretes, is the site of elaborate chemical processes, perhaps including the occasional detonation of unstable components of the mixture. The grains even have an interesting life cycle. They are born as silicate "seedlings" ejected from old stars; after an extensive physical and chemical evolution they end by being taken up into newly forming stars.

In spite of the presence of gas and grains, interstellar space is a much better vacuum than any created on the earth. The average density of interstellar matter in the Milky Way is one hydrogen atom per cubic centimeter. The distribution of the matter, however, is far from uniform. On a grand scale the gas in a spiral galaxy such as the Milky Way is concentrated in the central plane of the galactic disk. It seems to be particularly dense along the inner edges of spiral arms. On a local scale too the gas has an uneven distribution: much of it is aggregated in clouds.

Two types of clouds are distinguished. Diffuse clouds are regions of low density in which hydrogen and other elements are present only as isolated atoms. The density may be less than 20 atoms per cubic centimeter. Molecular clouds are regions of greater density in which most of the hydrogen atoms have combined in pairs to form diatomic hydrogen molecules (H_2). More complex molecules are found as well. In a molecular cloud the density may be as great as a million atoms per cubic centimeter. Even the densest molecular clouds are extremely tenuous compared with the earth. Still, the mass of the interstellar gas in the Milky Way is equal to about 10 percent of the mass of the stars in the galaxy.

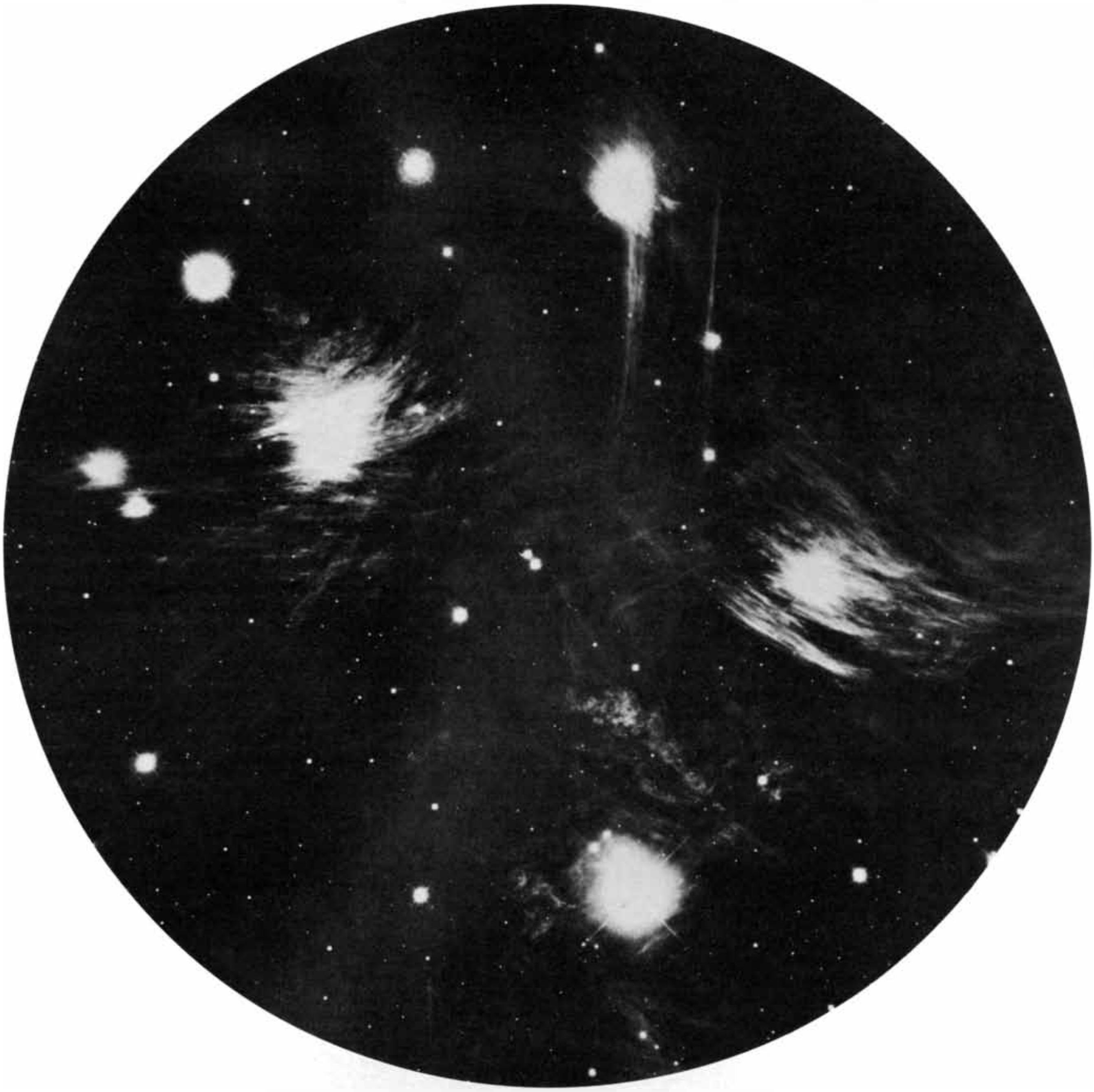
The distribution of interstellar grains seems to match that of the gas. What reveals the grains, however, is the way they scatter starlight. Fundamentally, the interaction of particles with light depends on the size of the particles and on the wavelength of the light. Consider particles of chalk dust. They are larger than any wavelength of visible light, and so they scatter all wavelengths equally. Light passing through a suspension of chalk dust is dimmed, therefore, but its color is not changed. In contrast, particles comparable in size to a given wavelength scatter that wavelength most efficiently. For example, particles whose size is somewhat smaller than a typical wavelength of visible light scatter blue light more than red, thereby removing that part of the spectrum from the light reaching an observer.

Starlight passing through the interstellar medium is reddened, then, by a pattern of "extinction" due to interstellar grains. The pattern has been measured over a range that extends from the long wavelengths of the far infrared to the short ones of the ultraviolet. At first the extinction tends smoothly upward: as the wavelength decreases from the infrared through the visible range and into the near ultraviolet, the amount of radiation removed by scattering increases steadily. Then the curve becomes steeper, reaching a peak at a wavelength of about 2,200 angstrom units. Next it returns to a local minimum at about 1,700 angstroms. Then it begins to increase again in the far ultraviolet.

The interpretation of the pattern has been a source of controversy. Nevertheless, a detailed study of the pattern recorded by the International Ultraviolet Explorer satellite has convinced Grzegorz Chlewicki of the University of Leiden and me that interstellar grains fall into three distinct populations. The particles responsible for the 2,200-angstrom peak in the pattern of extinction must have a radius of less than a millionth of a centimeter. It is thought that they are carbon particles—something similar to graphite, perhaps. The particles responsible for the extinction in the far ultraviolet must also be quite small. The particles responsible for the extinction in the visible range and in the infrared must be at least 10 times as large: roughly a hundred-thousandth of a centimeter in radius, or the size of the particles in cigarette smoke. The only condensable elements sufficiently abundant in interstellar space to make these largest particles are the organics.

By terrestrial standards the largest particles are extremely sparse. One would have to search a cube of interstellar space whose side is the length of a football field to find just one such grain, on the average. Nevertheless, starlight passing through a molecular cloud of moderate size and density could easily be diminished by a factor of 100,000 because of scattering (and also absorption) by the grains. If the solar system were to pass through such a cloud, there would be an age of the earth in which stars would not be visible. One would see only the planets. Curiously, however, the sky would not be dark. It would be bright because of sunlight scattered by grains.

Perhaps the earliest suspicion that interstellar grains might be condensates in space arose in 1935 in the mind



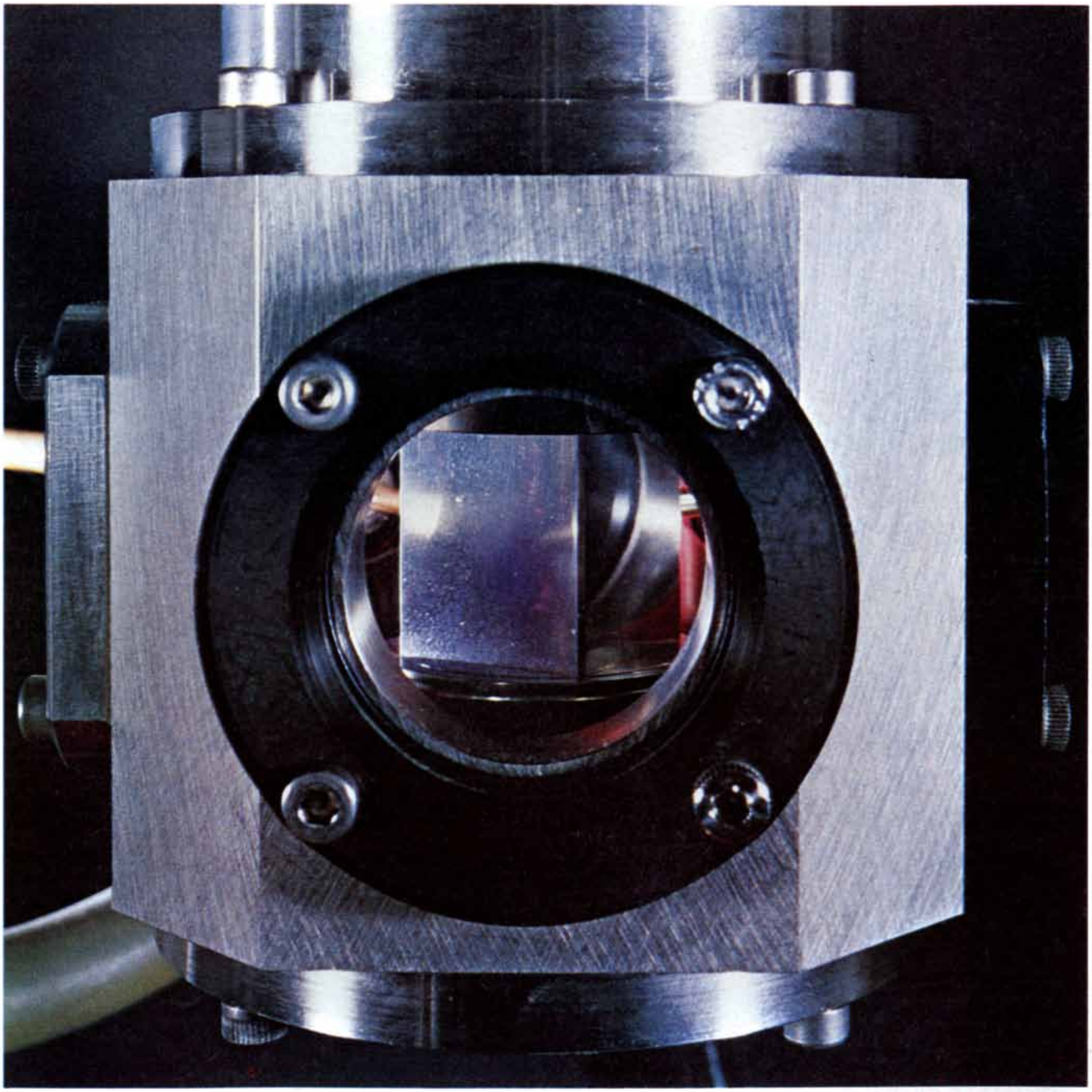
INTERSTELLAR GRAINS in a meshwork of streaming clouds consisting of grains and gaseous matter are revealed in this photograph of the Pleiades, a star cluster some 400 light-years from the solar system in the constellation Taurus. The grains make the clouds visible by reflecting the light of the stars. The bright patch at the bottom is the Merope cloud; at a density of a thousand atoms per cubic centimeter it qualifies as one of the denser clouds in the Milky Way. The star Merope is passing through the cloud at a speed of approximately 30 kilometers per second; thus the star will cease to illuminate the cloud, and its content of grains and gaseous matter will disappear from view, in a million years. The photograph was made with the four-meter telescope at the Kitt Peak National Observatory.

of the Swedish astronomer Bertil Lindblad. Then in 1949 the Dutch astronomer H. C. van de Hulst proposed that the condensates might be ices. There was a gap in the argument: at the low pressure of interstellar space ices could not condense except onto preexisting nucleation sites.

In the early 1970's it was established that small silicate particles surround the large, cool stars called *M* giants and supergiants. Further investigation suggested that the particles condense in the atmosphere of such stars and then are propelled into space, probably by the pressure of the radiation the stars emit. Soon the silicate particles are far enough from the nearest stars to cool to about 10 degrees K. They are then the seedlings needed for the growth of interstellar grains.

Ultimately the seedlings are caught up in a cloud that has an appreciable density of gaseous atoms and molecules. The latter stick to the seedlings and freeze, gradually forming a mantle of ices. One can attempt to predict the mantle's composition. Take the most abundant condensable elements—oxygen, carbon and nitrogen—and suppose that on the surface of a silicate core they combine with hydrogen atoms. The result is mainly ices of water (H_2O), methane (CH_4) and ammonia (NH_3).

The water ice is intriguing. If there is much of it in interstellar space, one ought to be able to detect it. In particular, an astronomer in the 1960's could well have expected that improved in-



LABORATORY SIMULATION of early stages in the growth of interstellar grains was done in an experimental chamber in the author's laboratory at the University of Leiden. A mixture of water (H_2O), methane (CH_4), ammonia (NH_3) and other simple molecules was introduced into the chamber; the elements in these gases represent the combining of oxygen, carbon and nitrogen atoms made in stars with the hydrogen atoms already present in interstellar space. The mixture was allowed to accrete on the surface of a "cold finger" cooled to a temperature of 10 degrees Kelvin. A high vacuum was maintained. Meanwhile the chamber was bathed in ultraviolet radiation. The blue color of the material on the cold finger is due to the creation of formyl radicals (HCO) under the influence of the radiation.

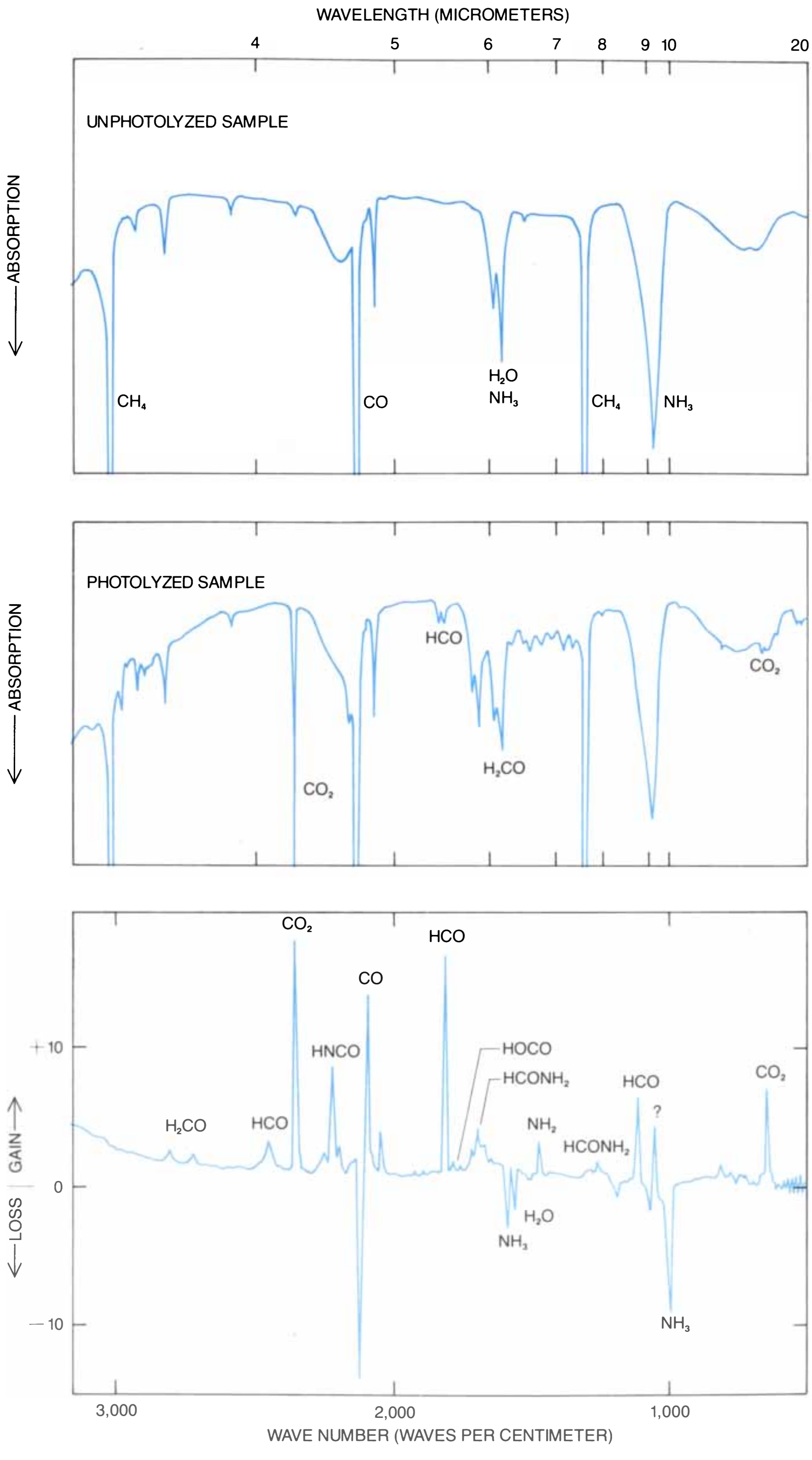
frared detection techniques would soon make it possible to observe the absorption of infrared radiation at a wavelength of about three micrometers. The absorption stimulates the vibration of an O–H bond in water ice. The initial results, available in 1968, were disappointingly negative. A possible explanation was photolysis: the breakup of H_2O molecules by ultraviolet radiation impinging on interstellar grains.

At about the time water ice was being searched for unsuccessfully, the detection of ammonia and formaldehyde (H_2CO) in interstellar clouds was proving that the chemistry of space is much more complex than had been imagined; hence chemists and astrophysicists began to search for mechanisms that might facilitate the interactions of molecules and atoms in space. The search ignored a connection between the formation of complex molecules and the absence of water ice. If water molecules could be broken apart in an interstellar grain, so could other molecules. A sequence of recombinations in the grain could then create large molecules from small ones.

Suppose a grain mantle consists at first of a frozen mixture of molecules such as water, methane and ammonia (a mixture I have called dirty ice), and suppose the grain has a radius of .12 micrometer, or about 10^{-5} centimeter. It turns out that the flux of ultraviolet photons (the quanta of electromagnetic radiation) in interstellar space is sufficient to break every molecular bond in the mantle in a period of tens or hundreds of years. An interstellar cloud has a lifetime of between a million and 100 million years, and so the mantle has no chance of remaining chemically static.

What can happen in the mantle as a result of ultraviolet photolysis is rather complex. Ultraviolet photons may break up the molecules in the mantle, leaving radicals such as OH and NH_2 frozen in place. The radicals may recombine to reconstitute the original molecules or may form new molecular species. Alternatively, the radicals may remain in place without reacting. At some stage the mantle must consist of a frozen mélange of molecules and radicals of varying complexity—a mélange that may well have a bearing on the fact that astronomers have now detected more than 60 kinds of molecules in interstellar space.

A radical is an incomplete molecule that includes an unpaired electron, and so it is highly reactive. Thus when radicals come in contact with one another they tend to combine quite readily, releasing a significant amount of energy: on the order of four or five electron volts. Suppose a thousandth of the stable molecules in the mantle of an interstellar grain were to form all at once by the recombination of radicals. The energy released would be sufficient to raise



ABSORPTION OF INFRARED RADIATION by the material on the cold finger reveals its changing composition as ultraviolet radiation reworks the mixture. The top spectrum shows the infrared absorption of a mixture of carbon monoxide, ammonia, water and methane. The mixture has not been irradiated; the peaks are due to the starting molecules alone. Each peak represents the absorption of a particular wavelength of infrared radiation to stimulate the stretching, bending or rocking of a particular type of molecule. The middle spectrum shows the infrared absorption of the mixture after irradiation. New molecules have formed; notable among them are carbon dioxide, formaldehyde (H_2CO) and the formyl radical (HCO). A number of unlabeled peaks indicate still other newly formed molecules that have yet to be identified. The bottom curve plots the ratio of the two spectra above it. Molecules depleted by the irradiation show downward peaks; molecules produced by the irradiation show upward peaks.

the temperature of the grain by at least 20 degrees. A triggering event in an interstellar grain could therefore lead to a chain reaction in which the heat generated by the recombination of radicals frees other frozen radicals, enabling them to diffuse through the solid mantle and find radicals with which to react. Indeed, the sequence could cause an explosion in the grain. It is only because the mean temperature in a grain is as low as 10 degrees K. that radicals are ordinarily prevented from diffusing and starting a chain reaction.

The description above is a simplified account of what must go on in an interstellar grain. A more complete account would doubtless require a better understanding of the processes occurring in a low-temperature molecular mixture under ultraviolet irradiation. A laboratory investigation therefore seems to be called for.

The earliest efforts in this direction were made by Carl Sagan and B. N. Khare at Cornell University and by Andrew J. Yencha and me at the State University of New York at Albany. Later I accepted a position at Leiden, and there, with the establishment of the astrophysical laboratory in 1975, my colleagues (principally Louis Allamandola and Fred Baas) and I were able for the first time to simulate in a chamber the conditions in space that govern the evolution of interstellar grains.

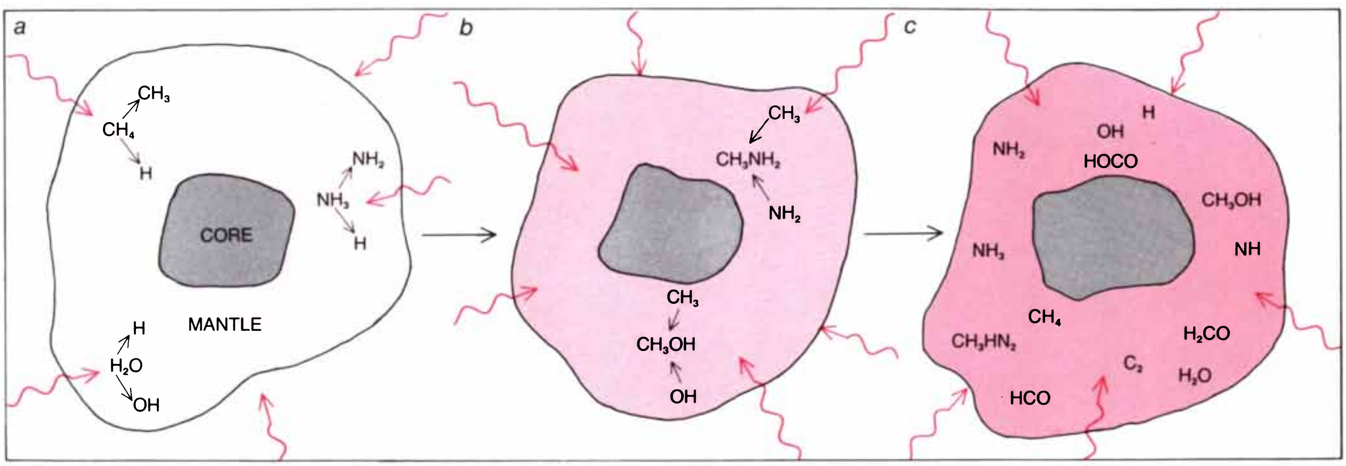
The key elements in the simulation are low temperature and ultraviolet radiation. The low temperature (as low as 10 degrees K.) is achieved by a liquid-helium cryostat that includes a "cold finger," which can be an aluminum block or a transparent window mounted on a metal ring. The ultraviolet radiation is introduced through a port in the chamber. Various gases enter the chamber through a tube. The pressure in the chamber can be as low as 10^{-8} torr. (The pressure in interstellar space is 10^{-19} torr or even less.) Typically the gases are mixtures of simple volatile molecules: CH_4, CO, H_2O, CO_2, NH_3, N_2 and O_2. The gases condense on the cold finger, which acts, therefore, like the core of an interstellar grain. Meanwhile the condensate is being irradiated.

The most important difference between the chamber and interstellar space is the time scale of the photolysis. One hour of irradiation in the laboratory is equivalent to 1,000 years of irradiation in a diffuse interstellar cloud. During the experiment we can direct through a second port the beam of an infrared spectrometer that measures the infrared absorptions of the sample at wavelengths between 2.5 and 25 micrometers. This is the "fingerprint region" in which molecules can be identified by their stretching, bending and rocking modes of oscillation in a solid. Other sensors measure pressure, luminescence, the masses of gaseous molecules and the absorption of visible light.

The creation of new molecules and radicals in any initial mixture is readily detected from changes in the infrared absorption as the experiment proceeds. Thus if we begin with a mixture of CO, NH_3, H_2O and CH_4, we find almost immediately that CO_2 shows up, along with formaldehyde and a significant amount of the formyl radical (HCO). Many additional peaks in the absorption spectrum have not yet been identified but surely indicate the presence of still other newly made molecules.

In a rapidly developing field, observation and theory tend to play leapfrog. Hence not long after the failure to detect water ice in interstellar space and somewhat before the successful simulation of interstellar conditions in the laboratory, a strong astronomical absorption at a wavelength of 3.1 micrometers was observed in the infrared spectrum of what has come to be known as the Becklin-Neugebauer object, a source of infrared radiation in the constellation Orion. This was convincing evidence that H_2O exists in grains at least in certain parts of interstellar space. The spectrum also had a broad absorption band at a wavelength of 9.7 micrometers. We attribute it to the silicate core of the grains. The current view is that the Becklin-Neugebauer object is a place where stars are forming. Water ice has now been identified not only in such places but also in molecular clouds.

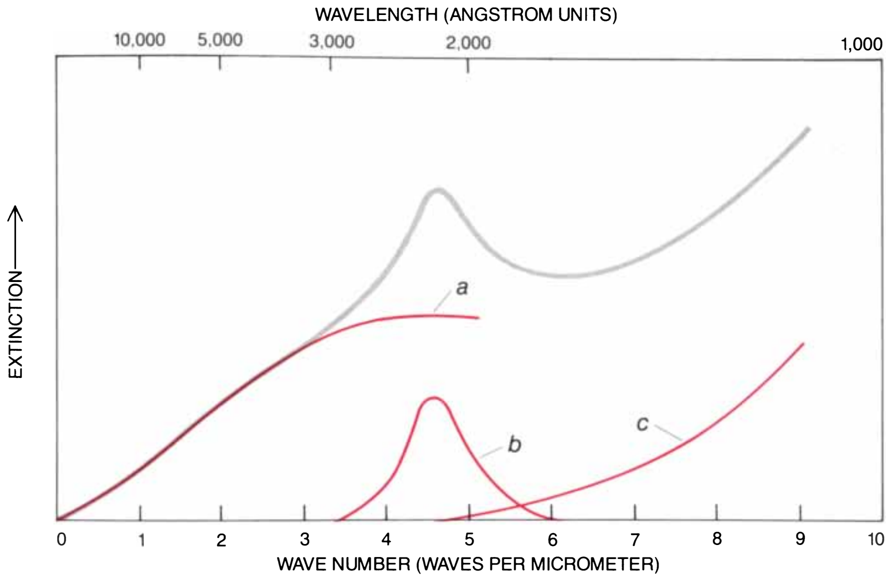
It should be said that the early measurements of astronomical water-ice absorption showed some discrepancies when they were compared with laboratory spectra of pure crystalline water ice. The absorption was displaced in wavelength from the laboratory absorption and also was much broader. Is there something peculiar about the crystalline structure of the water in interstellar grains? At Leiden, Allamandola, Wim Hagen and I decided to find out. We saw immediately that pure water deposited slowly on a cold finger at 10 degrees K. has an infrared absorption that bears a striking resemblance to the astronomical three-micrometer absorption. It is in precisely the right position in the spectrum and has the right width. We also saw the reason. Ice that forms at a temperature of 10 degrees is highly amorphous: its structure is not the regular crystalline array of ordinary ice but rather suggests that the randomly moving molecules of liquid water have been frozen in their tracks. With increasing temperature the ice becomes less amorphous, until, at temperatures greater than about 130 degrees, its crystalline structure becomes quite regular. Even



STRUCTURE OF GRAINS when they initially accrete is inferred from laboratory simulations in which mixtures of water, methane, ammonia and other simple molecules are subjected to ultraviolet irradiation at a temperature of 10 degrees K. Each grain begins as a silicate core that condensed in the atmosphere of a cool giant star. Around this core a mantle of ices forms. Ultraviolet radiation breaks some of the mantle molecules into radicals, or reactive molecular fragments (*a*). The radicals can then recombine in new ways (*b*). Over a longer period the continued ultraviolet irradiation of the grain can give rise to ever more complex mixtures of molecules and radicals (*c*).

a temperature of 80 degrees is warm enough to make the three-micrometer absorption significantly narrower and deeper than it was.

We also found that a mixture of water with some methane and ammonia produces a "wing" on the long-wavelength side of the absorption. We thereby succeeded in simulating a further aspect of the astronomical absorption. Comparisons between astronomical spectra and the spectra of pure and impure ices at various temperatures provide us with the data we need to follow the evolution of grain mantles in interstellar space.



EXTINCTION OF STARLIGHT by interstellar grains results from the selective scattering of certain wavelengths by the grains. (A solid particle scatters light most effectively at wavelengths close to its own diameter.) The overall effect is to make the stars look somewhat redder than they are. The pattern of extinction from the far infrared (*left*) to the far ultraviolet (*right*) is thought to have three components. The rise at the left (*a*) is attributed to particles roughly 10^{-5} centimeter in radius. The peak in the middle, at 2,200 angstrom units (*b*), is attributed to particles 10 times smaller that probably consist of pure carbon, perhaps similar to graphite. The rise at the right (*c*) is attributed to equally small particles, consisting perhaps of silicates.

What do interstellar grains consist of when there is no water ice in them? In an effort to answer the question we have traced the evolution of grains beyond the stages at which they form by accretion, get photolyzed by ultraviolet radiation and are maintained at extremely low temperature in interstellar space. To be sure, the period of low-temperature inactivity constitutes most of the lifetime of a grain. Still, there must be many situations that lead to the heating of the grain. An obvious example is the formation of new stars in a region of space rich in interstellar grains.

Our strategy is as follows. During the deposition of gases on the cold finger and the simultaneous ultraviolet irradiation of the growing mantle layer we maintain a steady low temperature of between 10 and 15 degrees. The layer gets thicker. For sufficiently low rates of deposition the layer can be amorphous, that is, glassy, and develop a brilliant blue color, which results from an increasing concentration of formyl radicals. If we stop the deposition, turn off the ultraviolet lamp and maintain a constant temperature, no further changes are observed. The mantle is quite stable for periods of at least a week.

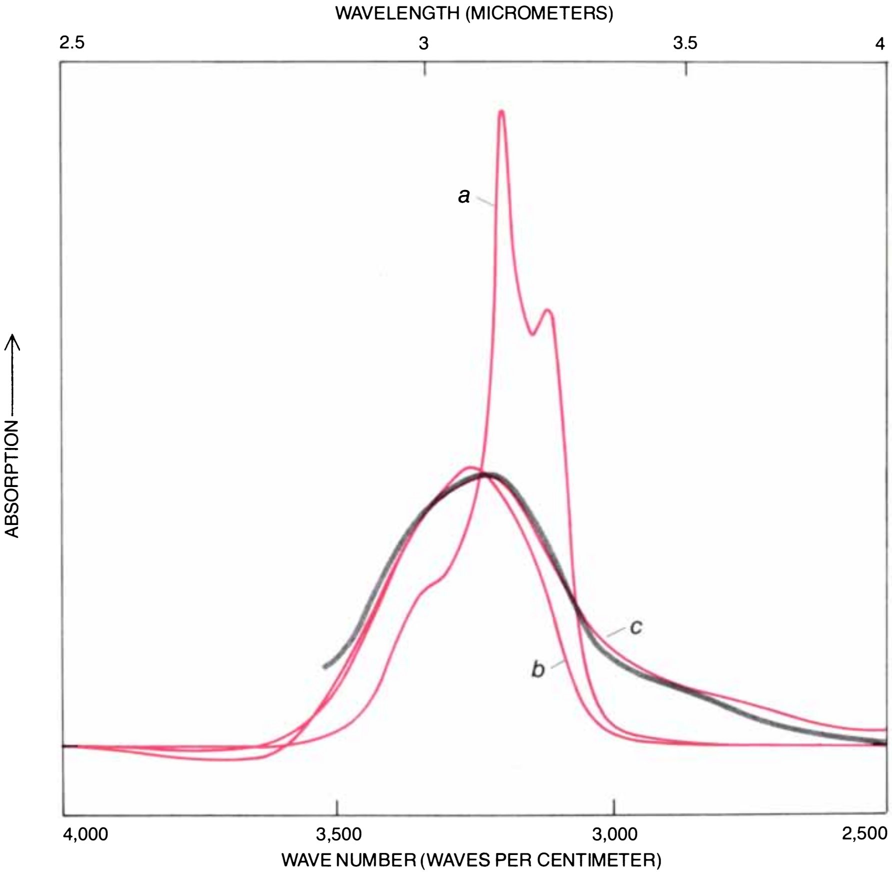
On the other hand, if we allow the temperature to rise slowly, the mantle emits a bluish green light. Working in our laboratory, Leo van Ijzendoorn has attributed the light to the release of energy by pairs of formyl radicals as they combine to form glyoxal molecules, that is, two HCO radicals connected at their carbon molecules. If carbon monoxide is present in the mantle, the CO molecules combine with hydrogen atoms to augment the concentration of HCO. The next step in the process is the formation of formaldehyde (H_2CO) as well as glyoxal.

The bluish green light represents only a small part of the energy released when the radicals combine. The rest goes into the heating of the sample. If the heating is sufficiently rapid, so that large numbers of radicals are freed from their sites, the sample can explode. Some aspects of the explosions have been revealed by motion pictures of various samples made by Louis d'Hendecourt. The main explosion takes place in a part of the mantle where the temperature has risen to about 25 degrees. There the mantle material is blown away from the cold finger, leaving the surface bare. Elsewhere material sticks, and one continues to see small flashes, both local and diffuse, showing that radicals may survive until the sample reaches a temperature as high as 100 degrees. A surprising observation is that ultraviolet photons create radicals in the mantle with an efficiency as great as 10 percent, at least until the mantle begins to become saturated with radicals. In other words, as few as 10 photons are enough to bring about a net increase of one radical in the mixture.

When a well-irradiated, well-photolyzed sample is warmed sufficiently slowly to prevent runaway reactions and the explosions they cause, we are left with a substantial yellowish residue that survives indefinitely even at room temperature (295 degrees K.). We think the residue resembles the mixture of complex organic molecules synthesized by the photolysis of grains in interstellar space. Indeed, our work resembles in a way the work of Stanley L. Miller and Harold C. Urey, who simulated the production of organic molecules in the atmosphere of the primitive earth by applying electric discharges to gaseous mixtures of water, methane, ammonia and other molecules.

The difference between the flux of ultraviolet photons in our laboratory and the flux in interstellar space leads to an estimate of the rate at which photolysis in space converts simple volatile molecules into complex organic ones. Between 1 and 10 percent of the simple molecules in an interstellar cloud are transformed in 10 million years. Here, then, is an explanation for the interstellar grains that lack water ice. The ice, along with other small molecules, has been converted into more complex substances.

The analysis and chemical identification of our laboratory-created residue—we call it yellow stuff—has been hampered by the relatively small quantity made in each experiment. Nevertheless, we note that by astronomical standards the residue is quite nonvolatile and consequently can survive much harsher conditions than an icy mantle could. For example, water ice evaporates in space at about 90 degrees K., whereas the yellow stuff does not evaporate at temperatures of less than about 450 degrees. Furthermore, both chemical and physical analyses reveal that the residue is markedly enriched in carbon. Mass spectroscopy of one residue, done by H. J. de Jong at Leiden, showed that carbon is twice as abundant as oxygen. In the interstellar medium (and in our initial mixture of gases) oxygen is twice as abundant as carbon; hence in the yellow stuff the oxygen fraction has been reduced by a factor of four. A systematic study of the chemistry of the yellow stuff is now in progress at Leiden in collaboration with James P. Ferris of the Rensselaer Polytechnic Institute. At



SPECTRUM OF BECKLIN-NEUGEBAUER OBJECT, an infrared source in the constellation Orion, marked the first detection of water in interstellar space. The spectrum itself is shown in gray. It includes a peak at an infrared wavelength of about 3.1 micrometers. The absorption of light at that wavelength stimulates the vibration of an O–H bond in water ice. Three laboratory spectra are shown for comparison. The spectrum of crystalline water ice (*a*) matches the astronomical curve rather poorly: its 3.1-micrometer absorption is far too sharp and narrow. Also the absorption is displaced in wavelength. The spectrum of amorphous water ice that accreted on a cold finger at 10 degrees K. (*b*) matches the curve rather better. The spectrum of water, ammonia and methane in a ratio of six to one to three (*c*) matches best of all. The Becklin-Neugebauer object may be a dense interstellar cloud in which stars are forming.

Leiden, meanwhile, we are making increasingly complicated residues. We are also undertaking the long-term ultraviolet irradiation of residues in order to follow their further evolution under simulated interstellar conditions.

With the support of our laboratory results we are now in a position to place astronomical observations in a theoretical framework and propose a scenario for the evolution of both interstellar grains and the gaseous clouds in which they are found. First consider the clouds. Their overall evolution depends on events in the galaxy. The clouds collide with one another; they interact with stars; on the largest scale they are modified by gravitational and hydrodynamic forces induced as they revolve about the center of the galaxy. Presumably dense clouds coalesce from diffuse ones. Then, in the densest clouds, stars are formed by gravitational collapse. When the stars begin to generate energy by thermonuclear fusion, the leftover cloud material is returned to interstellar space. Often it is ejected by shock waves and winds of gas and particles emitted by newly born stars. Heated and under low pressure, the leftover material expands. The result is a diffuse interstellar cloud. Thus a cycle is closed.

The cycle can be repeated over and over, but each time a star is formed a fraction of the interstellar gas and dust must be consumed. Present estimates are that one or two stars per year are born in the Milky Way; hence one is led to estimate that all the interstellar medium is consumed in about 5×10^9 years (approximately the age of the earth). On the average, then, no interstellar grain survives longer than that. Still, each phase of the evolution of a cloud lasts no longer than some 10^8 years. Thus a grain can have a rich and varied history, passing into and out of dense clouds 25 times or more before it is finally incorporated into a star.

Let us follow a grain through one of its cycles. It starts out in a diffuse cloud. I shall assume it is a grain that has already gone through at least one cycle since its first appearance as a silicate seedling in the atmosphere of an old supergiant star. Thus the grain has a mantle, and since its infrared absorption spectrum shows no sign of H_2O, I assume the mantle consists of yellow stuff. A calculation shows that these core-and-mantle grains (along with the smaller carbon and silicate particles responsible for the extinction of starlight at ultraviolet wavelengths) account for about 20 percent of all the oxygen in the galaxy, along with 70 percent of all the carbon and close to 100 percent of the silicon, magnesium and iron. What remains in gaseous form in the cloud is distinctly different, therefore, from a mixture of the chemical elements in their relative galactic abundances. Observations of diffuse clouds confirm this supposition. The ratio of oxygen to carbon in a diffuse cloud is five to one.

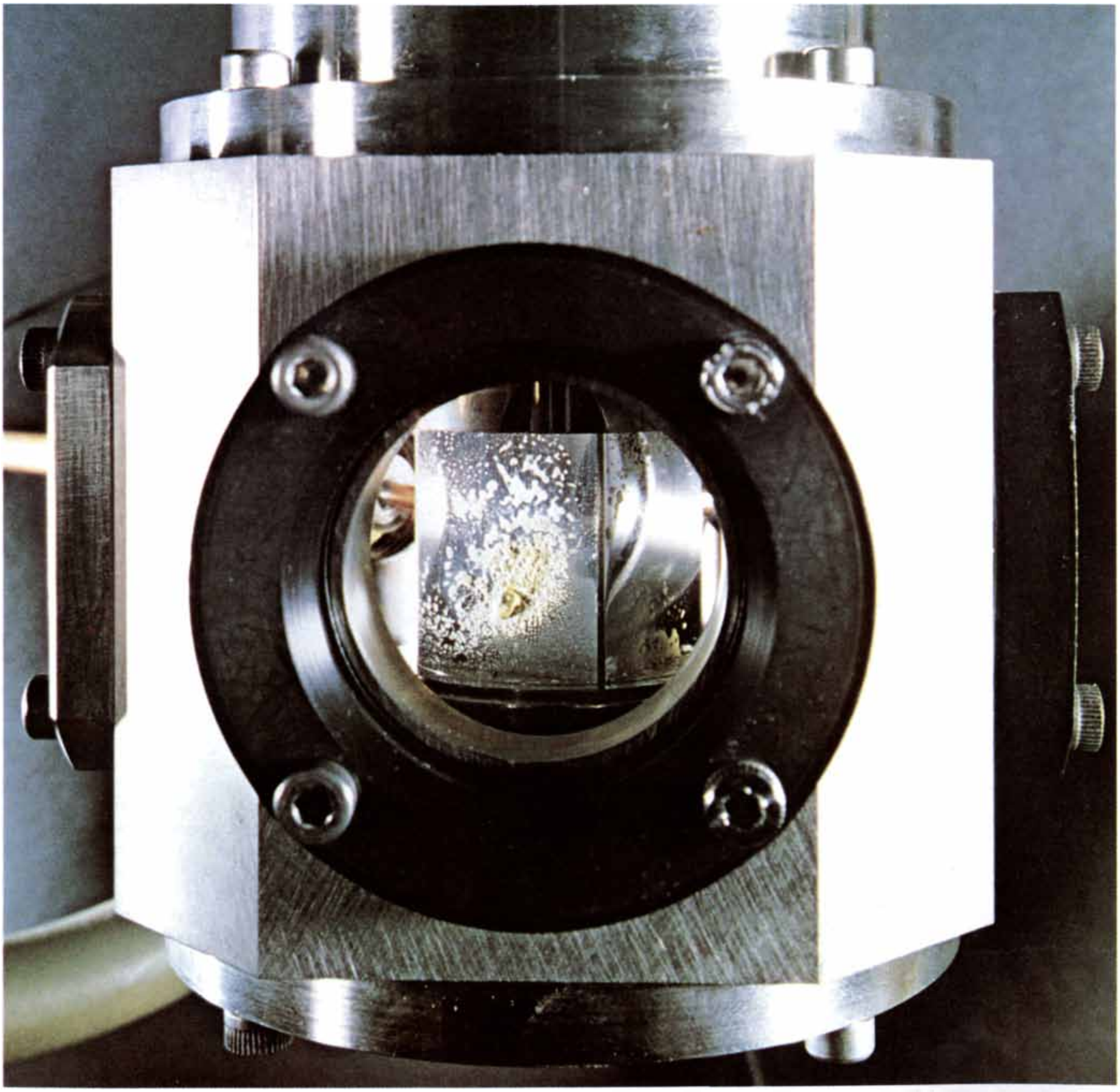
The abundance of gaseous oxygen suggests that when the cloud has become dense enough to allow molecules to form, gaseous water should be abundant. Why is that not the case? Why is the water not observed? Observations of dust grains at infrared wavelengths made by Douglas Whittet and his colleagues at the Preston Polytechnic in Britain show that interstellar grains in ordinary molecular clouds (not necessarily the ones in which stars are forming) exhibit ice-absorption features at three micrometers. Evidently H_2O is being made on core-and-mantle grains. At Leiden we are studying this possibility. In particular, Xander Tielens and d'Hendecourt have formulated a chemical-reaction scheme embracing reactions not only in the gaseous phase but on the surface of grains and also inside them. Already we are led to picture a grain in a molecular cloud as typically having two mantles: an inner mantle of yellow stuff and an outer mantle including a substantial fraction of water.

The increase in the size of an interstellar grain entailed by the growth of an outer mantle should alter the way it extinguishes visible light. Accordingly one expects to find a correlation between the pattern of visual extinction and the strength of the three-micrometer ice-absorption band. In a number of cases astronomical observations bear this out. Moreover, in theoretical calculations made at Leiden by C. E. P. M. van de Bult and me, dust grains in protostellar clouds such as the Becklin-Neugebauer object as well as grains in more tenuous clouds turn out to have as much as 60 percent of their outer mantle in the form of H_2O. Further still, studies by Gerard van de Zwet and Baas give promising support for the presence of H_2CO molecules in the solid phase. All things considered, the existence of the icy outer mantle seems to be rather well supported.

The existence of an outer mantle

leads, however, to a puzzle: What keeps the outer mantle from growing until it exhausts all the condensable gas in a cloud? In particular, what keeps gas molecules from sticking to the mantle, or, if they stick, what removes them? Many suggestions have been made, but in molecular clouds only one mechanism is effective enough to be important. It is the explosion of the grain mantle. The sequence begins when the grain first grows a mantle by capturing atoms and molecules. Throughout the accretion process the grain is bombarded by ultraviolet photons. Thus the mantle accumulates a certain fraction of stored radicals as long as it stays extremely cold. Then comes a triggering event that suddenly raises the temperature of the grain. According to our laboratory simulations, an increase of merely 15 degrees K. is enough to cause a mantle detonation.

A collision of grains at a relative speed of 50 or 100 meters per second turns out to be an excellent trigger. Such a speed is a thousand times greater than the characteristic "thermal" speed of a solid body in a cloud at a temperature of, say, 100 degrees K. Nevertheless, the speed is possible: it can be generated by turbulence in the cloud. (The broadening of features in the spectrum of molecular clouds confirms that the gas in a cloud swirls about at speeds of thousands of meters per second. Doubtless the grains are swept along with the gas; all the same, the slippage must be sufficient to produce speeds between grains on the order of a tenth the turbulent speed.) Moreover, the collisions need not be very frequent in order to maintain an equilibrium between the slow but steady accretion of gas onto grains and the sporadic release of grain material back to the gaseous cloud. The explosion of no more than one grain in 10 in a million years is enough to main-



"YELLOW STUFF" is produced by the slow irradiation of the icy mantle of interstellar grains; here it is shown on the surface of a cold finger in the author's laboratory. The analysis of the material has been hampered by the small quantity made in each experiment. In general, however, yellow stuff is a complex mixture of organic molecules markedly enriched in carbon with respect to the average composition of the interstellar medium. It is notably stable, even at room temperature. Doubtless it can survive harsh conditions in space.

tain the density of molecules observed in the gaseous state.

During its tenure in a molecular cloud the grain does more than serve as an intermediary in the formation of gaseous molecules. In addition its mantle accumulates a complex residue. After all, for each collision or other triggering event that leads a grain to detonate, there are many gentler events, such as a gentle collision, that lead to a self-limiting sequence of reactions and a slow buildup of an ever more complex mantle. During a mean cloud lifetime of 10^7 years a grain probably undergoes some 10 detonations. In the same period it probably undergoes hundreds of noncatastrophic warm-ups. Its chemical composition must therefore be modified considerably.

I come now to the events that occur when local condensations or knots of high density in a molecular cloud provide the conditions needed for the final contraction of matter into a star or a group of stars. At such a time the rate of accretion of gaseous molecules onto interstellar grains may increase to the extent that nothing but hydrogen and helium remain untrapped. Soon some of the augmented grains must be swept up by collapsing gas. They become part of a protostar. Then, when the star commences nuclear fusion, they evaporate. Indeed, the matter inside them is torn apart into atoms. Other grains escape. They too are larger than average. Shortly, however, they are subjected to a variety of destructive and erosional processes. For example, all the volatiles in a grain that is heated by its proximity to a newborn star must evaporate. Still other grains, more distant from the protostars, may preserve their augmented mantle, including volatiles such as H_2O. This would account for the observation that grains detected in the direction of a strong infrared source (presumably a protostar or a very young star) have the highest probability of exhibiting a strong three-micrometer ice-absorption feature.

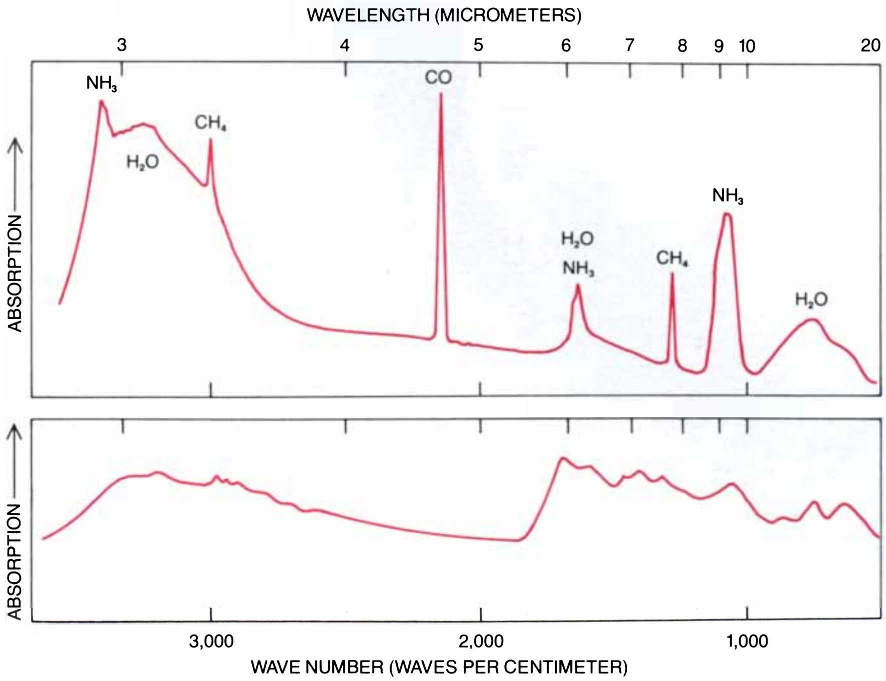
A complex of molecular clouds and the stars that continue to form inside it survives on the order of 10^8 years. At the end of this period the complex emerges from a spiral arm. (It is thought the spiral-arm pattern of the Milky Way rotates as a set of density waves at half the rotational velocity of the matter composing the galaxy. Hence at periodic intervals a given parcel of matter helps to form a spiral arm. Some 10^8 years later it outraces the leading edge of the arm.) The matter is then in an interarm region, where the density is lower, and it tends to dissipate. The grains are in a diffuse cloud once again. Quickly they lose whatever volatile matter may have remained on their surface. In addition they are subjected to a variety of erosional processes. They are eroded, for example, when clouds collide or when supernova explosions generate shock waves. The erosion may gradually reduce the thickness of the mantle of yellow stuff.

Estimates of the rate of erosion have been offered by a number of investigators, but the physics of the processes is poorly known at best. The work of Erwin E. Salpeter and Bruce T. Draine at Cornell does lead one to expect that yellow stuff is destroyed in diffuse clouds at about the rate at which it is made in molecular clouds. Moreover, one can estimate that an interstellar grain spends about half of its time in diffuse clouds and half in molecular clouds. One concludes that a typical grain attains a stable average composition. Thus it is not surprising that the extinction of starlight is much the same in any direction in the diffuse interstellar medium.

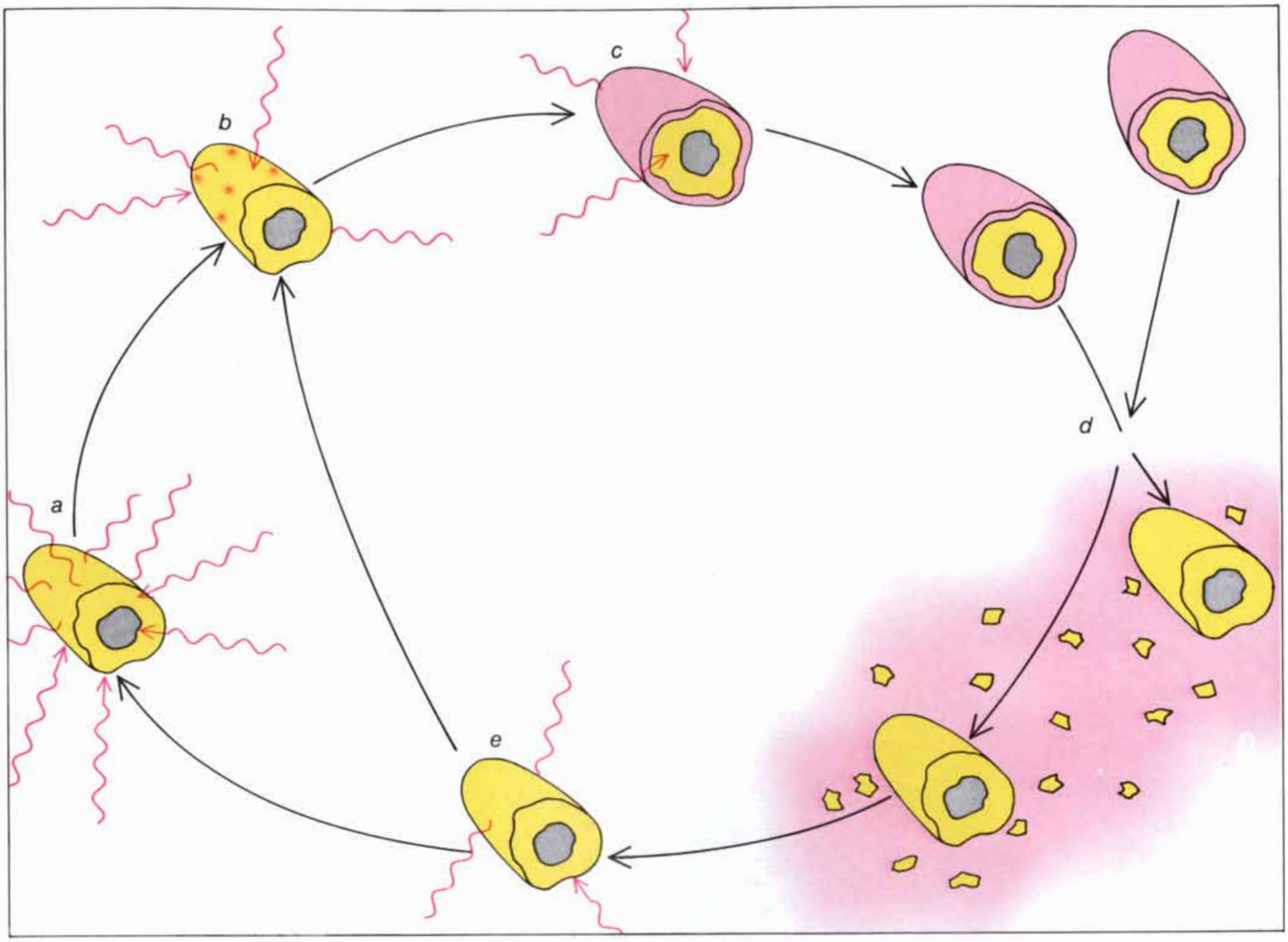
Yellow stuff is clearly an important component of interstellar grains. Indeed, yellow stuff appears to constitute close to 1 percent of all the mass in the Milky Way. It seems safe to say its mass exceeds the mass of all the planets in the galaxy. That makes it all the more vexing that yellow stuff cannot be collected by spacecraft. A vehicle traveling at a speed of one kilometer per second and carrying a sail 100 square meters in area would collect only 10^{-11} gram of the stuff per year in our interstellar neighborhood. Perhaps, however, the sample we seek will be captured when a piece of a comet is retrieved by a spacecraft and brought back to the earth.

Comets consist of interstellar grains. In particular, theoretical studies by Ludwig Biermann of the Max Planck Institute for Physics and Astrophysics in Garching and L. Mestel of the University of Sussex favor the hypothesis that comets formed at much the same time as the planets but that they coalesced directly from the dust grains in a dense interstellar cloud gravitationally bound to the presolar nebula (the cloud from which the solar system condensed). Today comets occupy the Oort cloud, a region containing from 10^{11} to 10^{12} comets in random orbits around the sun at distances equal at most to roughly half the distance to the nearest stars. The comets seen close to the sun have been perturbed from these more distant orbits. One fact is crucial: not only were comets born cold; they have stayed cold throughout the 4.5 billion years that have passed since their birth. The nucleus of a comet is in effect a cold-storage container for presolar interstellar grains. Even comets whose orbit takes them rather close to the heat of the sun must have preserved in large measure their presolar composition.

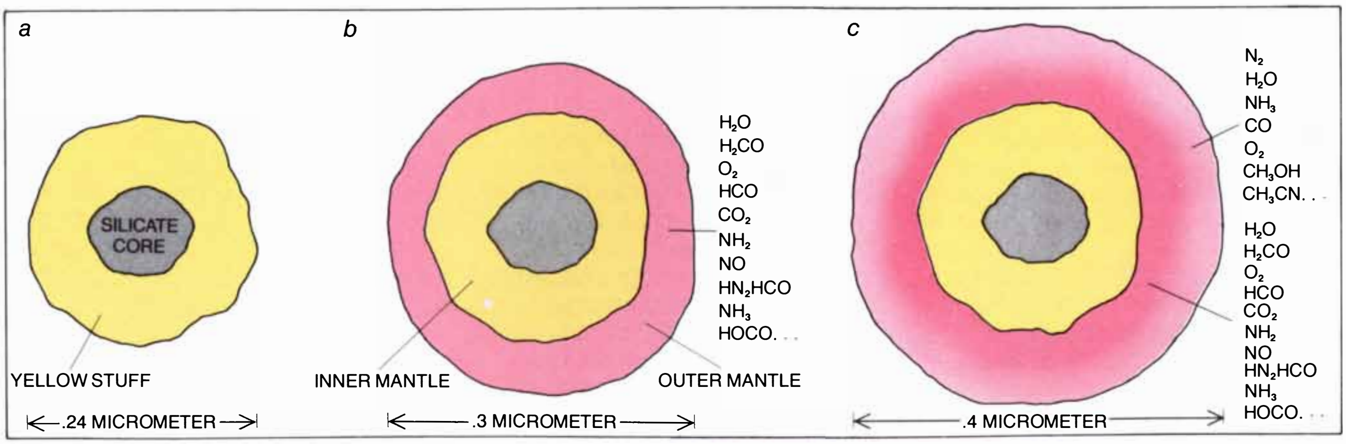
The nucleus of a comet is a solid body no more than a few kilometers in radius. Nothing is known about it directly. Instead, one observes the gas and dust in the head and tail of a comet, that is, the material that evaporates or is otherwise



INFRARED SPECTRUM OF YELLOW STUFF (*lower graph*) **is compared with a spectrum of a mixture containing the same proportions of oxygen, carbon and nitrogen** (*upper graph*). **The latter spectrum includes a prominent water-ice absorption at 3.1 micrometers; the former lacks the water-ice peak. Evidently the oxygen in yellow stuff is bound up in organic molecules to such an extent that none is left to combine with hydrogen, yielding water. The abundance of yellow stuff in mature interstellar grains may explain why the grains show no water.**



LIFE CYCLE OF INTERSTELLAR GRAINS takes them from a diffuse cloud to a dense cloud and then, if they do not become part of a newborn star, to a diffuse cloud once again. In a diffuse cloud the grains start out as silicate particles. They are shown with a mantle of yellow stuff preserved from a previous cycle (*a*). The cloud grows denser, and the grains accrete, at an increasing rate, a layer of ices (*b, c*). Eventually the cloud is dense enough for its gaseous matter to assume a molecular form. Ultraviolet irradiation gives rise to radicals in the icy mantle of the grains; then occasional collisions among the grains heat the mantle sufficiently for the radicals to recombine in large numbers, releasing energy. In some cases the mantle explodes, repopulating the gaseous phase of the cloud (*d*). In the densest parts of the cloud stars form by the gravitational collapse of gas and dust. The heat of the newborn stars evaporates the icy grain mantle. What remains is yellow stuff (*e*). The grain may repeat the cycle within a molecular cloud. Alternatively, the cloud may disperse; either the new stars blow it away or an entire complex of clouds and stars moves out of a spiral arm of the galaxy. Thus the cycle is closed. The arrival of an occasional ultraviolet quantum continues the slow, cool, chemical reworking of the yellow stuff in the mantle of the grain.



GRAINS IN DIFFERENT CLOUDS appear to have different layers, depending on the stage of their life cycle. Grains in a diffuse cloud have only a silicate core and a yellow-stuff mantle (*a*). Grains in a molecular cloud have a silicate core, a yellow-stuff mantle and an additional mantle consisting of icy condensates reworked by ultraviolet irradiation (*b*). Grains in a cloud so dense that stars are about to form have an even more complex pattern (*c*). A rapid accretion of matter has given them an outermost mantle of ices not reworked by irradiation. There has simply not been time. The polarization of the light that passes through interstellar clouds suggests that interstellar grains with mantles are elongated particles rather than spherical ones. When such particles are aligned, they act weakly as a polarizing filter.

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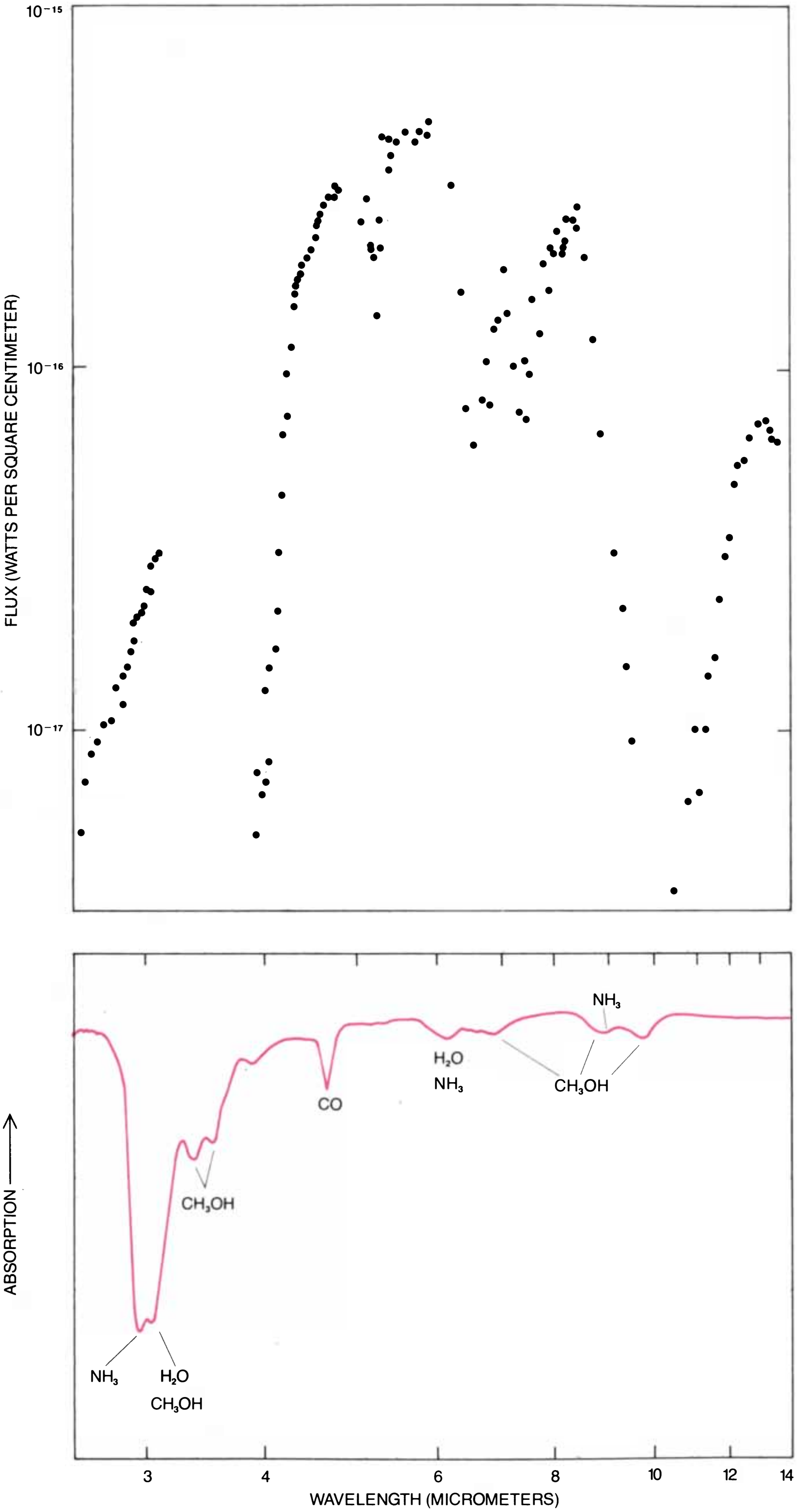
lost from the nucleus when the comet comes close to the sun. Perhaps the single thing least in dispute is the surmise that the nucleus of a comet includes a substantial water-ice fraction. In the 1950's Fred L. Whipple of Harvard University conjectured that a comet is like a dirty snowball. The conjecture I would make is based on the hypothetical composition of interstellar grains evolved to the presolar stage. I think about 30 percent of the volume of the nucleus of a comet is water. About 20 percent would be yellow stuff, about 8 percent silicates, about 3 percent pure carbon and the remaining 40 percent or so would be molecules including CO, CO_2 and H_2CO and radicals such as HCO. In sum, a comet might be a very dirty snowball.

The carbon in such a comet would resemble the carbon in a fully developed population of interstellar grains; hence part of it would be incorporated into volatiles including CO, CO_2 and H_2CO, part would be incorporated into yellow stuff and part would be pure carbon. A pleasing aspect of this three-way distribution is that it accounts for what Armand H. Delsemme of the University of Toledo describes as a comet's "missing carbon." By this he means that the ratio of carbon to oxygen in a comet (deduced from comets' spectra) is distinctly lower than the solar system's ratio. Where could the carbon be hidden? One answer is that the carbon detected in a comet's spectrum arises solely from the comet's reservoir of volatiles, and that almost half of the carbon in the comet is locked in yellow stuff.

Additional evidence that comets consist of interstellar grains has recently been adduced by Michael F. A'Hearn of the University of Maryland at College Park and Paul D. Feldman of Johns Hopkins University. They find that diatomic sulfur molecules (S_2) are present in comets and say that such molecules can have originated only in solid matter bathed by ultraviolet radiation.

Meanwhile comets and the earth have been linked in a dramatic way: it has recently been suggested that a 26-million-year cycle of comet impacts on the earth caused the extinction of species including the dinosaurs. Such impacts must have been frequent when the earth was very young, and comets must then have deposited interstellar grains in great quantity. The grains must have included yellow stuff, that is, complex organic matter, and in this way interstellar grains may well have supplied the chemical environment needed for prebiotic evolution. The laboratory study of interstellar grains not only probes the physics and chemistry of interstellar space but also may provide a link between astronomical observations made today and the reconstruction of events in the early solar system.



SPECTRUM OF AN INFRARED SOURCE designated W33 A (*upper graph*) shows a number of features, notably the absorption of infrared radiation at wavelengths of 3.1, 4.6, 6, 6.8 and 10 micrometers. The source is perhaps a very young star embedded in a molecular cloud. The laboratory spectrum of H_2O, CO, CH_3OH and NH_3 in a mixture of six to three to three to two (*lower graph*) accounts for four of the peaks. Apparently the four at the lower wavelengths are due to the icy mantle of interstellar grains. The absorption at 10 micrometers can be attributed, meanwhile, to the silicate core of the interstellar grains. The spectrum of W33 A was measured by B. T. Soifer and his colleagues at the California Institute of Technology.

Nuts and Bolts

The notion that a threaded bolt and a matching nut could serve as a fastener dates back only to the 15th century. Today nuts and bolts and ways of making them are still actively evolving

by Frederick E. Graves

In thinking about how machines and other manmade structures are fastened together one might suppose the combination of nut and bolt is of ancient origin and is by now so well developed that nothing new could be expected of it. In actuality the threaded nut and bolt date only from about the middle of the 15th century, when they were made by hand and a nut that fit one bolt was highly unlikely to fit another. Moreover, even though the technology of the nut-and-bolt fastening is well established, it has recently benefited considerably from several evolutionary advances. They include electronic systems for tightening nuts, special coatings for nuts and bolts and new tools for making nuts and bolts.

The combination of a nut and a bolt is, of course, only one member of a family of fasteners—a large family when one takes into account the diversity of designs, sizes and applications. The other members of the family include nails, screws and rivets. I shall focus on the nut-and-bolt fastener because its history is a central theme in the development of interchangeable parts.

A bolt can be defined as a cylindrical, externally threaded fastener with a head. If the bolt is not threaded all the way from the head to the tip, the diameter of the unthreaded part is about equal to the diameter of the thread crest (the maximum diameter of the thread). The shape of the bolt's head can be square, hexagonal, round, countersunk, elliptical or oval.

A nut can be defined as a block of metal, usually square or hexagonal, with a hole through its center. The hole is internally threaded to mate with the external threads of a standard bolt. Variations of design include locknuts, slotted or castle nuts and wing nuts. Most of the variations seek to deal with the problem of preventing a nut from working loose in a vibrating joint. The locknut incorporates an insert of nylon or some other plastic material to increase the frictional resistance to rotation, or it may be made with deflected threads to achieve the same objective. Slotted and castle nuts have an aperture that a cotter pin or a safety wire can be put through to hold the nut in place.

Notwithstanding such arrangements, vibration or wobble often causes a nut to work loose. If the nut comes off or the loosening of it causes the bolt to wobble, the joint can fail.

Some idea of the structural importance of fasteners can be conveyed in a list of familiar objects with the number of fasteners (of all types) holding them together. A telephone has 73, a dishwasher 115, a refrigerator 275, a fork-lift truck 940, a railroad boxcar 1,200, a turret lathe 1,650, an automobile 3,500 and a jet airplane 1.5 million.

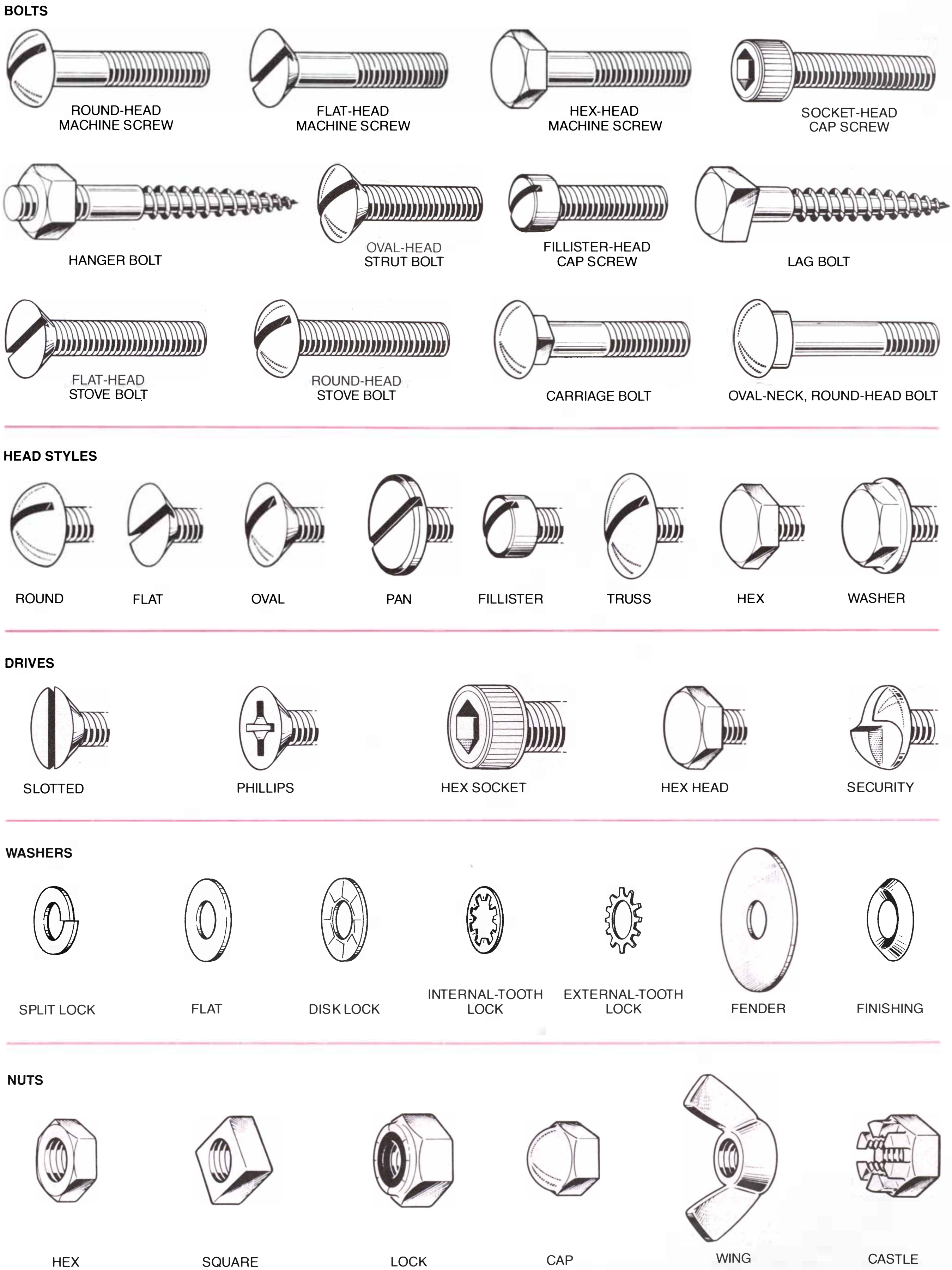
It is not easy to convey the enormous range of sizes, strengths and types of thread available to the design engineer choosing a bolt. A few examples of standard bolts in the U.S. may indicate the possibilities. Standard A-307 of the American Society for Testing Materials covers bolts of low-carbon steel with a range of diameters from 1/4 inch through four inches that serve in general applications. Such a bolt must have a minimum tensile strength of 60,000 pounds per square inch. Standard A-325 of the same organization covers medium-carbon, high-strength bolts ranging in diameter from 1/2 inch through $1\frac{1}{2}$ inches that serve in bolting structural steel. The bolt's tensile strength must be at least 120,000 p.s.i. in diameters from 1/2 inch through one inch and 105,000 p.s.i. in diameters from $1\frac{1}{8}$ through $1\frac{1}{2}$ inches. Grade 8 of the Society of Automotive Engineers encompasses bolts from 1/4 inch through $1\frac{1}{2}$ inches in diameter that are installed in automobiles, farm equipment and various assemblies where the strength and durability of a fastening are critical; the minimum tensile strength is 150,000 p.s.i. Standards for aircraft bolting include bolts with a minimum tensile strength of 195,000 or 260,000 p.s.i.

A sense of the economic importance of fasteners can be had from a recent estimate in the United Kingdom that the joining of components accounts for between 20 and 40 percent of total manufacturing costs. The same would be true in the U.S. Much of the expenditure is for labor. Although the cost of fasteners for a mechanical assembly averages less than 5 percent of the cost of the finished assembly, a little more than half of the total production time is spent on fastening work. The result is that the cost of the installed fasteners in an assembly ranges from three to 10 times the cost of the fasteners as parts.

The fastener industry is economically significant in its own right. Some 625 companies in the U.S., employing between 50,000 and 60,000 workers, make approximately 250 billion fasteners per year. The final users pay $10 billion just to buy these fasteners and much more to install them. The final installed cost is some $50 billion.

Although the threaded bolt dates from the 15th century, the unthreaded bolt (far more limited in application) is much older. Records show that unthreaded bolts served in Roman times for barring doors, as pivots for opening and closing doors and as wedge bolts: a bar or a rod with a slot in which a wedge was inserted so that the bolt could not be moved. The Romans also seem to have developed the first wood screw, which was made out of bronze or even silver. Its threads were filed by hand or consisted of a wire wound around a rod and soldered on. Apparently this invention disappeared with the Roman Empire, since the first printed record of screws is in a book dating to early in the 15th century.

Later in that century Johann Gutenberg included screws among the fasteners in his printing press. Before long the makers of clocks and armor were relying on screws too. (I have a piece of Spanish horse armor authentically dated to 1614 that contains a number of screw eyes for the attachment of battle ribbons.) Leonardo da Vinci's notebooks from the late 15th and early 16th century include several designs for



ILLUSTRATED GLOSSARY presents bolts according to type, head style and drive: the means by which a turning force is applied to the bolt. Also shown are several washers, including those that lock the nut into position when it is tightened. At the bottom is typology of nuts.

screw-cutting machines, but the first practical machine for the purpose was invented in 1568 by Jacques Besson, a French mathematician. By the late 17th century screws were common components of firearms.

With these developments the unthreaded bolt and the concept of threads were in hand, but the nut was yet to come, as was the idea of adding threads and a nut to the bolt. The first printed references to a threaded nut appeared in the late 16th and early 17th century. As with the first screws, the first nuts were both handmade and extremely crude.

Apparently by the early years of the 17th century nuts were being added to the screws of the period, which had straight sides and a blunt end and so looked more like a modern bolt than like today's tapered and pointed screws. A 1611 book in English mentions a "Nut for a Scrue." The screw would have qualified as a threaded bolt. For the threads of a nut to fit the threads of a particular bolt or screw was a matter of luck; when such a combination was found, the nut and the bolt were tied together until they were installed in a machine or a building.

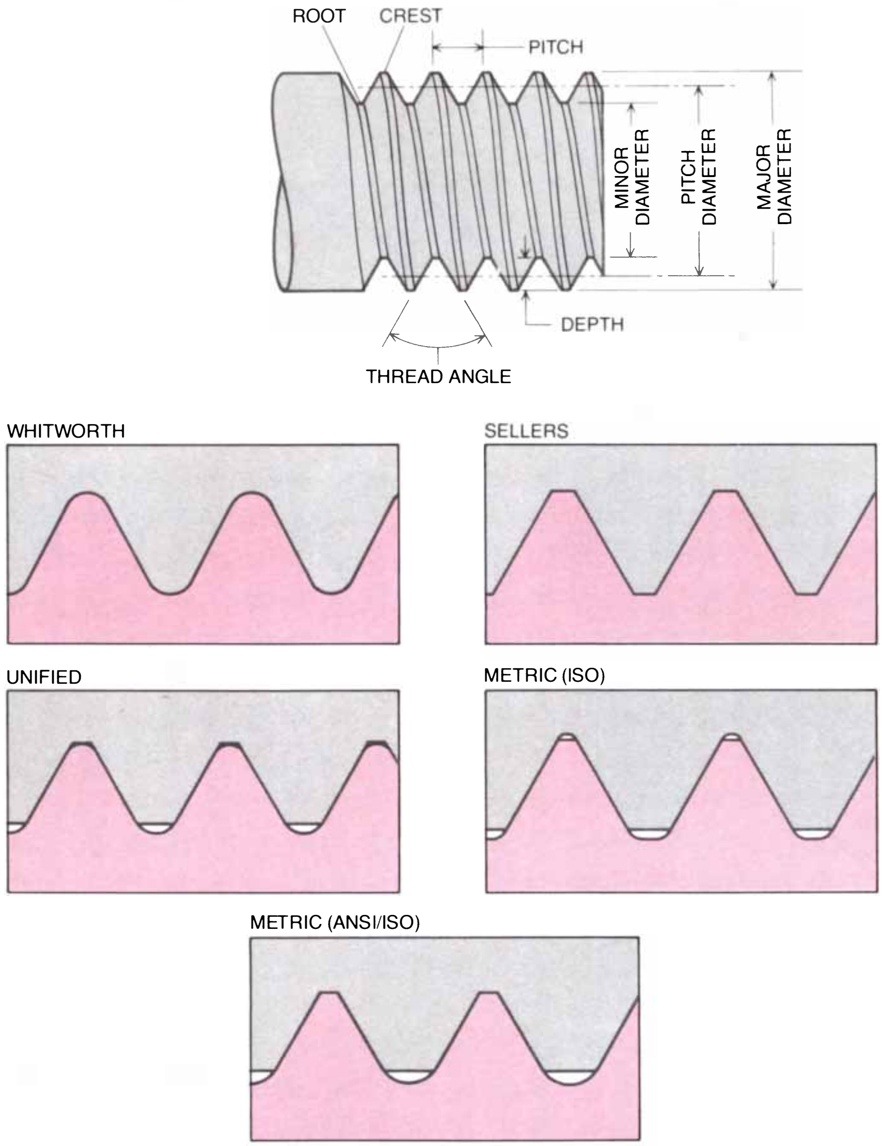
As one might suppose, it was with the advent of the Industrial Revolution that nuts and bolts became commonplace as fasteners. If such a far-reaching epoch can be said to have a beginning, it is with James Watt's invention of the steam engine in 1765. To the makers of the early machines and of the products of those machines it soon became apparent that threaded fasteners are crucial in the efficient design of mechanical assemblies, in the ease of assembling a machine or a product and in the reliable operation of the finished assembly. Many well-known inventions of the time relied extensively on threaded fasteners. Among them were James Hargreaves' spinning jenny and Eli Whitney's cotton gin.

It was Whitney who showed the way in 1801 to the next crucial concept: the interchangeability of parts. In that year he appeared before a group of officials in Washington, including President Adams and Vice President Jefferson. There he arranged several piles of musket parts on a table, each pile containing 10 identical parts. Picking a part at random from each pile, he quickly assembled a complete working musket. The idea was so plainly sound that it soon became an important factor in the success of several other inventions, among them Samuel Colt's handgun, James Nasmyth's steam hammer, Cyrus McCormick's reaper, John Deere's steel plow, Eli Terry's mass-produced clocks and Elias Howe's sewing machine.

A problem that persisted until early in the 19th century was the lack of uniformity in the threading of nuts and bolts. Until late in the 18th century the standard technique for forming large threads was for a blacksmith to pound a special swage, or forming tool, against a hot blank bolt. Smaller threads were cut on a primitive lathe. Usually the cutting tool had to be held against the blank by the operator, and so it was virtually impossible to get uniform threads.

By 1800 the lathe had been improved with slide rests and gearing so that the threads on a lead screw—the screw that moved the cutting tool—could be reproduced with good accuracy, but there was still no system for proportioning the number of threads to the diameter of the screw. As Nasmyth put it: "All bolts and their corresponding nuts had to be especially marked as belonging to each other. Any intermixture . . . led to endless trouble and expense, as well as inefficiency and confusion—especially when parts of complex machines had to be taken to pieces for repairs."

The man who changed that was the English inventor Henry Maudslay. In 1800 he built the first lathe that enabled the operator to make screws of any desired pitch and diameter. (Pitch is the distance from the crest of one thread to the crest of the next. The major diameter is measured from the crest of a thread to the corresponding crest on the opposite



BOLT THREADS have a distinctive nomenclature (*top*) and have evolved in a variety of standardized patterns. The Whitworth thread, designed by Joseph Whitworth in 1841, became the British standard, and the Sellers thread, designed by William Sellers in 1864, became the U.S. standard. The Unified system, incorporating features of both the Whitworth and the Sellers standards, was adopted by the U.S., Canada and Britain in 1948. A standardized metric system devised by the International Organization for Standardization (ISO) was adopted in 1964 for nations employing metric measurements. An Optimum Metric Fastener System proposed by the Industrial Fasteners Institute in 1971 as an improvement on the ISO standard led to the American National Standards Institute/ISO system, now the international metric standard.

side of the bolt, the minor diameter from the bottom of the valley between two threads to the bottom of the corresponding valley on the opposite side.) His contemporary Charles Holtzapffel wrote in his five-volume work on *Turning and Mechanical Manipulation* that between 1800 and 1810 Maudslay "effected nearly the entire change from the old, imperfect and accidental practice of screw making... to the modern, exact and scientific mode now generally followed by engineers."

The screw-cutting lathe served for many years as the principal means of threading fasteners. Today the standard practice is to roll threads by holding threaded dies against a blank and turning them. The crucial difference is that the lathe cuts thread, removing material from the blank, whereas the rolling dies reshape the surface of the blank with no loss of material.

Toward the middle of the 19th century William E. Ward of Port Chester, N.Y., developed machinery for the hot-forging of nuts and bolts. In this procedure bar stock is heated to about 870 degrees Celsius (1,600 degrees Fahrenheit) and fed into the forming dies. Later Ward developed machinery to do the work by cold-forming. The procedure is much the same except that the bar stock is not heated. The dies must be strong, and the machine that holds them must be capable of exerting powerful forces. A cold-formed product can be made to closer dimensional tolerances than a hot-formed one and is stronger. Cold-forming is now the basic method of manufacture for mass-produced nuts, bolts and screws.

In the late 19th century the manufacture of mass-produced fasteners was gradually converted from the machining of bar stock into continuous cold-forming from coils of wire or rod. A coil is fed continuously into, say, a bolt-making machine. The machine cuts off slugs of the appropriate length. A slug is transferred through a series of forming dies and emerges as a blank bolt, on which threads are rolled to finish the operation. The continuous cold-forming process is how most nuts and bolts are made today.

The capability of making uniform threads was not enough to guarantee uniformity, since every manufacturer was likely to have his own standard. What was needed was a set of national or international standards. In the U.K. the first significant move in that direction came in 1841, when Joseph Whitworth presented to the Institution of Civil Engineers his paper *A Uniform System of Screw-Threads.*

Whitworth proposed that for screws and bolts of given sizes the threads should be identical in pitch, depth and form. He recommended an angle of 55 degrees between the side of one thread and that of the adjacent thread. The number of threads per inch should be specified for each diameter of screw or bolt. The thread should be rounded at the crest and valley by one-sixth of the depth. By 1881 the Whitworth system had been generally adopted as the British standard.

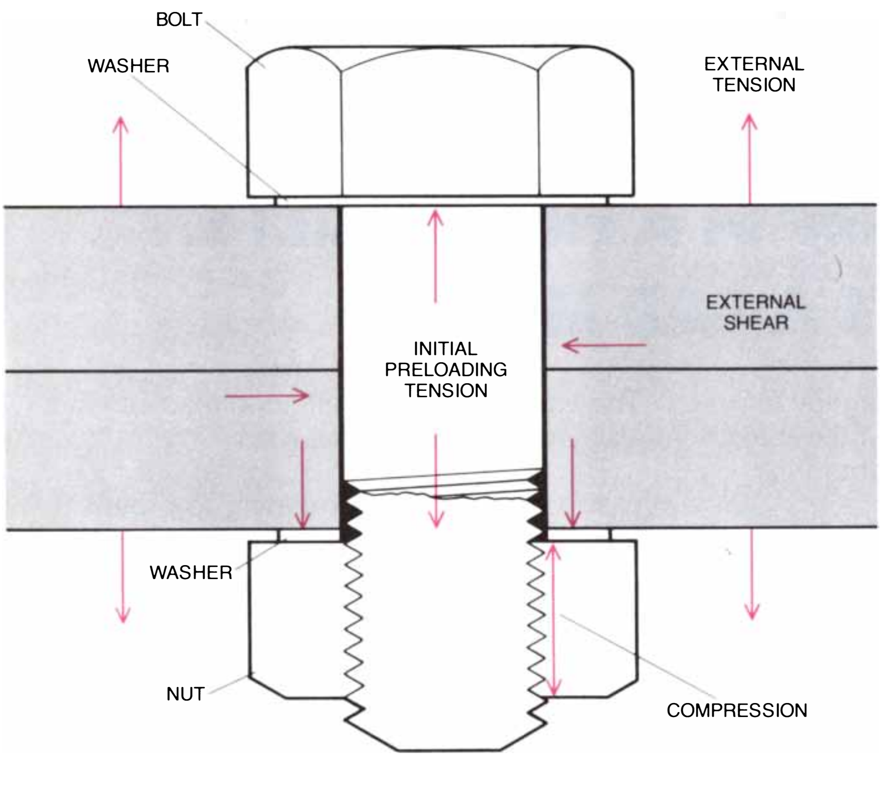
In the U.S. the move toward standardization began in 1864. William Sellers, a manufacturer of machine tools in Philadelphia, persuaded the Franklin Institute in that city to set up a committee that would seek the establishment of national standards. Sellers had several objections to the Whitworth system. Saying that the 55-degree angle of cut was hard to gauge, he argued for 60 degrees, which, he added, would result in stronger threads. He also said Whitworth's thread-rounding standard resulted in an uncertain fit between bolt and nut and for weaker threads. He proposed threads with flat crests and valleys.

In its final report the Franklin Institute adopted the Sellers system, recommending as a national standard that "screw-threads shall be formed with straight sides at an angle to each other of 60 deg, having a flat surface at the top and bottom equal to one-eighth of the pitch." By the end of the century the Sellers system had become the standard for the U.S. and much of Europe.

The incompatibility of the Whitworth and Sellers systems gave rise to difficulties in World War I and World War II, when U.S. and British armed forces had many occasions to need interchangeable parts. Beginning in 1918 and continuing intermittently until 1948 the two countries sought ways to reconcile the systems. At a conference in Washington in 1948 the U.S., Canada and the U.K. adopted a Unified Thread System that incorporated features of both the Whitworth and the Sellers systems. A prominent role in the standardization of inch screw threads was played by the Industrial Fasteners Institute, made up of the major manufacturers of fasteners in North America.

In the same year the International Organization for Standardization (usually abbreviated as ISO) began work on a standardized screw-thread system that would apply worldwide. When the work was finished in 1964 and adopted at an international conference in New Delhi, it consisted of two systems: the ISO Inch Screw Thread System (the same as the Unified system) and the ISO Metric Screw Thread System, which was a new entity designed to replace the various and numerous national metric systems.

On the ground that the fasteners made under the new metric system were inferior to those made according to the ISO inch formula the Industrial Fasteners Institute recommended in 1970 that a better metric system be devised. In 1971 the group put forward its proposal as the Optimum Metric Fastener System. Among other things, the plan called for a thread profile based on a form that had



FORCES OF FASTENING are diagrammed for a joint fastened with a nut, a bolt and washers. Ideally a bolt should be tightened only to the yield point, when the metal begins to deform.

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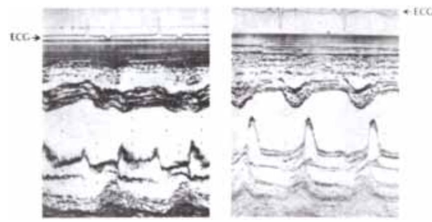
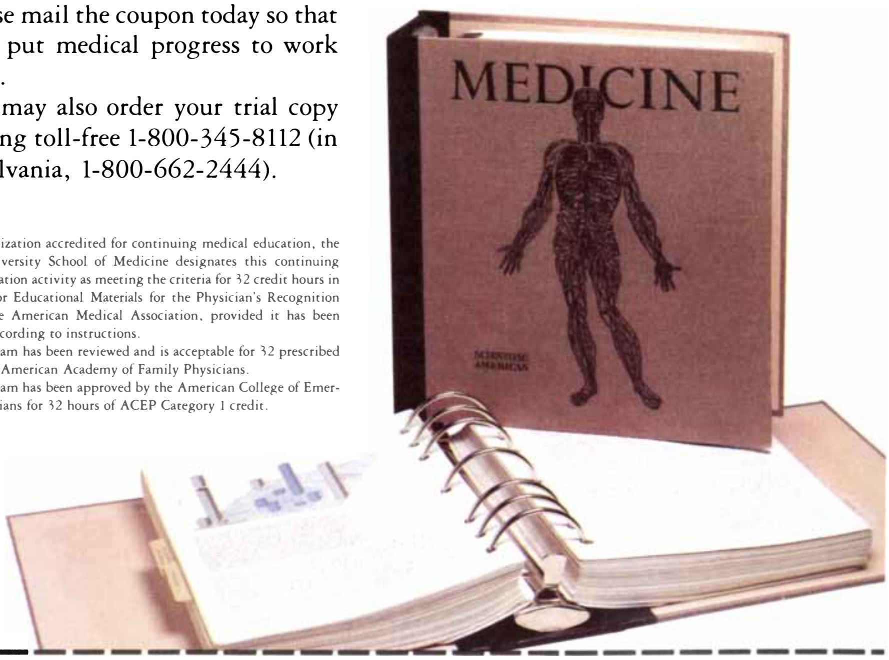
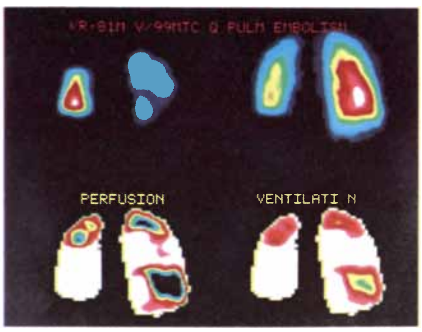


Echocardiograms from patients with aortic regurgitation.





Computerized scintigraphy reveals pulmonary thromboembolism.

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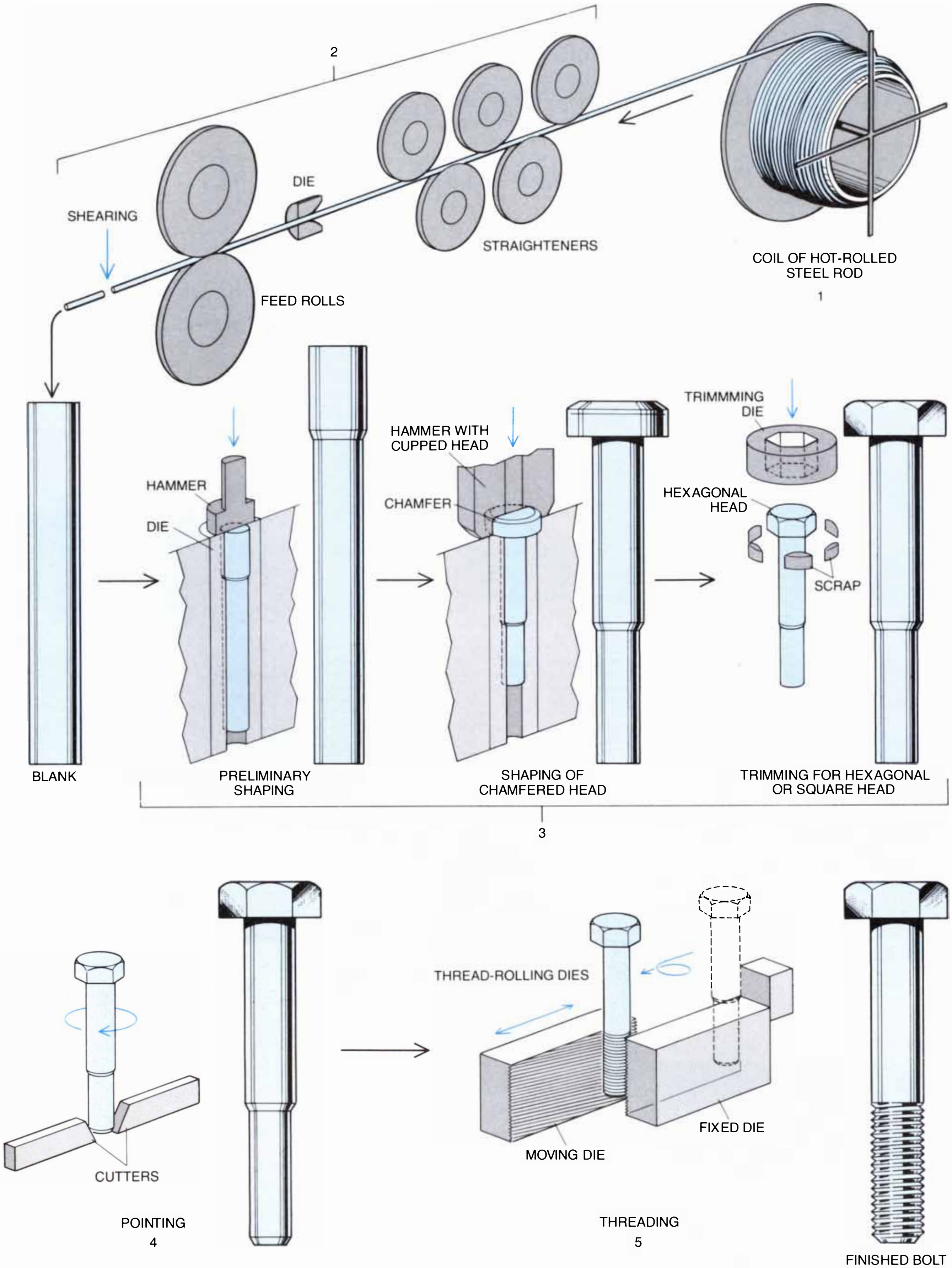


MANUFACTURE OF A BOLT by the cold-forming process begins with coiled, hot-rolled steel rod (*1*). The rod is run through straighteners and a die, which reduces it to the wanted diameter, and is then sheared (*2*). The resulting blank goes through a machine with three hammer-operated dies; one die gives it a preliminary form, one shapes a round head with a chamfer and one trims the head so that it is square or hexagonal (*3*). The bolt is then pointed (*4*) and finally threaded between a fixed and a moving die (*5*). Nuts are made from similar stock.

become standard for aerospace fasteners and for fasteners with better resistance to metal fatigue. This proposal led to a similar system that is now the international metric standard: the ANSI/ISO system (ANSI standing for the American National Standards Institute).

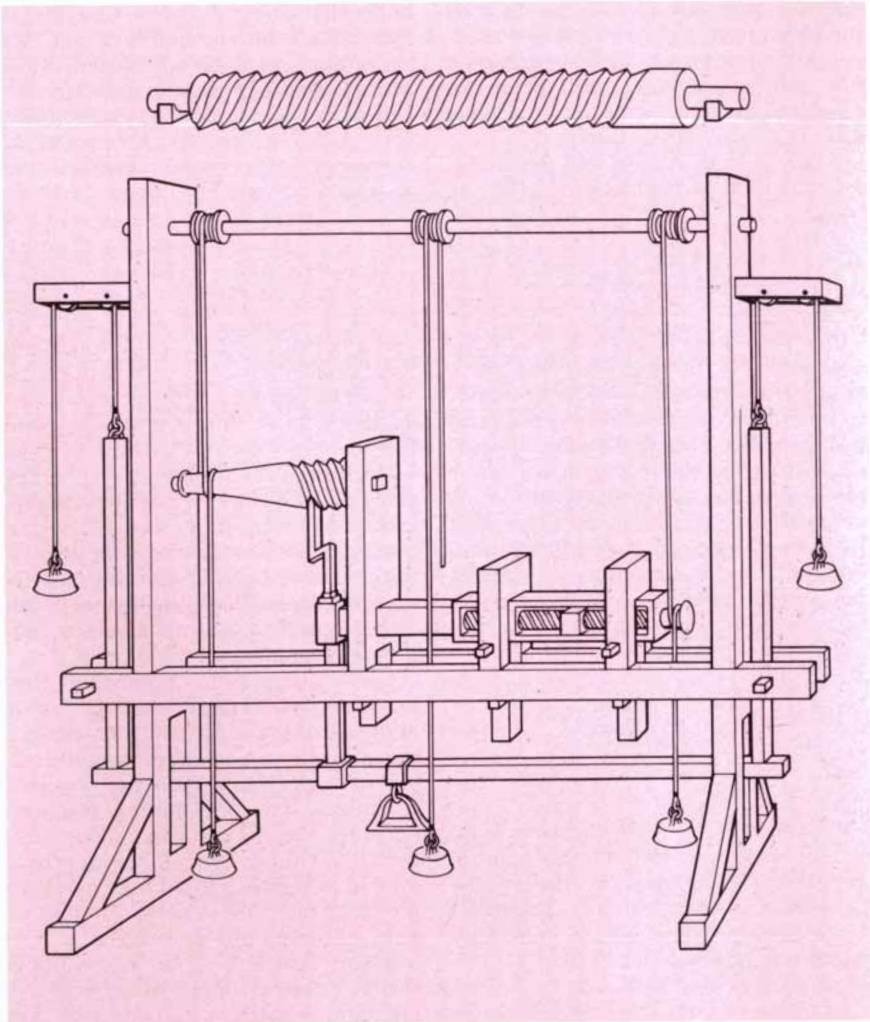
Many other organizations concern themselves with fastener standards, often relating to which of the standardized fasteners are most appropriate for a particular industry. In the U.S. these organizations include the American Society for Testing and Materials, the American National Standards Institute, the Society of Automotive Engineers and others. Taken together, their activities encompass some 8,000 standards for fasteners, which cover such matters as materials, configurations, dimensions, tolerances and mechanical attributes. If one includes special and proprietary fasteners, various surface finishes and coatings and all combinations of diameter and length, the total of different fastener items is more than two million.

With so much to choose from, the manufacturer would do well to guard against the proliferation of fastener types and styles. Unless care is taken at the time a piece of equipment is designed, the proliferation of fasteners can become a significant cost drain.

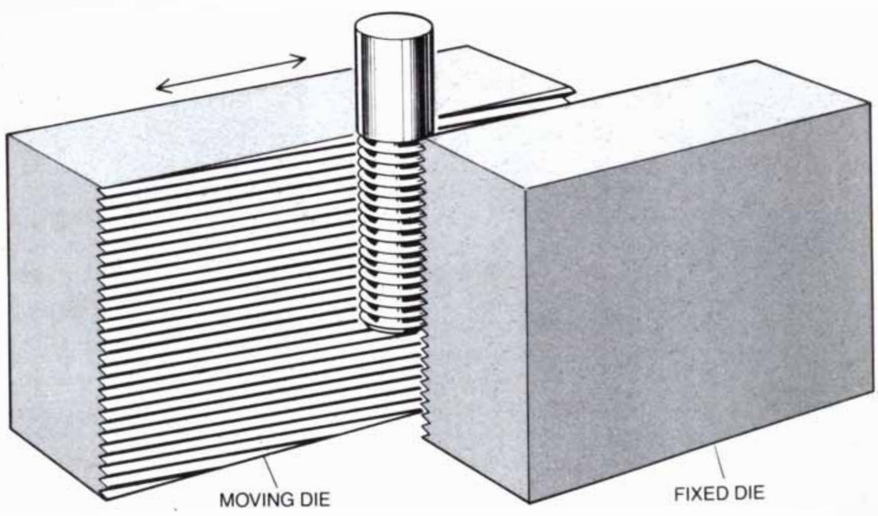
Suppose a machine is being designed that will require the installation of a self-tapping screw at a certain stage of assembly. Suppose also only one combination of diameter and length will be needed. For this application the design engineer has the following choices in the published standards for self-tapping screws: nine thread forms, six head styles, three types of recess for driving the head and four types of surface finish. The total number of choices available is 648. It is easy to see how a company with many design engineers and draftsmen might end up with a proliferation of fasteners, each one given a part number and carried in stock.

A simpler example shows that the problem does not diminish. The requirement is for a combination of bolt, nut and washer. Checking the possibilities among standard fasteners, the engineer finds that for a bolt of a given length and diameter he can choose from three head styles, four specifications of strength, two thread pitches, three surface finishes, at least two types of washer and at least two types of nut. The total number of possible combinations is 288.

It has been well established that the cost of maintaining a single item in inventory is more than $2,000 per year. The type of item must be recorded in a computer data bank, from which the information can be retrieved; an inventory of the number of items of a given type on hand must be maintained; space must be provided for storing the supply,



SCREW-CUTTING LATHE invented by Jacques Besson in 1568 was the first practical device for the purpose and contributed significantly to the evolution of the threaded nut and bolt. The operator powered the machine by means of the stirrup at the bottom. The workpiece, which is the tapered screw at the left, was cut by a tool moved by the drive screw at the right. The motion of the tool and the rotation of the workpiece were coordinated by the pulleys.



MODERN THREADING is not a cutting operation that removes material from bolt stock but rather a reshaping of the surface by dies. In a typical machine the bolt stock is pressed firmly between a fixed die and a moving one, which causes the bolt to turn as it is moved.

and a system must exist for drawing the item out of storage when it is needed. All of this must be done for each nut, bolt, washer and other type of fastener the manufacturer employs in assembling machines or parts.

Many manufacturers tend to give far less attention to fasteners than they do to other parts of their assembly operation. It is easy to think of nuts and bolts as standard, inexpensive, ready-to-hand components that can be plucked out of a bin as they are needed. The result is that with a few exceptions (the manufacturers of automobiles and farm equipment among them) a lot of money is wasted through the proliferation of fasteners and through the use of fasteners that exceed the requirements of the job in strength, material, thread design or coating. It has been my experience that any manufacturer spending $1 million per year on fasteners can save 15 percent per year by close attention to this part of the operation.

The slow spread of the idea that close attention to fasteners is worthwhile has given rise in recent years to a new engineering discipline concerned with fastener applications. When a machine is being designed, such an engineer considers the design of the fasteners that will be needed, the type of fasteners that should be chosen from the large number available and the methods whereby the fasteners should be installed. The result is a great improvement in the reliability and safety of machines.

Along with a somewhat casual attitude toward nuts and bolts in many companies is a remarkable lack of knowledge about the proper method of tightening a nut-and-bolt fastening. For the most efficient joint the fastener must be tightened into what is unfortunately called the yield region. The term refers to the stage at which a permanent deformation of the metal (specifically an elongation of the bolt) begins. It is far from the breaking point, but it results in the highest possible clamping pressure.

In general because the work is done manually the larger fasteners (5/8 inch or more in diameter) tend to be undertightened and the smaller ones tend to be overtightened. A variety of special wrenches and tightening techniques are available for dealing with this problem, but for joints that are critical in terms of high performance or safety the new principle of electronic control is finding increased application. In such a system a microprocessor monitors the tightening operation (which may nowadays be done by a robot), employing torque and angle signals to shut off an electrically driven wrench at the yield point.

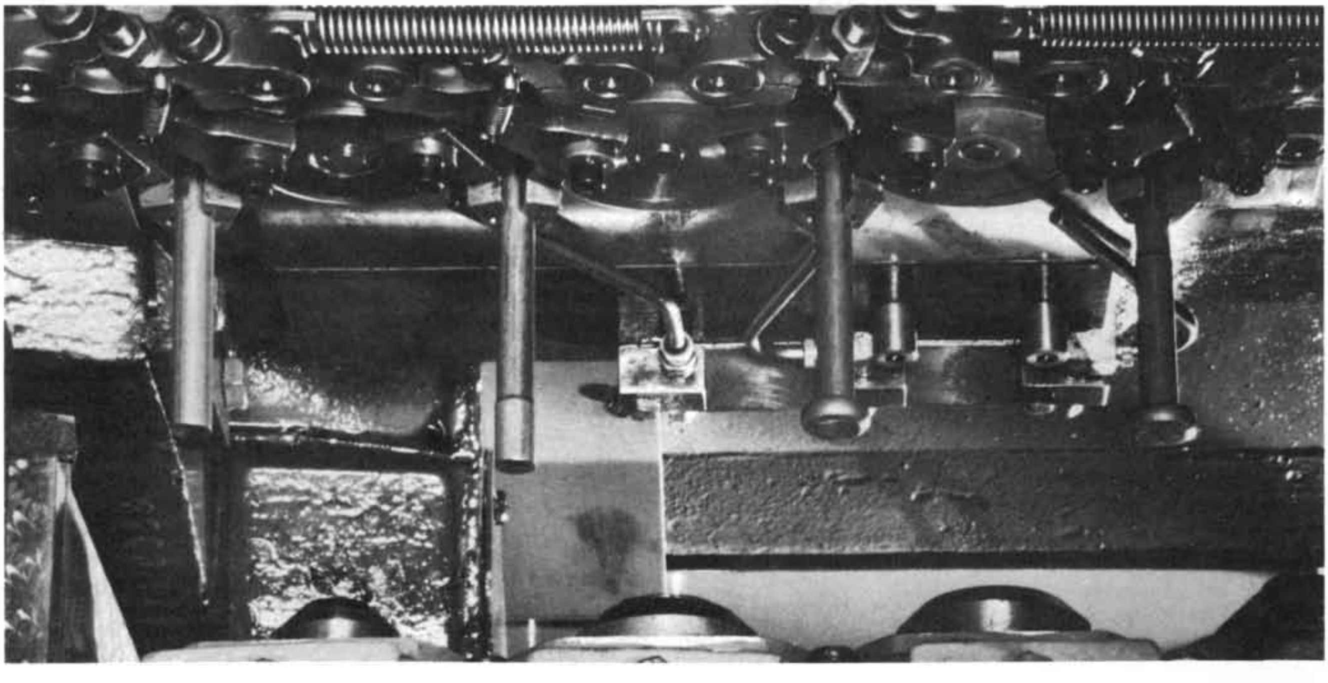
Close attention to tightening often makes it possible to put a smaller fastener or one of lower classification in a given joint, at a saving of perhaps 10 cents per fastener. For a manufacturer who assembles, say, one million machines per year the change can reduce costs by $100,000 per year. If the improved joining also means that fewer machines are sent back to the manufacturer for repair, still more money is saved.

Many fasteners serve in conditions that call for resistance to corrosion or high temperature or perhaps both. The standard means of providing a fastener with such properties has been to apply a coating consisting of phosphate and oil or of a black oxide. If unusual resistance to corrosion is required, zinc or cadmium is applied by electroplating. All these techniques can fall short of perfection. Zinc and cadmium, for example, can cause the metal to become brittle.

A recent development is the adaptation to fasteners of a technique of coating with aluminum that has served in the aerospace industry for parts operating in extreme conditions, such as in turbine engines. The aluminum is dispersed in a phosphate or chromate carrier. Aluminum coatings increase the ability of the fastener to withstand high temperature and to resist many chemicals and organic fluids.

Another advance is in coatings for tools employed in the cold-forming of fasteners. These tools are made out of hard and strong materials, but they nonetheless wear rapidly. Indeed, the most expensive feature in the manufacture of fasteners is the cost of replacing the tooling.

Efforts to extend the life of fastener-forming tools have included surface treatments such as carburizing, nitriding and electroplating. The tools have also been fitted with inserts of titanium carbide or titanium nitride in the places where wear is severest. The new technique is to apply a thin layer of titanium carbide or titanium nitride by chemical or physical vapor deposition. The coatings not only are extremely hard but also have lubricating properties that diminish the friction between the tool and the fastener. The treatment enables most tools to last for from three to five times longer than uncoated tools.



BOLT-FORMING MACHINE is shown at the point where bolt blanks are being shaped by dies that move upward. Four partially formed bolts can be seen. The machine, made by the National Machinery Co., can manufacture up to 100 fully formed bolts per minute.

THE AMATEUR SCIENTIST

Gismos that apply non-obvious physical principles to the enjoyment of cooking

by Jearl Walker

Cooking is all physics (including, of course, chemistry), but most people (including me) cook largely on the basis of instinct guided by experience. Still, it is great fun when physical principles can be enlisted to make cooking better or easier. Recently I have encountered several kitchen contrivances based on principles that are not obvious. Among them are a heat pipe that speeds the cooking of meat, a liquid crystal that monitors the boiling of an egg, a butter dish that keeps butter cool in a warm place and an Oriental pot that makes it possible to cook with steam even if the food is partly liquid.

A heat pipe designed for the kitchen is a closed hollow tube, usually pointed at one end so that it can pierce meat. It contains a small amount of fluid that transports heat from the oven to the cool interior of the roast. Since the transfer is faster than the rate at which heat is conducted through the meat, the cooking time is reduced, diminishing the shrinkage caused by prolonged cooking.

The outer end of my favorite heat pipe is embedded in a solid metal cylinder. I have bought a dozen more heat pipes from Jerryco, Inc. (601 Linden Place, Evanston, Ill. 60202), that are longer and have smaller cylinders at the end. Heat pipes made specifically for cooking are marketed by Thermo Pin Manufacturing Corporation (67 Sheer Plaza, Plainview, N.Y. 11803). These pipes have heat fins. The cylinders and the fins are intended to absorb heat from an oven so that the fluid inside the pipe is vaporized. As the vapor spreads through the pipe some of it condenses in the part of the pipe surrounded by the relatively cool interior of the meat, releasing heat to the pipe wall and the surrounding meat.

Normally the pipe is put in the meat at an upward angle so that the condensed fluid is returned to the bottom of the pipe by gravity. To assist the process the pipe usually has an inner lining of porous material that draws the liquid by capillary action. At the bottom the liquid vaporizes and the cycle begins again. When the upper section of the pipe gets warm, the condensation diminishes and the cycle slows. When the interior of the meat is almost as hot as the oven, the circulation through the pipe stops.

The liquid in such a pipe can be water, methanol or something else that requires a large amount of heat to vaporize. Consider a pipe containing a gram of water at room temperature (say 19 degrees Celsius). To heat the water to the normal vaporization temperature of 100 degrees C. requires about 340 joules of energy, which is not much compared with the amount of heat needed to vaporize the water (2,256 joules). That much energy is needed to free the molecules from one another so that they can form a gas.

The energy needed to vaporize water is often called the latent heat of vaporization. This is the energy the heat pipe conveys to speed the cooking of meat. Every time the water condenses on a cool section of the pipe it loses its latent heat as the forces between the molecules re-form the liquid. The heat released by the water is conducted through the wall of the pipe to the surrounding meat. If one gram of water deposits its latent heat every second, 2,256 joules per second are released into the meat.

For a comparison I calculated the amount of heat that would be conducted into the meat by a solid rod made of an aluminum alloy. A rod with the same diameter as my heat pipe would deposit only 35 joules per second, considerably less than the heat pipe.

I ran two trials. One night I cooked a small (2.22 pounds) sirloin roast. The heat pipe was my old one with the solid cylinder on the end. It passed through the meat at an upward angle, with the pointed end sticking out.

With a nail I made a hole in the top of the meat so that I could install a heat-detecting thermocouple. The hole, which was snug for the wires of the thermocouple, was 3.5 centimeters deep. The temperature was measured at about two centimeters from the pipe, which at that point was 2.2 centimeters from the top of the roast and about midway across its length and width. I monitored the temperature of the thermocouple with a thermocouple thermometer from the Cole-Parmer Instrument Company (7425 North Oak Park Avenue, Chicago, Ill. 60648). The thermocouple probe was an unmounted Type *K*.

I put the roast on the middle rack of my electric oven, which had been preheated to 400 degrees Fahrenheit (204 degrees C.). The temperature measured at the tip of the thermocouple rose by 25 Celsius degrees in the first 25 minutes. It increased by a total of 58 degrees in 44.5 minutes.

At that point I removed the roast from the oven and sliced it into several vertical sections. One clue to the extent of cooking could be seen in the color of the meat in the sections. The slice through the middle was brown for only a few millimeters below the top of the roast but for two centimeters above the bottom. A circular brown region about two centimeters in diameter surrounded the hole made by the heat pipe. The rest of the slice was still red. (At this point I should state in passing that this expensive experimental material did not go to waste. Clearly the situation was not conducive to serving it, but it found its way into some very fine dishes that need not be described here.)

A slice near the point of entry of the heat pipe was browner around the hole made by the heat pipe. A slice at the other end of the roast was less brown around the hole. Thus the transfer of heat into the roast is more efficient near the lower end of the pipe than it is at the upper end, presumably because the liquid condensing at the lower end has a shorter distance to travel to return to the bottom and so returns quickly.

The next night I cooked without the heat pipe a similar roast weighing 2.18 pounds. I buried the thermocouple at about the same place and kept the cooking procedures as nearly the same as I could make them. This time the temperature at the thermocouple rose only 12 degrees in the first 25 minutes of cooking. An increase of 58 degrees took one hour and nine minutes, about 50 percent longer than it had with the heat pipe. (This time we ate the roast. Incidentally, in case the reader is wondering if a heat pipe tends to make a roast well done throughout, the answer is yes. This may sound terrible for a beef roast but is of course an advantage for a pork roast. Each to his own taste.)

Thermo Pin also sells a device for baking potatoes. The one I bought has six vertical heat pipes about nine centimeters long. Potatoes are speared on the pipes and the rack is placed in the oven. Since potatoes conduct heat poorly, I have often put nails in them, thinking that the rapid heat conduction by the metal would speed up the baking. I

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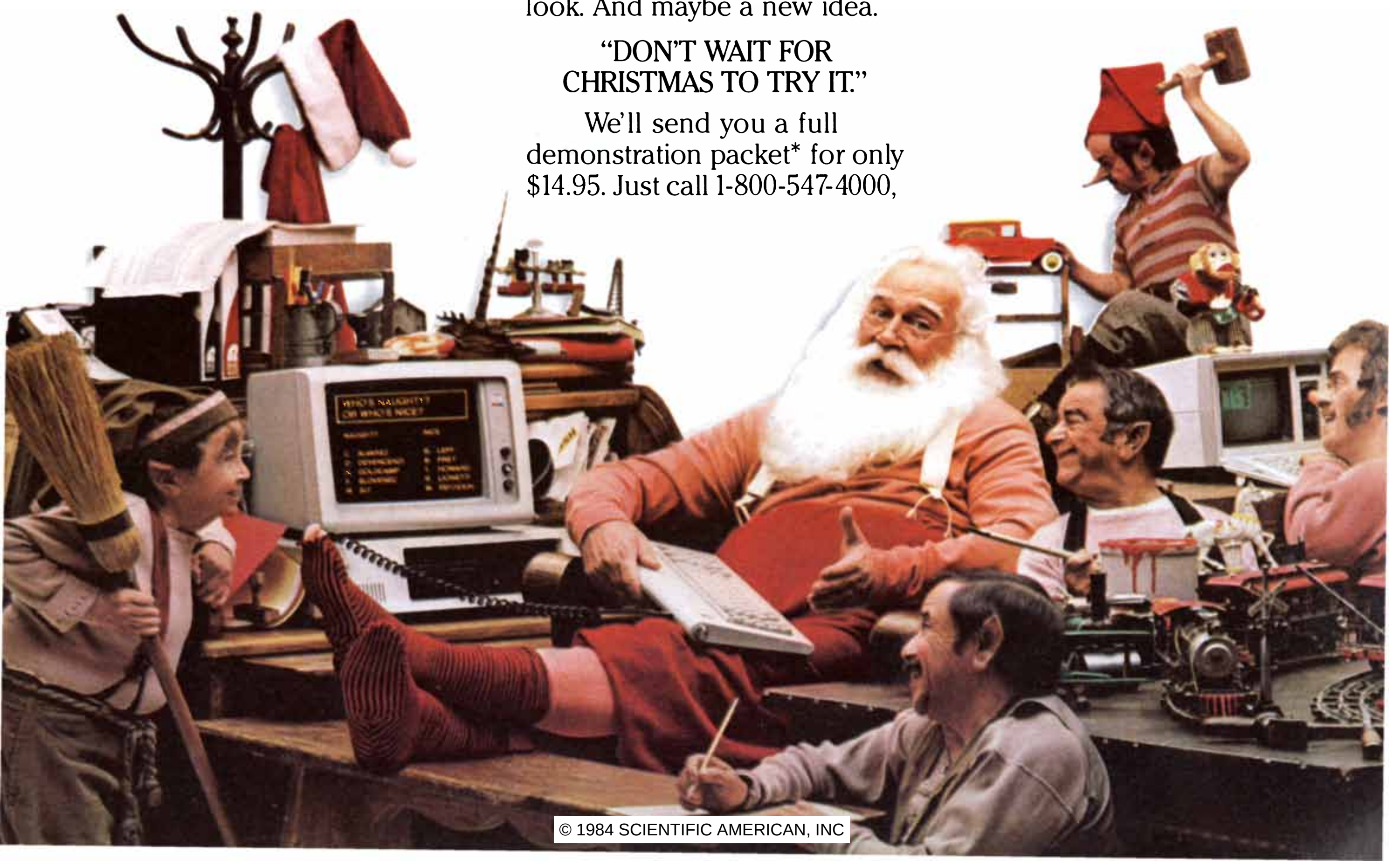

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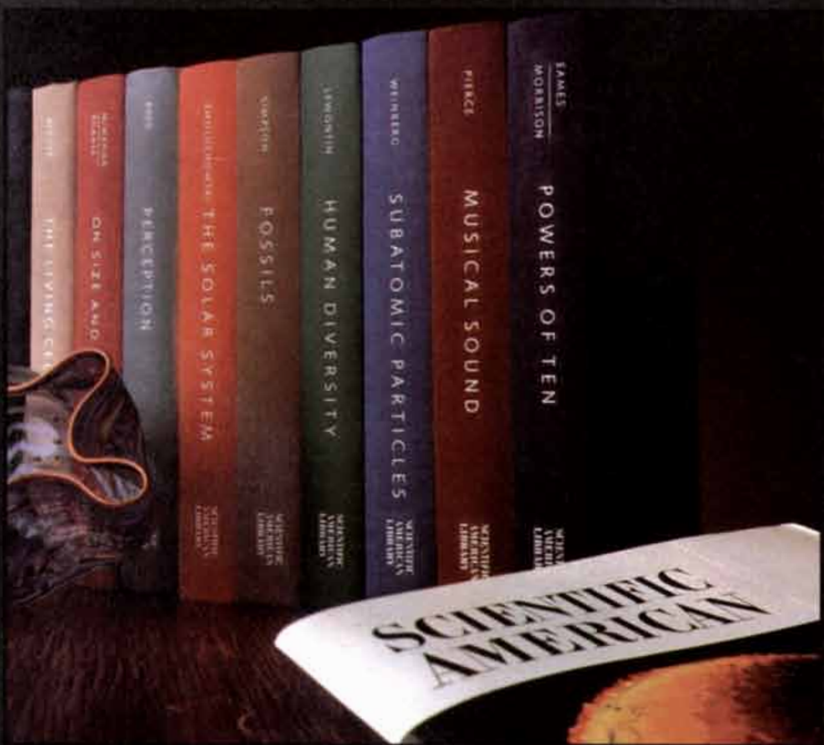

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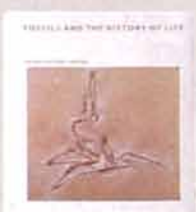
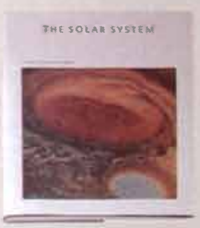




THE SOLAR SYSTEM

Roman Smoluchowski

Standing on the moon, men have seen the Earth "small and blue and beautiful." Beyond doubt, the space expeditions of the U. S. and the U. S. S. R. must be reckoned as the most successful, as well as the most extravagant, ventures in the popularization of science.

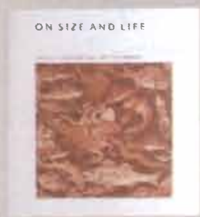
In THE SOLAR SYSTEM, Roman Smoluchowski assembles a wealth of images from satellites and earthbound telescopes to give us a magnificent picture of the Earth and its cosmic neighborhood.

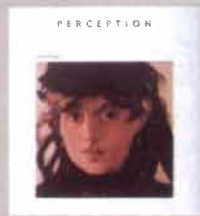
ON SIZE AND LIFE

Thomas A. McMahon and John Tyler Bonner

A biologist and an engineer bring their disciplines to bear in showing how nature obeys its own physical laws in fashioning living things. They demonstrate how size relates to shape and how this in turn controls the upper limit to the sizes of animals and plants.

Beyond the diversity of life, the authors show orderly ratios and relations that surprise and delight: the time for 50 percent of a mammal's growth is about three percent of a lifetime, and every mammal, no matter how long it can live, will take about 330 million breaths, sustaining 1.5 billion heartbeats.





PERCEPTION

Irvin Rock

The eye, we say, is a camera. Consider, however, that an object appears to us unchanging in size, shape, or orientation despite changes in our position with respect to it. How can we explain this constancy of perception when we know that the size, shape, and orientation of an image projected by the lens of the eye upon the retina must vary as we move?

In PERCEPTION, Irvin Rock explores the problems posed by both correct and illusory perception and examines the traditions of thought which inform contemporary investigations of the subject.

CONSTRUCTING THE UNIVERSE

David Layzer

In this beautifully illustrated volume, Harvard astrophysicist David Layzer gives us a bold view both of the origin, dynamics, and structure of the universe and of the processes which have enabled this picture to evolve. Layzer examines the two great theories of space, time, and gravitation — Newton's and Einstein's — and surveys the modern theories of the early universe and the origin of astronomical systems.

A GUIDED TOUR OF THE LIVING CELL

Christian de Duve

Trillions of cells compose the human body, each cell about four orders of magnitude smaller than the world in reach of our unaided senses. In A GUIDED TOUR OF THE LIVING CELL, Nobel Laureate Christian de Duve takes us on an engrossing, beautifully illustrated expedition through a world far removed from everyday experience yet vital to our very existence.

A bold but reassuring guide, de Duve puts the wisdom and knowledge gained from a lifetime of research at our service with his narrative, nontechnical, and often anecdotal style.

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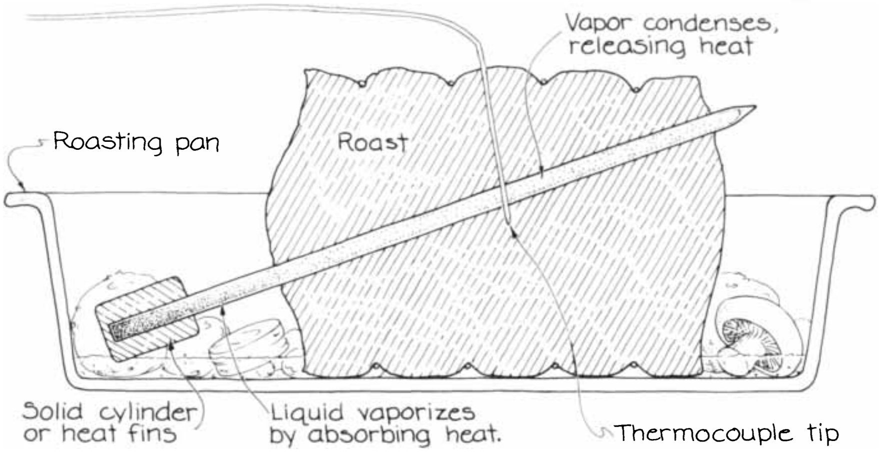
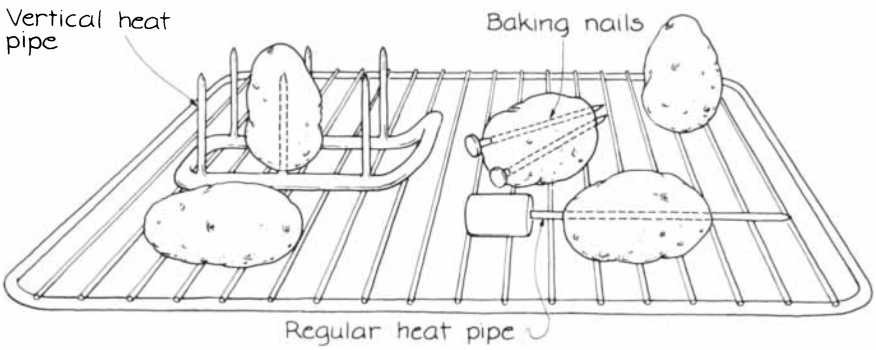
thought a heat pipe would transfer heat even faster.

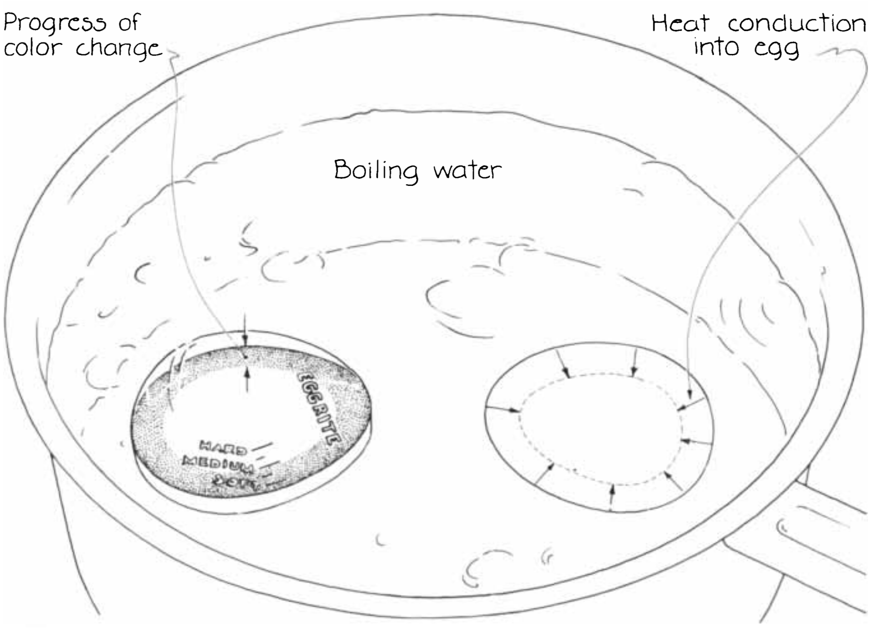
To check these assumptions I did an experiment with five potatoes of about the same size (11 by six by five centimeters). All were placed close to one another on the middle rack of an oven preheated to 400 degrees F. I pierced the sides of each potato with a nail so that the thermocouple could record the temperature at a depth of two centimeters. One potato was horizontal, one was vertical, one was pierced with two aluminum nails intended for baking potatoes and one was speared on a vertical heat pipe. The fifth potato was pierced with my old heat pipe and placed horizontally on the rack. (Because it was too large for the potato, the pipe ripped open a small part of one end.)



A heat pipe to speed the cooking of meat



Experiments in baking potatoes



The Eggrite egg timer

After 10 minutes I checked the internal temperature of each potato. The one with the large heat pipe had warmed by 28 Celsius degrees, the horizontal potato by 23, the potato on the vertical heat pipe by 19 and the other two by 17. After 20 minutes the potato with the large heat pipe was still in the lead but the others were closely clustered in temperature. The vertical potato remained the coolest.

I continued the race until the potatoes reached approximately 100 degrees. The potato with the large heat pipe won, taking about 55 minutes. The other four took about 74 minutes to finish.

The baking nails did not decrease the time of baking. Although they conduct heat rapidly, they do not bring much into the potato. A potato cooks faster with a heat pipe but is at a disadvantage if it is vertical. Then it presents a small cross section to the heating coils at the bottom of the oven and intercepts a small amount of the direct infrared radiation. The heat delivered by the heat pipe might be offset by this loss in absorption of direct radiation. One might do better by placing the potato horizontally over the coils. My conclusions are tentative. If you try this experiment, I would enjoy hearing about your results. (We sacrificed the potatoes.)

Until recently my method of timing eggs as they boiled was guesswork. I was never sure what state the eggs had reached. A new device neatly solves the problem. This clever egg timer is sold by the Wahl Company (5750 Hannum Avenue, Culver City, Calif. 90230) under the trademark of Eggrite. I bought one from a mail-order company (Williams-Sonoma, P.O. Box 7456, San Francisco, Calif. 94120). The Eggrite consists mostly of transparent plastic. Horizontally through the middle is a thin red film marked with a scale reading "soft," "medium" and "hard."

The Eggrite is put in the water along with the eggs. As the temperature rises the red film in the Eggrite begins to change color from bright to dark red. The color change appears first at the edge of the film. As heat is conducted through the plastic more of the film darkens. Soon the color change reaches the label "soft," indicating that the eggs are soft-boiled. Further heating drives the color change toward the center of the film, passing "medium" and "hard." With some experimentation one can calibrate the scale to get eggs with any degree of firmness. One can also calibrate the scale in terms of the size of the eggs.

The Eggrite is as sensitive as the eggs are to the initial temperature of the water, the number and size of the eggs in the pan and the rate at which the water is heated. Suppose I decrease the rate of heating by turning down the heat or by adding eggs. The conduction of heat into the eggs and the Eggrite is slowed and the color change is slower.

The Eggrite even allows for a change in air pressure. Suppose I carry an Eggrite from sea level to a high altitude. Since air pressure decreases with altitude, the boiling temperature of water is lower. An egg conducts less heat into its interior each second, hence taking longer to cook. The same thing happens with the Eggrite.

To investigate the film I cracked open an Eggrite with a small sledgehammer. (I was careful to protect my eyes from pieces sent flying.) The film consists of two layers. The top layer is a clear flexible plastic. The bottom layer is a spongy red material that appears to have been painted on the top layer. I dipped the film into water with tongs and heated the water while measuring its temperature with a thermocouple.

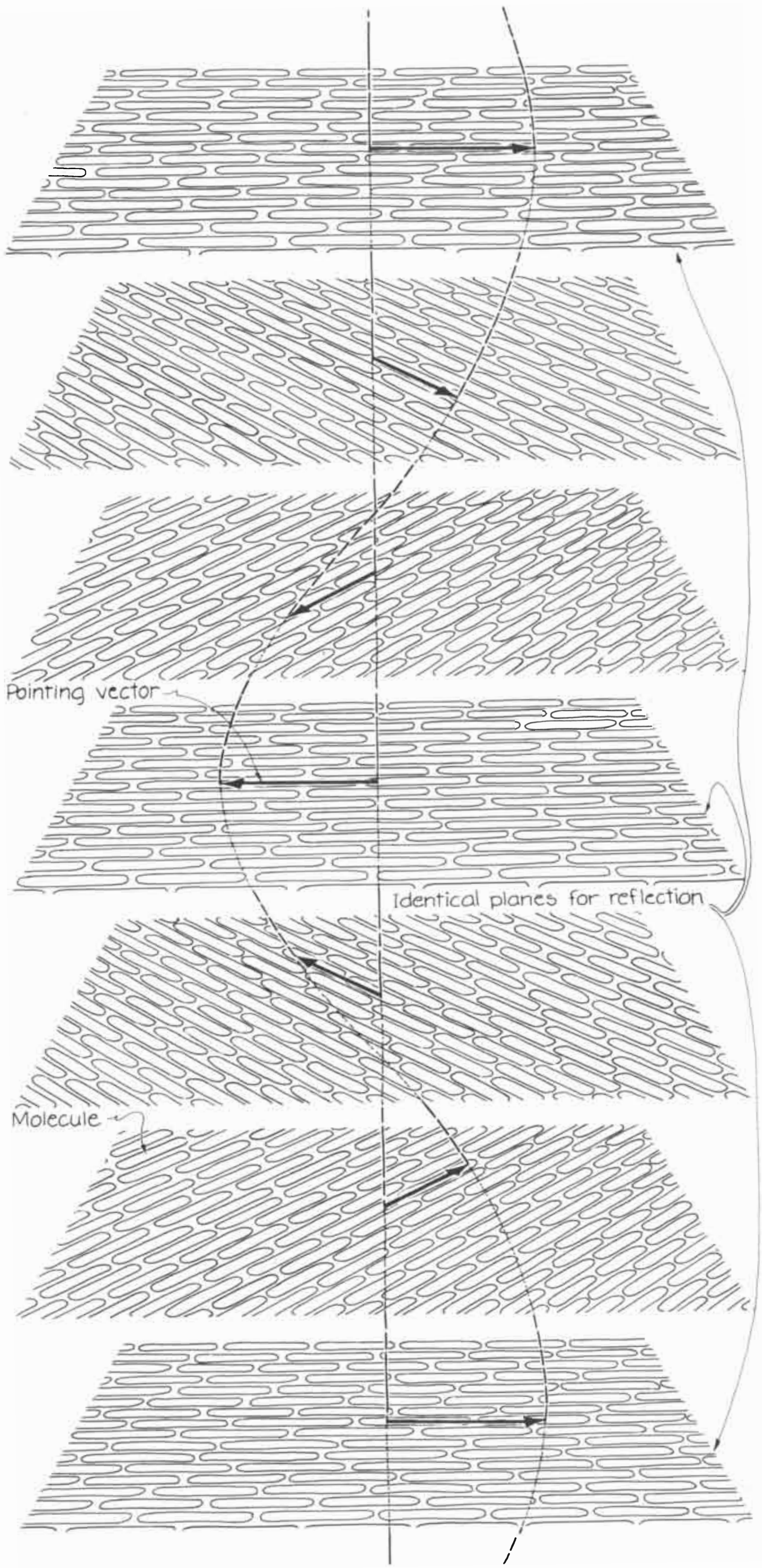
When the water near the film reached about 68 degrees, the layer quickly turned from bright red to dark red, maintaining the dark hue up to the boiling point of water. I lifted the film from the water and touched one edge. The cooling effect of my finger immediately changed the edge back to bright red. Cool water restored all the bright red.

I believe the spongy bottom layer of the film consists of a liquid crystal, probably of the cholesteric type. In such a substance the molecules have a certain type of crystalline order even though the substance is fluid. My guess is that the liquid crystal in the Eggrite strongly reflects red light until it reaches approximately 68 degrees. At higher temperatures it absorbs most of the light, becoming dark red.

A cholesteric liquid crystal has a layered structure in which rodlike molecules lie with their long axes in the plane of each layer. The orientation of the molecules gradually shifts from layer to layer. If a vector is made to point in the direction of the long axes of the molecules for each layer, the vector rotates through a helical path as it travels through the layers.

The crystal can be thought of as consisting of uniformly spaced planes that reflect light from the environment. The separation between the planes is the distance one must bring the pointing vector up through the layers so that it turns through 180 degrees. Since the molecules are considered to be rods with indistinguishable ends, those two planes have identical molecular alignments.

Suppose white light shines on such an arrangement of uniformly spaced planes. Light reflecting from one layer interferes with the light reflecting from another layer. For most wavelengths of



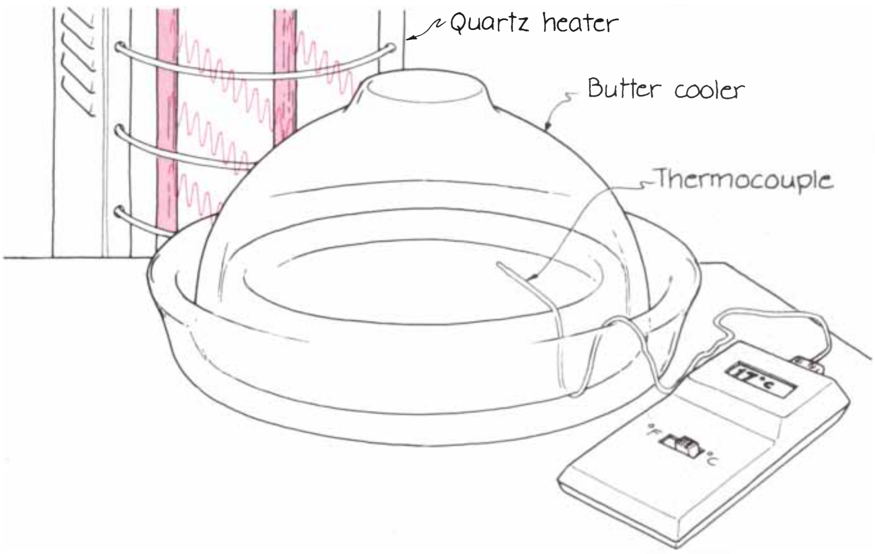
Molecular layers in a cholesteric liquid crystal light these reflected rays interfere destructively to yield darkness or at best a dim color. For other wavelengths the rays interfere constructively to yield a bright color that corresponds to those wavelengths.

Often cholesteric liquid crystals are noticeably fluid and iridescent. The colors from different sections of the fluid depend on the orientations of the crystal planes in those sections. Warming the sample changes the distance between planes and thus the color that is most strongly returned to the observer. If the temperature is high enough, the molecular vibrations disrupt the structure of the crystal, and the fluid loses its ability to reflect strongly at certain colors.

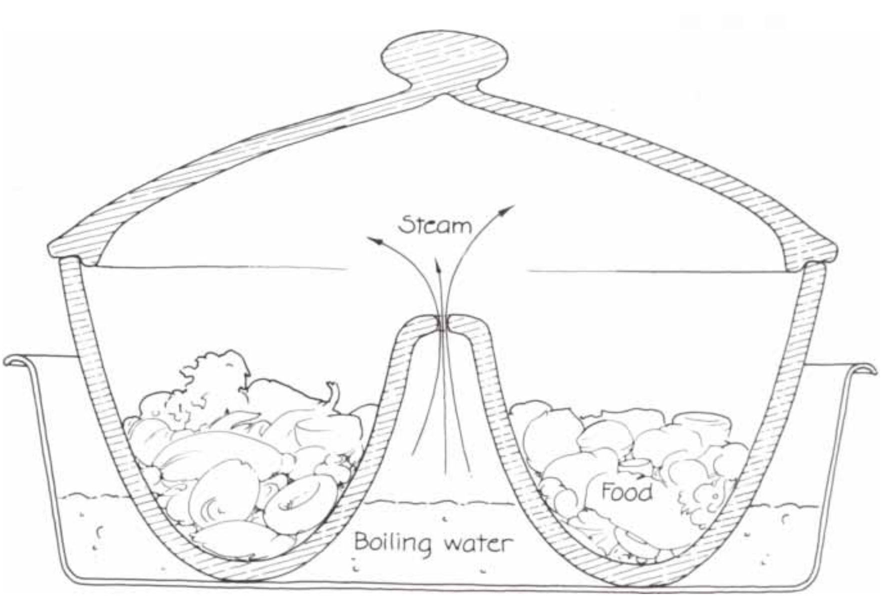
In the Eggrite I believe a liquid crystal has been mixed with some other substances and then painted on the flexible plastic layer. The mixture is not iridescent, but when it is illuminated with white light, it does strongly return red light to the observer. At about 68 degrees the selective return of red light is lost. Instead most of the incident light is absorbed, leaving the film dark red. As soon as the film is cooled the ordered structure and the selective reflection of red are reinstated.

The terra-cotta butter cooler is a clay container from Italy that retards the tendency of butter to melt on a hot day. I use it for backyard picnics. Without the container the butter soon gets too soft. With the container it remains firm through most of the festivities.

The bottom dish of the container is glazed so that the butter does not penetrate the clay. The unglazed cover is responsible for the temperature control. About half an hour before dinner I invert the cover and fill it with cool water. By dinnertime the clay is saturated. I pour out the remaining water and put the cover over the butter (fresh from the refrigerator) and the bottom dish.



The terra-cotta butter cooler



A Yunnan pot for steam cooking

As soon as the container is taken outdoors it begins to warm because it absorbs heat from its surroundings. Even if it is not in direct sunlight, it still absorbs visible and infrared radiation. It also receives heat from the convection of warm air past it. Even more heat is conducted into the container from the table unless it is put on an insulator such as a potholder.

If the container is completely dry, the energy gained from the radiation and air at the exterior is gradually conducted through the walls to the interior. When the cover is wet, the transfer of heat through the wall is retarded because much of the energy is consumed in the evaporation of water. As the exterior dries, more water is drawn from the interior of the wall to replenish the supply on the exterior. Because of the delay in heat conduction, the interior air and the butter remain cool.

To check my explanation I set up an experiment in which the butter cooler was warmed by a quartz heater, which delivers infrared radiation and some visible light. I first soaked the clay cover by inverting it and filling it with water. The external surface was noticeably dry. After a few minutes the water inside the cover developed a great many air bubbles as water displaced air from the clay. After about 45 minutes water had soaked through the wall and wet the external surface.

After emptying the cover I put it on the dish and ran a thermocouple wire into the interior of the container. The tip of the thermocouple was near the center of the dish and a few millimeters above it. With the thermocouple I monitored the temperature of the air inside the container. The container and the thermocouple were then placed about 30 centimeters in front of the quartz heater, which provided more heat than would be expected on a summer day. One side of the container was bathed with infrared and visible radiation; the other side faced a cool basement room and so received comparatively little infrared.

As the container received heat the temperature of the interior air began to rise. Initially the increase was at the rate of one Celsius degree per five minutes. After half an hour the rate slowed to about one degree per eight minutes. By then the air temperature had risen by only five degrees and the side facing the heater looked and felt dry. The side shaded from the heater still appeared to be wet.

After letting the container dry for a day I repeated the experiment with a dry cover. This time the interior air warmed at the rate of one degree every three minutes. After half an hour the temperature rose by 10 degrees, twice as much as it had when the cover was wet.

Later I weighed the cover before and after soaking it with water. The soaked cover holds about 85 grams of water (after it has been emptied, of course). To evaporate that much water approximately 192 kilojoules of energy must be provided. If I assume that the intensity of the sunlight at my picnic table is about one kilojoule per second over a square meter, the cover should take about two hours to absorb enough sunshine to dry completely. It actually dries faster because nearby objects also provide infrared and visible radiation and because convection and conduction are delivering heat.

The Yunnan pot, which I obtained from Williams-Sonoma, also employs water, but for a different purpose. The glazed clay pot has a central chimney through which steam rises to heat food inside the pot. When I cook chopped meat or vegetables, I place the pot in a deep pie pan filled with water. As the water heats up, steam rises through the chimney and gently cooks the food.

The heat transfer is somewhat like that in a heat pipe except that the water does not return to the heat source. Instead it collects in the pot with the food, keeping the food moist. Steam cooking is more often done with a perforated metal basket mounted just above boiling water. The steam rises through the holes of the basket and condenses on the bottom of the food, transferring the latent heat of vaporization to it.

Some of the condensed water clings to the food, but most of it drains back to the bottom of the pan and is revaporized. The food remains moist but is not soaked. The advantage of the Yunnan pot over the metal basket is that the pot enables one to steam a food that is already liquid. In the basket the liquid would be lost to the pool of water.

I checked the pot with two simple experiments relying on a thermocouple probe mounted inside the pot about three centimeters from the bottom and about midway between the wall and the chimney. The temperature of the air inside the pot was initially 21 degrees. When I put the pot in a pan of boiling water, the air temperature began to rise at the rate of about .6 Celsius degree per second, reaching 90 degrees after slightly more than three minutes.

After cooling the pot I covered the top of the chimney with heavy tape and repeated the measurements. This time the increase in temperature was about four times slower. After three minutes the temperature was still less than 55 degrees. Clearly the normal rapid rise in the temperature inside the pot is driven by the latent heat of vaporization of the steam in the chimney. The conduction of heat through the bottom of the pot is less important.

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With the Guyed Tower step into

Exxon's engineers developed a series of innovations to turn theory into reality.

It has been called a technological breakthrough. The completed structure stands taller than the Empire State Building. It employs engineering techniques never before used in production platforms. And it will make oil and gas recovery from deep waters more economically feasible in the future.

It is the guyed tower—a new kind of drilling and production platform. And it is now operating 110 miles southeast of New Orleans in 1,000 feet of water.

The Leading Edge of Technology.

When Bob Rugeley of Exxon USA's Southeastern Production Division and his engineering team were given the assignment of putting the unique tower in place, they found themselves at the leading edge of deepwater technology. There were no precedents to guide them. Nothing like this had ever been done before.

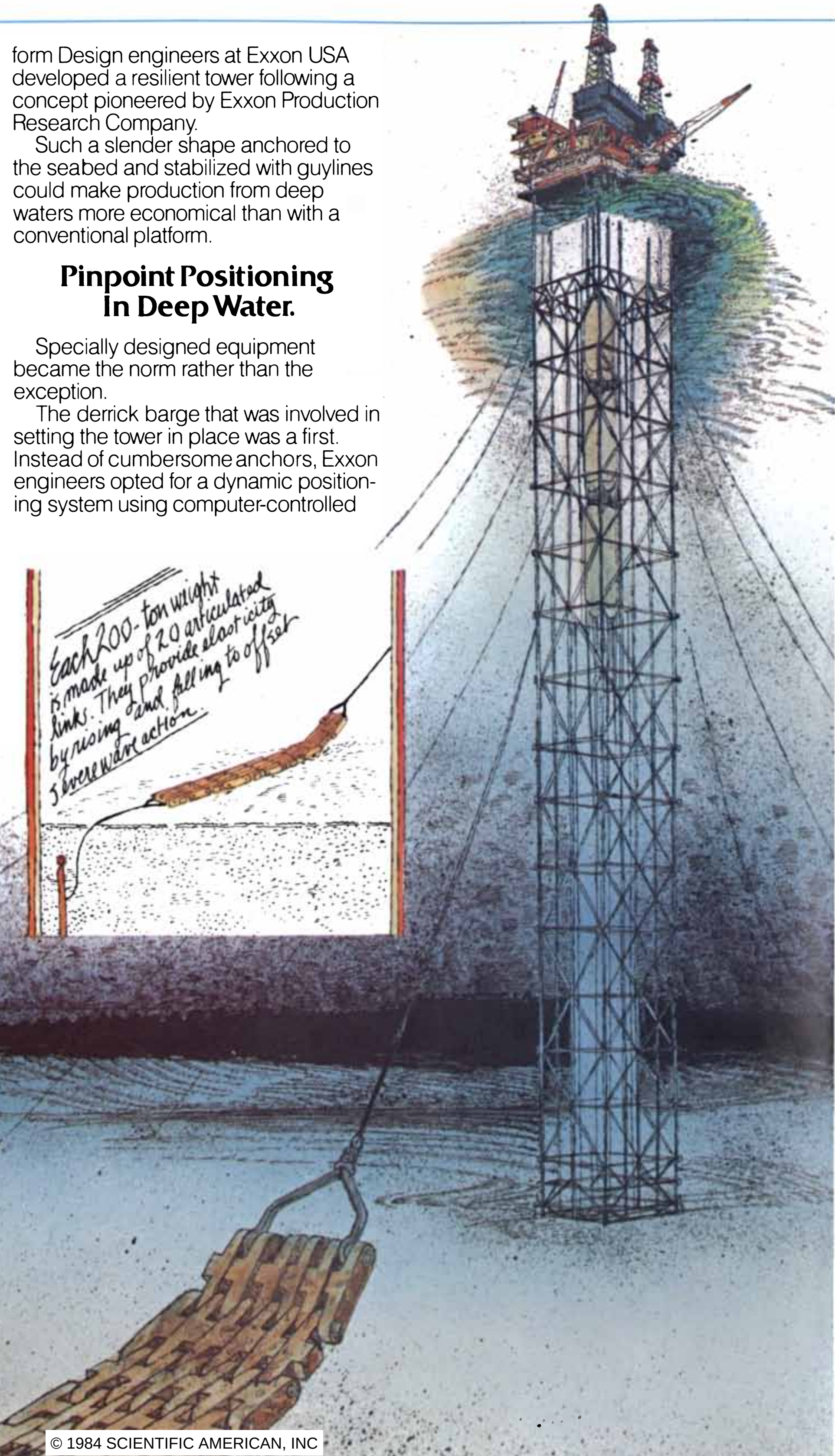
Instead of a conventional structure that depended on brute strength to withstand Gulf hurricanes, Offshore Platform Design engineers at Exxon USA developed a resilient tower following a concept pioneered by Exxon Production Research Company.

Such a slender shape anchored to the seabed and stabilized with guylines could make production from deep waters more economical than with a conventional platform.

Pinpoint Positioning In Deep Water.

Specially designed equipment became the norm rather than the exception.

The derrick barge that was involved in setting the tower in place was a first. Instead of cumbersome anchors, Exxon engineers opted for a dynamic positioning system using computer-controlled



Exxon takes a giant deeper water.

thrusters at all four corners to keep the vessel precisely on location.

Specially designed equipment was needed to lower the guylines into place on the seafloor and to drive the 72-inch-diameter piles which anchor them.

Twenty 3,400-foot guylines were attached to the tower, each with a designed breaking strength of almost 3 million pounds. But a full-fledged Gulf hurricane is an awesome force. Considering this, Exxon engineers developed clump weights, similar to segments in a bicycle chain and weighing 200 tons each, which are incorporated in the guylines to provide elasticity. This system keeps the deck virtually motionless most of the time. However, in a severe hurricane, it allows it to sway as much as 40 feet.

More Steel Than The Brooklyn Bridge.

At Harbor Island, Texas, building the tower was a formidable task.

With 15 miles of welding and more steel than the Brooklyn Bridge, it became the largest offshore structure ever assembled as a single unit. Then came the problems of transportation and installation.

Exxon engineers modified a barge nearly as long as two football fields to carry the mammoth launch weight of 27,000 tons over 400 miles of open sea. Then, instead of the normal launch off the end of the barge, they had to provide for a unique side-launch–a 10-second operation that took months to prepare

Today the job is done...the enormous structure has been placed in position and on target in 1,000 feet of Gulf water with all guylines connected. Drilling equipment has been installed, the first of 54 wells has been drilled and oil is being piped to shore.

This premier installation is far from the limit of the guyed tower's potential. Our new technology will make it more practical to recover oil in waters as deep as 2,000 feet or more in the years to come.

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